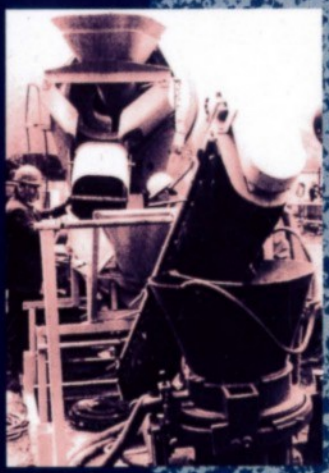
SPRAYED CONCRETE

PROPERTIES, DESIGN AND APPLICATION







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Sprayed Concrete:
Properties, Design and Application

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Whittles Publishing

Typeset by
Whittles Publishing Services,
Published by:
Whittles Publishing,
Roseleigh House,
Latheronwheel, Caithness, KW5 6DW,
Scotland

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British Library Cataloguing in Publication Data

Sprayed Concrete: Properties, Design and Application
I. Austin, Simon A. II. Robins, Peter J.
620.136

eISBN 978-1-84995-285-9

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Preface

The impetus for this book developed naturally through our involvement with sprayed concrete and from the realisation that, in many instances, engineers who were confronted with the design or construction of this material had a problem: they had limited knowledge which they could not easily supplement from published information or from the expertise of others. Although there are many articles relating to sprayed concrete, they are difficult to locate and usually of a very specific nature. There are also few books on the subject, although sprayed concrete has a history which began in 1911. Thus our objective has been to present in one volume the data, knowledge and views of an experienced group of practitioners, to provide a ready form of reference.

The structure and content are conventional: materials and properties; design and installation; and issues surrounding a range of applications. In each case the aim is to provide both facts and interpretation, and all the chapters are supported by substantial references to redirect those interested in further reading.

We thank our contributory authors, all busy practising engineers, for their time and effort. We believe it is important that such people are prepared to share and hand on their experience and know-how to the many who currently face the challenge of providing quality construction with this versatile material. We also thank Keith Whittles for his support, humour and understanding in the preparation of the manuscript.

Simon Austin and Peter Robins

1 Introduction to Sprayed Concrete

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1.1 Why this book?

Diligent researchers will find a substantial amount of published material on sprayed concrete, but many people do not have the time or resources to collect and assimilate the information scattered in conference proceedings, journals and trade literature, nor the contacts who can share their personal experience. This book is for those people – consulting, contracting and materials engineers, clients, manufacturers, students and researchers – and seeks to provide a comprehensive reference text covering the performance, design and installation of sprayed concrete as seen by a group of international practitioners.

Many who use this specialist material are involved on a one-off or infrequent basis and are inevitably inexperienced. We hope that this book provides the basic knowledge that will assist the unfamiliar in correct design, specification and construction, whilst also providing up-to-date and detailed information for the more proficient. The text is divided into three sections:

Section I deals with the materials technology, describing the ingredients and their blending (both on site and pre-bagged), production by dry and wet processes and the physical properties of sprayed concrete in both fresh and hardened states. It contains a substantial amount of technical data, but also gives views and advice on its interpretation.

Section II covers design and installation, the former in particular being an area that has received insufficient attention in the past. These are obviously two important subjects and, as in all branches of construction, the causes of problems can be attributed to these two sources in roughly equal proportions. But why do we still get problems with a process and material which when developed 80 years ago could produce a high quality, durable concrete? The answer must lie partly in the increasingly complex mixes and performance requirements with which the designer is faced and also with the change from a select group of traditional craftsmen-based companies to the widespread availability of sprayed concrete contractors and subcontractors, some of whom have little training and experience. There are many other contributing factors, but the key is knowledge of good design and construction practice, whether gained directly or through the efforts of others. The chapters in this section provide some of the latter in the context of structural, repair and tunnelling applications.

Section III provides specific guidance on the use of sprayed concrete for new construction, repair, rock stabilization, tunnelling and cathodic protection. The emphasis here is less on illustration of examples, which is well covered in other sources, and more on detailed description of aspects of materials selection, design and construction relevant to each particular situation.

Most readers will make reference to the parts of the book relevant to their needs at the time. An inspection of the complete text will inevitably find some repetition of subject treatment between chapters. However, we believe that some overlap is desirable because it maintains continuity within sections and reduces the need to cross-reference to other parts of the book to obtain a full picture. It also allows different views to be expressed, which is felt to be both honest and helpful in giving a fair account of the state of the art.

1.2 Terminology

Sprayed concrete can be defined as *'mortar or concrete pneumatically projected into place'*. There have been many definitions over the years which have changed from specific (e.g. for gunite) to general covering all aggregate ranges and both dry and wet processes. Glassgold (1991) gives a comprehensive discussion of the evolution in terminology. The above definition would seem to be generic and succinct, avoiding perhaps unnecessary reference to hoses, nozzle and velocity of the material.

Linked to these semantics has been a debate on the choice of terms to refer routinely to the material and the activity of placing it. This issue has occupied an unjustifiable amount of time and energy and most people are now reasonably relaxed and tolerant about the use of a range of words. The relevant adjectives are (in alphabetic order!) projected, shot and sprayed, each of which has found favour in languages around the world (for example béton projeté, shotcrete and spritzbeton). This book has been titled as sprayed concrete, because it is probably the nearest english translation of the various european terms. However, the contributors have been free to use whatever terminology is most familiar to them, and no editorial policy has been enforced. We hope that readers will be equally flexible in this respect.

1.3 Historical background

The inventor of the process is widely acknowledged to be Carl E. Akeley (1864-1926) who experimented with the pneumatic application of first plasters and then cement mortars at the turn of the century. He was an explorer and naturalist associated with the Field Museum of Natural History in Chicago and invented the 'Cement Gun' (Figure 1.1) to make models of animals. He obtained patents for the equipment and method in 1911 and the material was called 'Gunite' the following year by the Cement Gun Company of Allentown, who had taken over the patents. The company expanded internationally, moving into Germany in 1921 and the UK in 1924 (it became wholly British owned in 1953).

The process involved placing a dry sand/cement mixture in a pressurized chamber from which it was conveyed pneumatically to a nozzle where water was added. It was therefore a dry-mix process and the main equipment has continued to be called a gun, whether of the original simple or double chamber style or the more

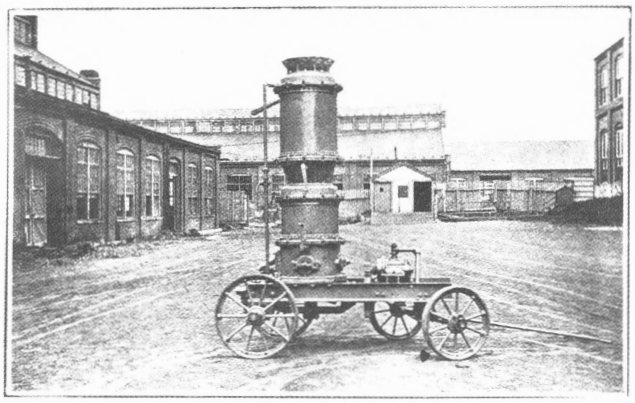

Figure 1.1 *The original Cement Gun of Carl E.Akeley* (courtesy of thePortland Cement Association, USA)

modern rotating barrel and feedwheel types. Within a short time some applicators were also adding larger aggregate to make a concrete and by the 1950s the term shotcrete became widely used to cover both sprayed mortars and concretes. Between 1942–1951 the American Concrete Institute had a standing committee on the subject (Committee 805 on Pneumatically Placed Mortar; this was reactivated in 1957 as Committee 506 on Shotcrete) and this has become one of the most authoritative sources of technical information and standards.

The wet mix process started to be developed around this time in the form of the 'True Gun', although the method had been experimented with (largely unsuccessfully) at the time of the invention of the dry process Cement Gun. Some users (including the American Gunite Contractors Association, founded in 1951) chose to use the term shotcrete to refer specifically to the wet process.

Terminology thus became confused over the next two decades until the general acceptance of 'shotcrete' in the USA and 'sprayed concrete' (or its equivalent) in Europe to describe all pneumatically/pumped spray applied mortars and concretes. This was reflected in the change of name of the British trade association, the Association of Gunite Contractors which was formed in 1976 but later renamed itself the Sprayed Concrete Association.

Another milestone was the development in the USA of rotating-barrel machines, which were based on a Dutch patent of 1929. These machines, which were rugged, high output and easy to use, became very popular for the dry process and have more recently been adapted to spray wet concretes. There was a parallel evolution in wet process equipment with the availability of small, powerful displacement (piston) and peristaltic pumps. This in turn led to the introduction of robot controlled equipment to cope with the high output (hence high weight) and rapid, falsework-free application required in underground rock support.

These novel methods of placing concrete rapidly established sprayed concrete across its full range of applications, which are all still relevant today. Each makes use of the uniquely flexible nature of the application technique which requires minimal formwork and access space to produce flat or curved surfaces. They include: fire protection of steel framed buildings; new construction and repair of reinforced

concrete structures; thin arches, domes and shells; swimming pools, dams and sea defences; rock stabilization; underground rock support and tunnelling; chimney and tower linings; and refractory concrete for the iron, steel, power and petrochemical industries. Notable historical examples include the doubly curved St Louis Priory Church, the thin arch Spitfire hangars in the UK, the Rabodanges dam in France, Baillard Cut on the Panama Canal and the Mersey tunnel.

Following behind developments in practice (as always) has been the introduction of standards for practice, testing and specification. The USA has been most prolific in this respect, starting with the American Concrete Institute Committee 805 Standard of 1951, which was subsequently revised and augmented by a range of documentation under Committee 506 and complemented by the production of five ASTM national standards since 1988. Europe was slower to respond, with codes of practice and standard specifications being produced in the UK between 1976 and 1981, by the Association of Gunite Contractors and the Concrete Society, and in Germany with DIN 18 551 in 1979. French and Norwegian standards have followed in the last few years.

Those wishing to read more on the historical development of sprayed concrete should refer to the reviews of Glassgold (1991), Lorman (1966) and Teichert (1979).

1.4 Current and future trends

Sprayed concrete continues to be applied across the broad range of construction established in its early years, although the proportion devoted to underground support has increased in the last two decades. Recent examples which demonstrate its unique properties are:

- In new construction, the Janadriyan complex near Riyadh, Saudi Arabia, which contains a number of double-curvature tent structures. The membrane required extensive computer analysis and was constructed with dry process concrete sprayed onto a high-yield reinforcement mat fixed in the required catenary profile.
- In art, the sculpture 'House' by Rachel Whiteread, which won the Turner prize in 1993. Dry process sprayed concrete (containing white cement) was applied to the inside of a Victorian terraced house (193 Grove Road, London) and then the brick-walled structure was carefully demolished to reveal a negative image of the dwelling. The controversial sculpture was itself demolished on the orders of the local council two and a half months after its creation.
- In repair, the reconstruction of the dome of the Church of the Holy Sepulchre, Jerusalem. This church, dating back to AD333, protects the Tomb of Christ and contains a 33 m diameter dome, last rebuilt in 1870 with wrought iron lattice arches. This was repaired in 1980 by the construction of a 115 mm thick outer sprayed concrete (dry process) shell designed to carry most of its self-weight directly to the masonry supporting walls, thus protecting but not significantly loading the original lattice arches.
- In rock stabilization, the completion of the 100 km North Wales A55 coast road in 1994 after 25 years of construction along a narrow coastal plain, over the Conwy estuary and through rocky headlands. Sprayed concrete was used in a number of locations including the Pen-y-Clip tunnel and Rhuallt hill, the latter involving stabilisation of Silurian mudstone cuttings with sprayed concrete coloured to match.

• In underground support, there have been many outstanding examples of both temporary and permanent construction in recent years, including: the Madrid-Sevilla railway line which has 15 tunnels of 75 m^2 cross-section totalling 15 km in length and constructed between 1986 and 1992; a variety of tunnel, shaft and station structures on the Washington metro, including the Fort Totten station constructed in soft ground by the New Austrian Tunnelling Method; the 2.6 km Sing Mun twin road tunnels, Hong Kong, excavated in granite and supported by 50–200 mm of sprayed concrete and rockbolts at 1–2 m centres using the Norwegian method of tunnelling (Q system); and pumped storage power station schemes at Dinorwig, Wales and Mingtan, Taiwan. These projects have utilized both dry and wet processes and, in several cases, steel fibre reinforcement, which has become a common element in tunnel construction.

It is perhaps difficult to imagine radical new applications for sprayed concrete, but it is also equally difficult to predict how the current usage will develop and expand. The evolution of sprayed concrete will depend on how the challenges to produce cheaper, higher performance, more durable concrete are met. Consistent high quality is a key issue and appropriate developments in materials technology, equipment and design methods should deliver the high performance that will be demanded of construction materials in the next decade.

There have already been significant changes in the materials used in sprayed concrete over the last ten years. Silica fume has become a common addition to increase adhesion, strength and impermeability, but there has as yet been little application of other cementitious materials such as pulverized fuel ash (fly ash) and slag. Admixtures have extended their influence from simple accelerators to include water-reducers, super-plasticizers, air-entraining agents, hydration stabilizers and latex polymers. Fibre reinforcement (mainly steel but also polypropylene) has also become a common addition in both dry and wet processes to improve toughness and impact resistance. Special blends of combinations of these materials are available in pre-bagged form to give high performance mixes suitable for repair applications and situations with limited space for site batching.

Changes in mix formulations have been accompanied by steady developments in equipment design. The biggest innovations have centred around robot-controlled spraying, usually for tunnel and rock support applications. Whilst these machines do not have the precision or intelligence of the robotic systems used in other engineering fields, they are able to resist the severe demands that a harsh underground environment places on the design and manufacture of tunnelling equipment. Further developments in this area and its extension into other applications can be expected in the future.

Progress in spraying guns and pumps has been less marked. Although new types of gun have been developed, most contractors continue to use conventional rotating barrel/bowl guns for the dry process and worm or piston pumps for wet mix. Steady improvements have been made in recent years, including the introduction of flexible machines that can spray dry or wet. In some countries there has been a big swing towards the wet process, partly because of the better control over mix proportions (particularly the water/cement ratio). These include Norway and Sweden, where most work is wet process, and in the USA where the two techniques have a roughly even share. In the UK the proportion is low but increasing,

whilst countries like Germany are still predominantly orientated to the dry process. These differences partly reflect the functional emphasis (e.g. wet mix for tunnelling, dry mix for repair), but also what is perceived to be good practice in the engineering community. Undoubtedly there will be further shifts in the balance as trade barriers are removed, particularly in Europe, and technology is transferred across borders and fields of application. Dry mix proponents need to address the consistency and quality issues associated with manually controlled water addition, whilst the wet mix process could extend its range by improving its stop/start flexibility.

Finally, there needs to be more research and development of design methods. In recent years the industry has benefited from the introduction of a range of standard test methods and specifications. These must be regularly updated and augmented by other appropriate documentation. In Europe the Committee for European Normalization has just established a working group to produce a European standard specification for 1997. However, engineers also need a framework of acceptable design methods to cover the range of sprayed concrete structures. There has been progress in some areas, such as the Norwegian Method of Tunnelling which has evolved from the *Q*-system for rock support, although the collapse in October 1994 of part of the Heathrow Express tube line has raised doubts about the application of a modified New Austrian Tunnelling Method to construction in London clay (despite a £1 million experimental trial of the construction method in 1992). Other applications such as repair and slope stabilization have less well established rationales, making it difficult for engineers to quantify and justify their design proposals. Fibre reinforced concrete offers potential advantages in many situations, both above and below ground, but it is widely recognised that more research is required to produce design methods that are acceptable to the engineering community.

With these challenges in mind this is clearly not a time for complacency in the sprayed concrete industry. Much has been achieved over the last 80 years but further efforts are required to turn an established craft into a modern technology.

References

Glassgold, I.L. (1991) Shotcrete in the United States: a brief history. *Evaluation and Design of Concrete Structures and Innovation in Design* (SP-128), American Concrete Institute, Detroit, 289–305.

Lorman, W.R. (1966) *Engineering Properties of Shotcrete*. NCEL Report No. 429, U.S. Naval Civil Engineering Laboratories, Port Huenline. Also SP-14A, American Concrete Institute, Detroit, 1968

Teichert, Von P. (1979) Die Geschichte des Spritzbetons. *Schweizer Ingenieur und Arthitekt*, 47.

2 Materials

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2.1 Introduction

The materials used in sprayed concrete are basically similar to those used in ordinary cast structural concrete. Prior to the 1980s most sprayed concrete applications in the UK and North America used an ordinary Portland cement/aggregate mix placed by the dry-mix process, typically at a sand/cement ratio of around 3:1 by weight.

During the 1980s significant developments in both the equipment and the materials technology for sprayed concrete led to increasing use of the material in both new construction and repair. New developments in materials technology included:

- the use of fibres (usually steel or polypropylene) as an alternative to conventional mesh reinforcement;
- the use of supplementary cementing materials, such as fly ash and silica fume, as additions or partial replacements for cement;
- the use of special cements as an alternative to accelerators in sprayed concrete where high early strength is required; and
- the increasing use of special chemical admixtures, particularly in the wet-mix process.

Other major advances have arisen through the development of improved methods in the production process for sprayed concrete, i.e. in the batching, mixing, supply and application. Perhaps most notable of these is the development and use of fully-automated robotics systems for the placement of wet-mix sprayed concrete (see chapters 4 and 9).

2.2 Cements

Before the 1980s most sprayed concrete in the UK and North America (Morgan, 1992) used ordinary Portland cement as the binder, the exception being refractory concretes where the use of high alumina cements is customary. Sulphate-resisting or rapid hardening cements found occasional use where conditions required them. More recently, special cements for rapid setting and/or high-early strength gain have been used in sprayed concrete (see chapter 11). Gebler (1989) has discussed the durability of dry-mix sprayed concrete containing a regulated-set cement, and Morgan (1991) has reported on the use of high-early-strength blended cement in wet-mix sprayed concrete. Such cements are used as an alternative to an ordinary sprayed concrete with an accelerator, in order to achieve similar effects on the setting/hard-

ening properties but without the adverse side effects (e.g. on shrinkage, later-age strength and durability).

Ordinary Portland cement is likely to remain the most widely used type of cement in sprayed concrete, but is increasingly being used with supplementary cementing materials, such as fly ash and silica fume, in both the dry and wet-mix processes. As early as 1985/6, Opsahl (1985) and Skatun (1986) were reporting that nearly all sprayed concrete work carried out in Norway was done by the wet process with silica fume as an additive at 10% by weight.

2.3 Supplementary cementing materials

In recent years a significant research effort has been directed towards the use of supplementary cementitious materials (such as fly ash, slag and silica fume) in concrete. One benefit from the use of such materials is their potential for improving a concrete's impermeability, through a reduction in the porosity of the cementitious matrix (the porosity of the aggregate components in most cases being negligible). This is brought about by incorporating an additional material that reacts with the cement to produce a higher proportion of hydrated products in the concrete. Whilst fly ash (a waste product from the combustion of coal in power stations) has been used in concrete for many years, it is another 'newer' pozzolanic material, silica fume, that has found increasing use in the sprayed concrete industry, particularly in Scandinavia and North America. Silica fume is now no longer regarded simply as a waste by-product from the silica and ferrosilicon alloy industries but rather as a pozzolan that can be used to enhance both the fresh and hardened properties of concretes and mortars. The differences in properties between a silica fume and a fly-ash modified concrete arise because of the much smaller particle size of silica fume (approximately 100 times finer than cement) and its higher SiO_2 content. During the hydration of cement, quantities of calcium hydroxide, the weakest and most water soluble hydration product, are formed. However, if silica fume or another pozzolanic material is used, the SiO_2 present reacts with the calcium hydroxide to form calcium silicate hydrate, which contributes significantly to the strength and density of the hardened concrete. The physical properties of silica fume are compared with fly-ash and cement in Table 2.1

There are many advantages claimed for the addition of silica fume to a concrete mix, including improved strength and durability, but it is the changes in properties of the fresh concrete that are of major potential benefit in sprayed concrete. Improvements in the cohesion and adhesion of the concrete mix have obvious implications to the application of thicker layers, better adhesion to substrates, and reduction in rebound during the spraying process. Other advantages claimed for silica fume are lower levels of dust in the dry process and improved resistance to washout by water.

Silica fume is used in both dry and wet processes, usually at between 5 and 15% by weight replacement of cement. Silica fume was first used in sprayed concrete in Norway in the 1970s. Almost all sprayed concrete work carried out in Norway is done by the wet process (Skatun, 1986: Opsahl, 1985), with silica fume a common additive at around 10% by weight of cement. In the wet process a water-reducer or superplasticizer is invariably required to maintain workability. In the early 1980s,

Table 2.1 *Comparative properties of cement, fly ash and silica fume*

	specific surface (m^2/g)	relative density	SiO_2 content %
OPC	0.25–0.50	3.12–3.15	17–25
fly-ash	0.30–0.50	2.35	40–55
silica fume	18–22	2.16	88–98

the use of silica fume in sprayed concrete developed in North America, in the dry mix process. Morgan (1988) reports on the extensive application of dry process silica fume sprayed concrete reinforced with steel fibres for repair of marine structures, rock slope stabilization, tunnel linings and aqueducts. More recently, Morgan and Wolsiefer (1992) have reported on a study of the use of different forms of silica fume in wet-mix sprayed concrete and concluded that all three forms of silica fume studied (uncompacted, compacted low density and compacted high density) and types (silicon furnace fume and ferrosilicon furnace fume) can be readily batched, mixed and applied, using the wet-mix sprayed concrete process.

Because of its significant effect on the adhesion and cohesion of concrete, silica fume has found much wider use than other supplementary cementing materials. The use of fly ash in dry process sprayed concrete has been fairly limited, though by providing additional fines it can improve the cohesion and adhesion of the sprayed concrete. Morgan *et al.* (1992) have investigated the use of a high-volume fly ash wet-mix sprayed concrete containing polypropylene fibre for rock stabilization applications. They concluded that the 60% fly ash (by weight of cement), together with water reducing admixtures and superplasticizers, produced a sprayed concrete with low shrinkage, low permeability and good freeze/thaw durability when compared with a wet-mix Portland cement concrete.

2.4 Aggregates

The grading of aggregates is critical in sprayed concrete due to the lack of external vibration and the changes in mix proportions as a result of rebound (particularly in the dry process). Heavier particles rebound more than the lighter sand grains and cement, resulting in a more finely graded material in situ with a higher cement content. Gradings should therefore be kept coarse to ensure a balanced in-situ material.

In the UK the aggregates should conform to BS 882 (1983). For the dry process the old zone 2 sand with a maximum size of 6 mm was most common; this old grading falls at the coarse end of the newer *medium* grading of BS 882 (Figure 2.1). Aggregates are usually of marine or river origin because irregular, angular or flaky aggregates are more abrasive and can cause blockages. In the dry process the sand is often mixed in a damp condition – typically 3 to 5% moisture by weight – to reduce the dust which occurs both at gun and nozzle during spraying and to give improved

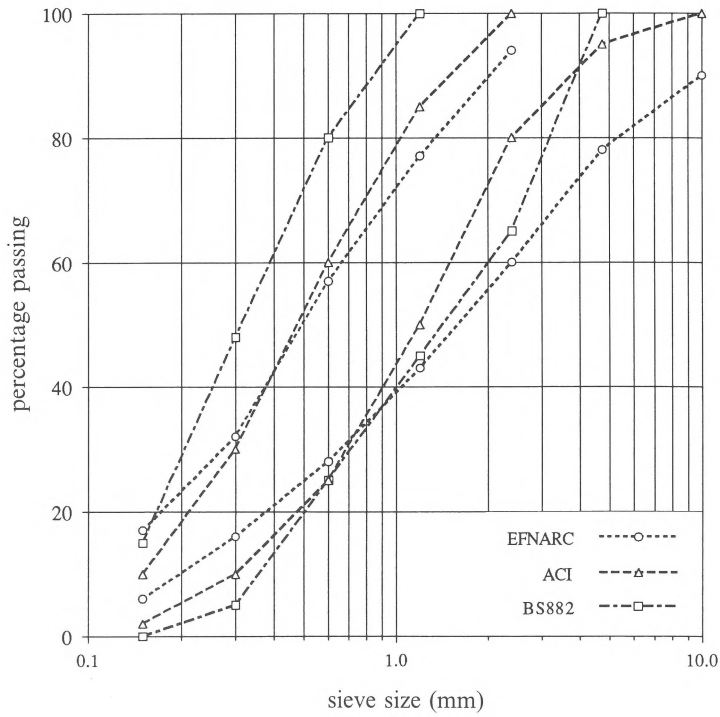

Figure 2.1 *Comparative aggregate gradings*

hydration. With pre-bagged dry mixes a pre-moisturizer can be used to dampen the material before it enters the gun.

ACI 506R-90 (1990) gives details of three aggregate gradings for sprayed concrete (see Table 11.1). Gradation No.1 is essentially a concrete sand gradation, commonly used in the dry-mix process Gradation No.2 is a coarser gradation with about 25% by mass of a 10 mm maximum size coarse aggregate and 75% by mass of a concreting sand, and is commonly used in both wet-mix and dry-mix sprayed concretes. Gradation No.3 contains a blend of 20 mm aggregate and concreting sand, and generally only finds application in large volume, thick-section new sprayed concrete construction with predominantly downward shooting (Morgan, 1992). Gradation No.1 of ACI 506 (1990), the medium BS882 (1983) grading and the EFNARC (1993) recommended range are compared in Figure 2.1.

Of crucial importance in the wet-mix process is the need to achieve a balance between the concrete characteristics required to produce a pumpable mix and those characteristics required to project it into place with minimum losses and segregation. Correct aggregate grading is more critical than in the dry process and dependent upon the pumping distance and equipment. Engineers should be guided by the equipment manufacturers' recommendations, but pumping and spraying gradings are discussed by Cooke (1990). The amount of large aggregate particles should be

kept low (because of high rebound) and the sand content high (to ensure adequate consistency). The sand should have a high fines content, one equipment manufacturer recommending approximately 500 kg/m^3 of material smaller than 0.25 mm, including cement.

Aggregates for sprayed concrete should, of course, conform to all the performance requirements of national standards. In particular, aggregates used in sprayed concrete applications subjected to freeze/thaw cycling, or exposure to de-icing salts should be durable in these aggressive environments.

2.5 Admixtures

A variety of additives and admixtures are added to sprayed concrete, particularly with the wet process, to improve strength, adhesiveness, cohesiveness, freezing/thawing and abrasion resistance characteristics, and reduce rebound. Higher material costs are offset by savings in the volume of sprayed concrete used and labour.

Setting of the cement begins with the reaction between the tricalcium aluminate and the gypsum to form tricalcium sulphoaluminate hydrate (ettringite). The setting process can be speeded up by the use of an accelerator. The choice of a particular set accelerator (Bürge and Bächli, 1991) and its dosage is largely governed by the setting time required, though it must be remembered that concrete strengths are related to the length of the setting time. Accelerators are being used increasingly in both dry and wet-process applications. Accelerators are common in the dry process to increase early strength and reduce dust, and in the wet process an accelerator is often added at the nozzle to achieve rapid set (Skatun, 1986). Jones (1985) discusses suitable admixtures, and Wallace (1987) reports on a potassium aluminate based accelerator that produced rapid set without early strength loss in the wet process; he also claims that it reduced dust and rebound in the dry process.

Various water-soluble salts of the alkali metals can be used to accelerate the setting of cement. Most of the set accelerators used today are based on alkali aluminates in combination with carbonates and hydroxides.

Manns and Neubert (1992) have recently reported on an investigation of dry-mix and wet-mix sprayed concretes with normal and high quantities of accelerating admixtures (alkali aluminates and alkali carbonates), *normal* being the upper limit as specified by the manufacturer and *high* being twice this amount. Compared to normal dosage mixes, compression strengths of the high-dosage sprayed concretes were reduced by 15% or more, depending on age, with the wet-mix strengths being affected more. Tensile strength and modulus of elasticity were reduced by around 25%, and both shrinkage and creep movements were substantially increased.

Water-reducers (commonly lignosulphonic acids or hydroxylated carboxylic acids) and superplasticizers are commonly employed in the wet process to improve workability and cohesiveness; Krantz (1984) describes the use of both types of admixture. Where silica fume is included in wet-mix sprayed concrete it is common to use a superplasticizer to control the high water demand of the mix resulting from the small particle size of the silica fume. Liquid water-reducers or superplasticizers are not used in dry-mix sprayed concrete because there is not enough time for the properties of these admixtures to be mobilized between the addition of the water at the nozzle and the placing of the material on its target.

Air-entraining admixtures can be used in wet process sprayed concretes to improve the concretes' resistance to freeze/thaw. Schrader and Kaden (1987) concluded that it was difficult to obtain in-situ air contents above 5%, but that there was some evidence that a sprayed concrete required a lower air content (2 to 3%) for freeze-thaw resistance than conventionally placed concrete. Gilbride *et al.* (1988) and Morgan (1989) found that as much as one half of the air content of wet-mix concrete is lost through spraying onto the receiving surface. Air entrainment in dry-mix sprayed concrete has generally proved unsuccessful. However, Beaupré *et al.* (1994) have shown that it is possible to entrain adequate air in the dry process by adding the air entraining admixture to mixing water that is injected at the nozzle.

Melbye (1991) describes a two-component additive system, developed specifically for the sprayed concrete market, to control the dynamics of the cement hydration. The system consists of a stabilizer and activator, the former to stop the cement hydration process and the latter to break down the barrier formed by the stabilizer and hence allow the cement to set. Whilst primarily developed for use with the wet process, the system has also been used in dry process sprayed concrete.

Polymer latex additives (such as styrene-butadiene) have been utilized in the dry process to try and improve adhesion, resistance to chlorides and freeze/thaw attack, and to reduce permeability (Krantz, 1984; Schrader *et al.*, 1987; Ramakrishnan, 1985). Schorn (1983) has investigated an epoxy resin (polyvinyl acetate) in the dry process, added as an emulsion through a special water ring in the nozzle, to try to minimize the effect of differential shrinkage between the sprayed layer and its substrate.

2.6 Fibres

The use of fibres in sprayed concrete is becoming increasingly common. Steel, polypropylene and glass fibres have all been used in a variety of applications, but of the three materials, steel fibres account by far for the largest usage, having applications in mine and tunnel linings, rock slope stabilization, thin shell dome construction, refractory linings, dam construction, repair of surfaces, and fire protection coatings. The first field application of sprayed steel-fibre reinforced concrete took place in 1972 when it was used in a tunnel adit at Ririe Dam, Idaho by the US Army Corps of Engineers (Kaden, 1977). Glass fibre reinforcement of sprayed concrete is less common, principally because of concern over long-term durability (due to alkali attack of the glass); one early application was the repair to a navigation lock in Washington State (Schrader, 1980). Uses of sprayed concrete with polypropylene fibres have only more recently been reported (Boyes, 1986), but include applications such as tunnel linings, shell domes, repair and as a component in stucco-type overlay systems (ACI Committee 506, 1984).

Steel fibres

Steel fibres for sprayed concrete may come from a variety of manufacturing processes (cutting wire, slitting sheet, milling blocks, and melt extraction) and are available in a wide variety of shapes, sizes and metal types. Cross sections may be round, rectangular, semi-circular or crescent shaped, and fibre lengths can vary from about 12 mm up to as much as 75 mm. However, most successful sprayed concrete appli-

cations have used fibres with lengths in the range 18 mm to 30 mm, with 20 to 25 mm being the most common. Typically, aspect ratios (length/diameter) are in the range 40–65, as values above this range tend to be more difficult to spray.

Perhaps the most common types of steel fibre used in sprayed concrete field applications are: (i) hooked-wire – a cold-drawn carbon-steel fibre, with hooked ends for improved bond; (ii) slit-sheet – a short slit-sheet carbon-steel fibre with a rectangular cross section and enlarged ends; and (iii) melt-extract – a melt extracted high-carbon or stainless steel fibre with crescent shaped cross-section and rough surface texture.

The stainless steel (AISI 430, 446 or 304) melt-extract fibre has the obvious advantage of being corrosion resistant. Stainless steel wire and slit-sheet fibres, though available, are prohibitively expensive for civil applications and are normally only used in high temperature refractory concrete. Corrosion of carbon-steel fibres in civil applications has been reported to be minimal with little effect on properties of steel-fibre reinforced concrete; fibre corrosion has been observed to be confined to fibres exposed on a surface, with internal fibres showing no corrosion (ACI Committee 506, 1984). Figure 11.4 shows some of the types of steel fibre currently used in sprayed concrete.

Polypropylene fibres

Whilst steel fibres dominated the sprayed fibre-concrete market during the 1970s and 1980s, by the mid-1980s monofilament and collated fibrillated polypropylene fibres were being used in wet-mix sprayed concrete with low fibre dosages of about 1 kg/m^3, which is typical for their use in cast concrete applications. At these low addition rates, the benefits are limited mainly to the enhancement of the properties of the fresh concrete (cohesiveness, etc.) and its resistance to plastic shrinkage cracking. A more recent development is the use of 'high-volume' (4–7 kg/m^3), wet-mix polypropylene fibre sprayed concrete (Malhotra *et al.*, 1989; Langley *et al.*, 1990; and Morgan *et al.*, 1992) typically using a collated fibrillated fibre 38 mm long. At these fibre addition rates, the fibres do provide reinforcement to the hardened concrete, resulting in load/deflection (and toughness) behaviour similar to that produced by steel fibre reinforcement. A typical fibrillated polypropylene fibre is shown in Figure 11.5.

Low additions (up to 1 kg/m^3) of polypropylene fibres are also used in dry-mix sprayed concrete, particularly in proprietary pre-bagged spraying repair mixtures. Austin and Robins (1989) have reported on a high volume application of polypropylene fibres using the dry-mix spraying process to repair a deteriorating brickwork water tower. The mix used 12 mm long fibres at an addition rate of c.10 kg/m^3.

2.7 Mesh and bar reinforcement

Light mesh reinforcement is common in applications where the sprayed concrete is not required to give major strengthening and hence is not subjected to significant structural loading. Examples include linings to existing structures and concrete repair applications where bar reinforcement is already present. The mesh serves to limit the development and depth of cracking resulting from shrinkage and temperature stresses, and is also intended to hold the sprayed concrete layer together in the

event of cracking or debonding from the substrate.

Meshes are typically 75 mm × 75 mm or 100 mm × 100 mm with a wire diameter of around 2.5 mm to 4.0 mm, giving a steel area of 90 to 130 mm^2/m. A sensible minimum spacing for the mesh wires is 50 mm; severe problems with placing of the sprayed concrete (and with rebound) are likely to occur with sizes less than this. A light mesh is an advantage for ease of handling and placing, but must be fixed in such a way as to make it rigid enough to prevent vibration during the placement of the sprayed concrete. A combination of small bars and mesh can be used where a mesh alone would not be sufficient structurally for the application, or where uniform spacing and cover are critical, as in curved or irregular surfaces. The bars will also aid in limiting both the deflection of the mesh during its installation and the flexing of the mesh during spraying. Reinforcing bars are rarely used in sprayed concrete with a thickness less than 40 mm. Meshes can be used in thicknesses of sprayed concrete down to about 25 mm.

Where the application is fully structural, conventional plain or deformed reinforcing bars will be needed. Reinforcement for sprayed concrete as a structural material is designed using the same criteria as for conventional cast concrete. Care must be taken however to size, space and arrange the reinforcing bars to cause the least interference with the placement of the sprayed concrete, and so minimize the development of sand pockets and voids.

All intersecting reinforcing bars should be tied rigidly to each other and to their anchors, as any vibration of the reinforcing bars during placing can cause sagging of the freshly sprayed concrete, creating voids and reducing in-place strengths. Where possible, bars should be spaced to permit shooting at a slight angle from either side of the bar. For sprayed concrete thicknesses of less than 200 mm, one layer of reinforcing is usually sufficient, with or without mesh (depending on the application). For greater thicknesses containing several layers of bars, the size and spacing must allow for effective spraying of the deeper recesses.

A fuller discussion of good practice relating to reinforcement of sprayed concrete can be found elsewhere (Ryan, 1973; ACI Committee 506, 1990).

References

ACI Committee506 (1984) State-of-the-art report on fibre reinforced shotcrete. *Concrete International*, **6**(12), 15–27.

ACI Committee 506 (1990) *Guide to Shotcrete*. American Concrete Institute, Detroit, 41.

Austin, S.A. and Robins, P.J. (1989) A repair application of polypropylene fibre reinforced sprayed concrete. *Proc. Int. Conf. on Recent Developments in Fibre Reinforced Cements and Concretes*, September, Cardiff, 21–31.

Beaupré, D., Talbot, C., Gendrau, M., Pigeon, M. and Morgan, D.R. (1994) De-icer Salt Scaling Resistance of Dry and Wet Process Shotcrete. *American Concrete Institute Materials Journal*, **91** (5), 487–94.

Boyes, R.G.H. (1986) Assimilating concrete progress. *Civil Engineering*, Aug., 43–53.

British Standards Institution (1983) BS 882 *Specification for aggregates from natural sources for concrete*. Milton Keynes.

Bürge, A. and Bächli, R. (1991) Additives and admixtures for shotcrete. *Tunnels and Tunnelling*, January, 54–56.

Cooke, T.H. (1990) *Concrete Pumping and Spraying, a Practical Guide*. Thomas Telford Ltd. 266pp.

EFNARC Technical Committee Sprayed Concrete (1993) *Draft Specification for Sprayed Concrete*. European Federation of National Associations of Specialist Repair Contractors and Material Suppliers for the Construction Industry, Aldershot, UK.

Gebler, S. (1989) Durability of Dry-Mix Shotcrete Containing Regulated Set Cement. *Concrete International, Design and Construction,* Vol.11, No.10, October, 56–58.

Gilbride, P., Morgan, D.R., Bremner, T.W. (1988) Deterioration and Rehabilitation of Berth Faces in Tidal Zones at the Port of Saint John. *American Concrete Institute, Detroit*, Concrete in Marine Environment, SP-109, 199–226.

Jones, M. (1985) Why add to shotcrete? *Tunnels and Tunnelling*, **17**(7), 53–58.

Kaden, R.A. (1977) Fibre reinforced shotcrete. Ririe Dam and Little Goose (CPRR) Relocation. Shotcrete for Ground Support, *SP-54, ACI/ASCE*, Detroit, 66–68.

Krantz, G.W. (1984) Selected pneumatic gunites for use in underground mining: a comparative engineering analysis. *US Bureau of Mines Information Circular 8984*.US Department of the Interior.

Langley, W.S. and Dibble, D. (1990) Field Trials of Shotcreting Fibre-Reinforced High Volume Fly Ash (ASTM, Class F) Shotcrete. *CANMET International Workshop on Fly Ash in Concrete*, Calgary, Alberta, October.

Malhotra, V.M., Carrette, G.G. and Bilodeau, A. (1989) Fibre Reinforced High Volume Fly Ash Shotcrete for Controlling Aggressive Leachates from Exposed Rock Surfaces and Mine Tailings. *Third CANMET/ACI International Conference on Fly Ash, Slag, Silica fume and Natural Pozzolans*, Trondheim, Norway, June 18–23.

Manns, W. and Neubert, B. (1992) Mechanical-technological properties of shotcrete with accelerating admixtures. *Otto Graf Journal*, Vol.3, 115–136.

Melbye, T. (1991) New advances in shotcrete additives. *Tunnels and Tunnelling*, July.

Morgan, D.R. (1988) Dry mix silica fume shotcrete in Western Canada. *Concrete International Design and Construction*, Vol.10, No.1, 24–32.

Morgan, D.R. (1989) Freeze-Thaw Durability of Shotcrete. Concrete International, *Design and Construction*, Vol.11, No.8, August, 78–85.

Morgan, D.R. (1991) High Early Strength Blended Cement Wet-Mix Shotcrete. *Concrete International*, Vol.13, No.5, May, 35–39.

Morgan, D.R. (1992) New developments in shotcrete for repairs and rehabilitation. *Advances in Concrete Technology Conference, Athens*, 699–739.

Morgan, D.R. and Wolsiefer, J. (1992) Wet-Mix Silica Fume Shotcrete: Effect of Silica Fume form. *Proc. 4th CANMET/ACI International Conference on Fly Ash, Silica Fume, Slag and natural Pozzolans in Concrete*, SP132, Istanbul, May, 1251–1272.

Morgan, D.R., McAskill, N., Carette, G.G. and Malhotra, V.M. (1992) Evaluation of polypropylene fibre reinforced high-volume fly ash concrete. *ACI Materials Journal*, Vol.89, No.2, March-April, 169–177.

Opsahl, O.A. and Buhre, K.E. (1985), Why wet process steel fibre reinforced shotcrete? *Proceedings of US-Sweden Joint Seminar on Steel Fibre Concrete*, Stockholm, 51–65.

Ramakrishnan, V. (1985), Steel fibre reinforced shotcrete - a state of the art report. *Proceedings of US-Sweden Joint Seminar on Steel Fibre Concrete*, Stockholm, 7–24.

Ryan, T.F. (1973), *Gunite: A Handbook for Engineers*, Eyre and Spottiswoode, Leatherhead.

Schorn, H. (1983), Epoxy modified shotcrete, *Polymers in Concrete (SP-89)*. American Concrete Institute, Detroit, 249–260.

Schrader, E. et al. (1986), Deterioration and repairs of navigation lock concrete. *Performance of Concrete in a Marine Environment (SP-65)*. American Concrete Institute, Detroit, Aug., 557–576.

Schrader, E.K. and Kaden, R.A. (1987), Durability of shotcrete. *Concrete Durability (SP-100)*, American Concrete Institute, Detroit, 1071–1101.

Skatun, O. (1986), Applications of wet process steel fibre reinforced shotcrete in Scandinavia. *Proceedings of the 3rd International Symposium on Developments in Fibre Reinforced Cement and Concrete*, Sheffield, July, Paper 9.6.

Wallace, M. (1987), Wet shotcreting just got better. *Concrete Construction*, **32**(11), 965–967.

3 Specialist Pre-blended Materials

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3.1 Introduction

The growth of the use of pre-blended and pre-packaged spray materials has been one of the phenomena of the '80s and early '90s. Traditionally, spraying has been carried out using site batched material, but the use of new techniques and work practices, the need to meet tight technical and environmental specifications and the availability and use of new materials has led to the development of new products in all areas of spraying.

The materials and the equipment suitable for spraying them have been produced in every continent. Wherever there is spraying there will also be found pre-packaged materials. This chapter describes the various factors that have influenced the development of these products and the way in which they are used. Specific areas of application will be covered separately but there will be no differentiation between the wet and dry processes since the borders of use are becoming blurred as the development of materials and techniques breaks down traditional boundaries.

3.2 Reasons for their use

There are many reasons why pre-packaged materials have come to the fore but they can be characterized as: (1) technical pressure, (2) innovative formulation, (3) application or environmental constraint and (4) quality of product and application.

Whenever spraying is used, there are increasing technical constraints. The need for the finished product to meet specific performance criteria has become the norm rather than the exception. National and international performance standards are now required, with test methods outside the scope of normal on-site testing. This is because either the conditions on site are not suitable for the test or the test can only be carried out in a controlled laboratory environment. Typical examples are carbon dioxide or chloride permeability testing, which are carried out on small prepared samples in a laboratory over a period of weeks, months or, in the case of chlorides, years. Fire testing of fire protection materials will be carried out in a specialized testing rig on samples prepared in a particular way. In these cases of set standards there is an implied commitment by the formulator to repeatable performance, which may not easily be achieved by the site batching of material. This repeatability and the need to meet increasingly rigorous standards is the major reason why pre-packaged material is now being used in such large quantities. It is also

the reason why these materials are being used in areas of higher technology. Wherever standards of performance are set for spray material, pre-packaged materials will predominate. The performance of the operator should not be confused with performance of material and operator performance is discussed elsewhere in the book. Levels of material performance are discussed in Section 3.6.

In modern formulated products the proportion of a raw material that is incorporated may be as low as 0.001% (by weight) of the total product. Site batching would be unable to guarantee the uniform distribution of such small quantities and so the technical advantages gained from the use of specialist materials is lost.

The addition of fibres, both steel and polymeric can also lead to problems. Krantz (1984) states in his conclusion, "Birds-nest blockages of gunite equipment, which was a serious disadvantage when attempting to hand mix the fibres in conventional mixers, have been virtually eliminated by pre-bagged mixes". The correct distribution of polypropylene fibres requires mixing and distribution methods that are not generally available on site. The most effective way of obtaining the correct distribution is to use the specialized mixing and blending equipment that is available in a modern factory.

The grading of aggregate and the achievement of an ideal distribution curve is neither achievable nor reproducible on site. It can however be achieved in a factory where dry aggregates can be sieved, graded and blended. Some pre-packaged materials may have as many as six or seven different aggregates and fillers blended together to give handling and performance characteristics far superior to site batched materials. The importance of grading is often forgotten, particularly in dry spraying, as even the worst graded mixes will spray. Wet spraying is quite different and pumping aids are normally added to standard site mixes, allowing them to be pumped or sprayed. With proper grading this is not necessary and pumping problems, such as water loss caused by gaps in the grading, do not arise. The ability to control grading accurately has a major effect on the handling and finishing capabilities of both wet and dry spray materials. It is also possible to incorporate fine fillers as part of the grading, down to and including particles as small as silica fume. This ability to produce material within a calculated range of physical parameters is one of the most important aspects of formulated factory-produced material. Because grading can be modified, it is possible to include in formulations single size particles that may be needed to impart specific performance. This will require careful adjustments to the grading to allow such materials to be sprayed, and this can only be achieved in the factory, where exact grading can be controlled.

Colour and the ability to reproduce colour over a long period of time is something that is only achievable in a factory environment. Wet spray application renders are a common sight in large areas of Europe and colour matching can only be achieved when the manufacturer continually monitors and modifies pigment quantities and blends to compensate for slight but unavoidable changes in the colour of natural sands.

The use of white cement together with naturally light aggregates and the addition of titanium dioxide were used to produce "House", a sculpture by Rachel Whiteread that was part of her prizewinning work in the 1993 Turner award (Figure 3.1.). The sculpture was produced by the application of a layer of white high-build pre-packaged dry spray material onto the inside of the external walls of a

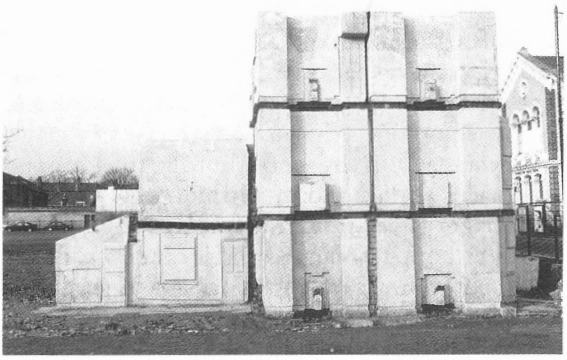

Figure 3.1 *"House" by Rachel Whiteread, a negative sculpture produced using pre-packaged dry spray material.*

terraced house. This was subsequently backed with a layer of sand and cement applied by the dry spray process. On completion, the external walls were removed to reveal the white spray material and the negative outline of the rooms. The project illustrates two areas where pre-packaged formulated materials have advantages: application and the environment. The pre-packaged mix used was modified with small quantities of materials to give specific advantages. The material contained a component which allowed the build up of substantial layers of material without the use of set accelerators, allowing the material to be finished over the normal time span of a dry spray material. It also reduced the likelihood of the occurrence of dry joints. This material was also low alkali which gives significant health and safety advantage to the operator, particularly in enclosed environments. The second modification was dust suppression. It is possible, with certain manufacturing techniques, to coat particles within a mix and hence reduce the dust which is normally generated at both the dry spray gun and nozzle.

Figure 3.2 shows the application of a dust-suppressed dry spray material. The rebound can be seen clearly, and is typical of this type of overhead application. However there is an absence of dust at the nozzle which is normally encountered with totally dry materials (site batched material will have a natural moisture content of approximately 5%). Figure 3.3 shows the site set-up on the same contract with the gun operator feeding dry powder into the gun. Again there are no signs of blowing at either the air outlet or hopper. These types of materials have significant environmental advantages over site mixed material and although it would be possible to add a build enhancer into a site mix, the dust suppression system must be added during manufacture in a factory blending plant.

Modern manufacturing facilities (Section 3.7) allow the formulator to produce products to a known and predetermined quality. Quality in formulation has its origins in research and the need to meet ever more stringent standards. The aim of the modern formulator of pre-packaged materials is to meet standards that are currently unobtainable with site mixes and to produce these formulations repeatedly. It is now customary to expect a manufacturer to operate a formal quality assurance scheme under the auspices of either the ISO or a local standards institute.

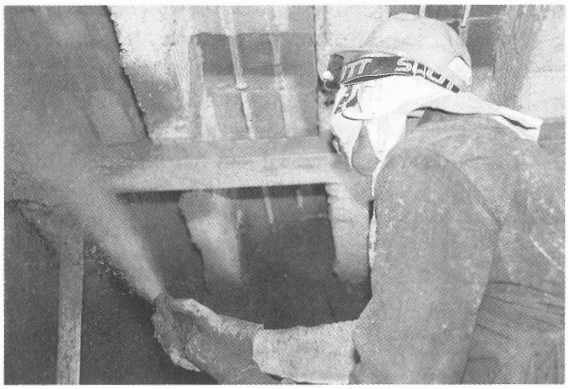

Figure 3.2 *An applicator applying a dust suppressed pre-packaged material for fire damage repair.*

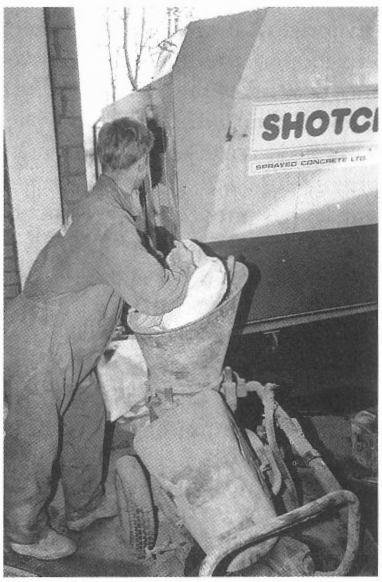

Figure 3.3 *The gun; as used in the same contract shown in Figure 3.2.*

3.3 New construction and repair application

There are three distinct areas of spray application of pre-packaged materials in construction: (a) new construction, (b) repair and refurbishment and (c) specialized areas, the largest use in this latter category being sprayed fire protection.

The use of pre-packaged materials in new construction has been limited by cost. The exceptions to this are, again, sprayed fire protection and coloured wet spray renders. Pre-packaged materials are only used in new construction for convenience,

or in environmentally sensitive areas where site mixed materials do not exhibit the specific characteristics required. The site mix of sand and cement for dry spray or truck supply of ready mix concrete for wet spray are standard in new construction.

Sites often have limited space available for equipment and storage. Pre-packaged materials from silos, "big bags" or sacks on pallets are a convenient way of minimizing the use of site space. Also, the material can be moved around the site by mechanical means, such as hoists, cranes and fork-lift trucks. The ability to supply material in small volumes, ready to use from off-site storage, can be especially valuable.

Dust and rebound are a particular problem in enclosed and built up environments, and it is advantageous to formulate for the reduction of these problems for dry spraying applications. Colour consistency is of great importance on external facades and pre-blending and pre-packaging material is the ideal way of achieving this. In many areas of the world, external coloured renders are applied using the wet-spray process with pre-packaged material.

Pre-packaged material would not normally be used for rock stabilization because of the physical requirements of the sprayed material and the cost constraints. However, in the stabilization of an area of cliff overlooking the main railway line in Dover, UK, pre-packaged material was used because its colour could be matched to the cliff and it limited the rebound and dust falling onto the busy railway line below. These requirements outweighed the cost benefit of a site batched material.

Probably the greatest growth area in the use of pre-packaged spray material is concrete repair. Concrete has been repaired with varying success for many years using both wet and dry spray techniques. Dry spray repair of fire damaged structures with a sand/cement mixture is one area of construction where spraying is the norm rather than the exception (Concrete Society, 1990). A simple sand/cement mortar is less than ideal for many repairs, as the need for guaranteed quality of material performance and application is most acute in repair.

It is not possible normally to remove the cause of the problem from the environment around a structure, and so it is essential that any repair material is capable of resisting the external influences which caused the original problem. The need for repair materials to resist the environment means that specific measurable properties are required. These are: resistance to carbon dioxide ingress (anti-carbonation properties); resistance to water absorption (freeze/thaw and chloride protection) and resistance to sulphates. This has been achieved through the formulation of the products to meet set standards. For example, the addition of polymers, silica fume and rheology-modifying additives (see Section 3.6.) will reduce the water/cement ratio (particularly in wet spray materials) from >0.5 to 0.3, due to the formation of polymer lattices throughout the mix. This also reduces dramatically both liquid and gas permeability. Careful grading of the aggregates and the addition of special fillers and pozzolanic cements (PFA or fly ash, GGBS and silica fume), will also effect the ability of the material to resist the environment.

Strengths and rate of strength gain can also be modified to meet specific standards. High early strength is not always required and the formulator can now tailor the strength to meet specific needs. In certain countries where alkali-silica reaction may be a problem, it is possible to formulate spray materials to give low alkali levels or to manufacture the material using non-reactive aggregates. The latter can

be problematical where the quality of suitable aggregates is not conducive to good spraying, leading to excessive water demand, rebound, dust and pumping difficulties in wet spray mixes, .

Typical modern pre-packaged spray material, formulated for wet or dry spray or both, will exhibit characteristic properties, such as compressive strength as sprayed in the range 40–60 MPa, with tensile strength, flexural strength and elastic modulus comparable to a similar strength cast concrete. These properties can, however, be modified if required. Exceptionally high strengths should be avoided as property incompatibility can lead to future problems (Emmons and Vaysburd, 1992). Bond strength will usually be in excess of the tensile strength of the concrete being repaired. Permeability will be exceptionally low and will readily meet recommendations for low permeability levels issued by various national bodies. The materials exhibit good handling properties with low rebound, dust levels and wastage. It must prove possible to finish the material to a high standard and to "roll " it behind congested steel (this ability to totally enclose steel reinforcement without voids is essential in concrete repair). The material will also be capable of application in substantial thicknesses. For example, a material which is typically applied 40 mm thick by hand to a vertical surface, can be applied 175 mm thick by wet spray and in excess of 300 mm by dry spray.

Both wet and dry pre-packaged spray materials are used for traditional repairs and in newer techniques. Thin cementitious overlays for external metallic anodes for cathodic protection should always be sprayed as it has been found that hand application is unacceptable and only wet or dry spray application can give the required assurances for bond quality. By using factory blended material it is possible to remove the variations that may occur due to site mixing. A predetermined and uniform resistivity will also result from using pre-blended material. Spraying is now the preferred method of repair in many instances, although it will not completely replace hand and form, or pump (King, 1992).

Both wet and low pressure spraying are a means of applying specialist materials for fire protection and particularly fire protection of steel. Application rates of 300–450 m^2 per man week are obtainable with spraying compared with 100 m^2 with boarded systems. The typical finished thicknesses will be 10–80 mm dependent on fire rating requirement. The actual thickness will be determined using the H_p/A concept. This states that the heating rate of a steel section in a fire depends on

(a) the perimeter of steel exposed to flames (H_p) and

(b) the cross sectional area of the section (A).

A high value of H_p with a low A corresponds to fast heating, while low H_p and high A reflect slow heating. Full tables for H_p/A values are currently available from the Association of Specialist Fire Protection Contractors and Manufacturers. From these tables, it is possible to determine the finished thickness of material required for any steel section under any given fire exposure.

All specialist spray applied materials used in fire protection are pre-packaged. There are two basic forms of spray fire protection: wet spray of an exfoliated vermiculite/cement mix or gypsum; and low pressure spray of mineral fibre/cement mix. The wet spray or "slurry" application material consists of exfoliated vermiculite mixed with cement binders and rheological and dispersion agents. It has a dry density of between 375 and 800 kg/m^3 depending upon grade (external or

internal), a wet density at the mixer of 650 to 1000 kg/m^3 and a density at the nozzle of between 900 and 1200 kg/m^3. The material is normally packed in bags of approximately 15 kg (because of the low density of the unmixed material, the manageable volume determines the size of the packaging). The dry powder is introduced into a forced action mixer and allowed to stand in a given quantity of water (approximately 1 litre per kilo of dry material). It is then mixed and dropped into a standard rotor stator pump unit, and is pumped to a nozzle where air is added to atomize and propel the material onto the surface to be protected. Typically the material can be applied up to 35 mm thick in a single application.

Dry spraying is undertaken at low pressure and the equipment is completely different from "normal" dry spray machinery. The dry material consists of a mixture of mineral fibres with a cement binder, typically in the ratio 80:20. The density is around 200 kg/m^3. At one time the material would be supplied loose in bags, but now it is compressed into 25 kg bales. The dry spray machine consists of a bale breaker, carding machine, gate and blower. The bale is introduced into the machine where revolving tines break up the compressed material. The material is next carded, rather as wool is treated, to complete the even distribution of the fibres and cement. The gate controls the rate of flow of material to the blower, which typically is powered by a 1.5 kW electric motor and fibres are blown along a 38–50 mm diameter hose to the nozzle. The nozzle operation is similar to a normal dry spray nozzle but due to the low pressure involved, a separate air supply is often added to atomize the water before it is introduced into the stream of blown material. The amount of water introduced will be similar to the wet process, typically 1 kg of water to each kg of material. The material feed rate is controlled by reducing the speed of the blower and closing the gate. The distance between machine and nozzle should be no more than 25 m although it is possible to work up to 10 m high. Spray application of pre-packaged fire protection material is a specialist field in formulation, design and application and should not be undertaken by non-specialists.

The use of pre-packaged materials in tunnelling is almost entirely confined to repairs to precast rings and in situ linings. The properties required for above-ground concrete repair pertain below ground with the need for a dust free or reduced dust output being essential. Spraying is particularly effective in soffit repairs where other methods of application are more difficult.

3.4 Mining applications

The mining industry has been a large consumer of pre-packaged materials for many years. The primary reasons for this are logistics coupled with cost, and quality. There is also a preference for the use of inorganic materials below ground as fire is an ever present danger. Cement-based materials will always be preferred. The cost of transporting material from the ground to the area of mine where it will be used is considerable. In some cases the cost of transport is greater than the cost of the material itself. It must be remembered that hard rock mines are now over 4 000 m deep (13 000 ft) and the distance from the lift bottom to the face may be measured in tens of miles.

Quality of product is a prime requirement where products are to be used in life threatening situations. As previously stated, probably the most important reason

for using pre-packaged material is the supply of material with a consistent, known performance. In addition to the material meeting the necessary level of quality, packaging must also meet required standards. Mines are inherently wet and it is essential that the packaging is waterproof. Studies in British mines have shown losses in transport to the job site of between 18% and 23% due to poor packaging.

Pre-packaged materials are used in three basic areas (a) strata control, (b) ventilation control and (c) void filling.

Strata control consists of spraying unstable areas of rock or of controlling water penetration in existing or new roadways. In certain mines when dykes in the rock strata must be crossed, the exposed rock may be susceptible to rapid weathering in the mine environment. Pre-packaged spray materials can be used to apply a thin coating to prevent this damaging weathering.

Ventilation control is an area where spray materials offer a quick and simple answer. Smooth surfaces speed air flow and help ventilation and a thin layer can be applied to a mine tunnel to turn a rough rock surface into a smooth and, if necessary, white surface to aid ventilation.

Void filling is also carried out using sprayed materials, although the majority of this work is now carried out using pumped foam mortars. In coal mines sprayed material has also been applied to the coal seams to stop spontaneous combustion.

For the future, two areas of spraying are being examined: protection against radon gas by the application of a gas-tight lining and insulation of mine tunnels. The deeper the hardrock mines are driven the greater is the need for cooling. The cost of cooling deep mines is considerable and research is underway to find suitable and if possible inorganic systems.

3.5 Refractory applications

This section describes the types of pre-packaged materials used, their methods of application and the uses to which they are put.

Wet and dry spraying (or *gunning*) are both used in the refractory industry. As with other sprayed concrete applications, refractory work can be split into new construction, and repair or renewal. The majority of new work is in the construction of power station boilers where there is extensive use of dry spray in ash hoppers, outside skin casings, and around the boiler tubes and in the boiler roof. In the petrochemicals industry, dry spray refractories are used in heater boxes, end tube sheets, flame stacks, catalytic converters, cyclone areas and duct work.

In repair and renewal, dry spray is the preferred method in most areas, and it is interesting to note that one of the major advantages quoted of dry spray over wet is the increased density due to the greater application pressure. This is, however, a disadvantage in some refractory work where the lower density of wet spray can be used to increase the insulation properties. The ferrous and non-ferrous industries both make widespread use of spraying for lining and repairing ladles, furnaces, tunndishes, and any area where hot metal is used. It is in the area of continuous casting tunndish lining that we find some of the most interesting advances in spray technology and materials. In certain systems, tunndish linings can be renewed on a continuous basis, the lining normally being replaced after perhaps 24 hours use. This process has been carried out using dry spray techniques for some time.

In Japan, robot machines are now programmed to carry out this work. These are true robots where the shape of the tunndish is fed into the machine and the robot sprays to a predetermined depth and pattern. The latest technology is in wet spraying where the lower spraying pressure is an advantage. Robot machines spray a pre-packaged refractory material based on magnesite and olivine aggregates with a resin binder onto the "skull" (the refractory concrete lining to the outer steel tunndish casing). The material is supplied in "big bags" that are positioned over the mixer pump unit. The material is fed into a hopper and thence through a continuous mixer where an exact, metered quantity of water is added. From a standard rotor stator pump the material is pumped to the nozzle where it is sprayed as a slurry, 20–25 mm thick. As with the Japanese dry spray machines, the robot follows a predetermined path that has been fed into the controlling computer. A sensor in the nozzle monitors the consistency of the material sprayed and adjusts the mixing regime. The material can be sprayed onto surfaces with temperatures reaching 90°C. After spraying, the tunndish is dried at a controlled temperature of approximately 700°C to remove all water. The resin binder also burns off and the aggregates sinter to form an abrasive and heat resistant lining.

Refractory materials are available in two basic forms, dense and insulating. They are normally based on natural or synthetic aggregates, exfoliated vermiculite, various grades of high alumina cement and clay. Natural aggregates such as basalt, bauxite and flint clays, are pre-calcined to give them thermal stability. Brick grogg is manufactured by crushing and grinding the brick lining of ceramic kilns. Synthetic aggregates, white fused alumina and tabular alumina are formed by fusing calcined alumina in carbon arc furnaces and then treating with an acid leaching process. This leaves a material with an extremely high alumina content (greater than 99%). Both stainless steel and polypropylene fibres can be added to the products. Stainless steel fibres impart particular mechanical properties to the material, whilst polypropylene fibres burn out during the drying phase to leave voids through which steam can vent. This is most important as the removal of all water from refractory linings before they are commissioned is essential for both process and safety reasons. The cost of the aggregates varies with the ability to resist heat. A pre-packaged refractory containing basalt and for use at 1000°C will cost around £200 per tonne whereas a material using tabular alumina and china clay and able to withstand 1700°C will cost £2000 per tonne. Refractory work is specialized both in the application and also in the formulation and manufacture of the product. Because of the demands of the industry for new and more advanced materials and methods of application, there is now a trend in the steel industry for the refractory work to be carried out by specialist manufacturer applicators.

3.6 Effects of spraying

When cement-based materials are sprayed, rather than applied by hand or poured, they have different physical and application properties. This is primarily due to the increase in density and reduction in entrapped air. It would seem logical that these changes would be calculable given the nature of the material and methods, though with pre-packaged materials this is not the case. Due to the involved formulations and the interaction between the constituents, each formulated material must be

Table 3.1 *Constituent effects on performance and application properties of pre-packaged spray materials*

	Physical properties	Application properties
sand grading	physical strengths, permeability shrinkage, water demand	spraying, rebound finishing, dust levels
other fillers	physical strengths, permeability shrinkage, water demand	spraying, rebound finishing, dust levels, build
aggregate type	physical strengths, permeability shrinkage, water demand	spraying, rebound finishing, dust levels
polymers	permeability, elastic modulus, creep, shrinkage, physical strengths, durability, chemical resistance	spraying, rebound finishing, dust levels, build
cement	strength gain rate, ultimate strength, shrinkage, physical strength, chemical resistance, durability	build
fibres	cracking, physical strength, creep	finishing, build, dust
rheology modifiers	permeability, shrinkage, water/cement ratio, air content, physical strengths	build, dust levels,spraying rebound, finishing

considered individually. This section considers the changing physical performance of a number of materials applied by hand and then by wet or dry spray methods. The effects of various basic constituent materials on the properties of a standard spray mix are shown in Table 3.1. Consider four different pre-packaged materials:

Mortar A – a hand-applied material, based on graded aggregates, lightweight fillers, ordinary Portland and shrinkage compensating cements and permeability controlling admixtures.

Mortar B – a hand-applied material, based on graded aggregates, silica fume, a higher proportion of lightweight filler than mortar A, ordinary portland and shrinkage compensating cements, spray dried polymers, polypropylene fibres and rheology modifying admixtures.

Mortar C – a hand-applied material, based on graded aggregates, ordinary Portland and shrinkage compensating cements, spray dried polymers, and rheology modifying admixtures.

Mortar D – a wet or dry spray application mortar, based on graded aggregates, silica fume, lightweight filler, ordinary Portland and shrinkage compensating cements, spray dried polymers, polypropylene fibres and rheology modifying admixtures.

Compressive strengths, fresh densities and water absorptions of the four mortar

Table 3.2 *Compressive strengths of mortars (Gordon, 1991, 1993)*

Application method	Compressive strength (MPa)			
	Mortar A	Mortar B	Mortar C	Mortar D
Hand	29	22	35	42
Dry spray	56	31	75	57
Wet spray	54	25	54	59

Table 3.3 *Wet densities of mortars (Gordon, 1991, 1993)*

Application method	Fresh, wet density (kg/m^3)			
	Mortar A	Mortar B	Mortar C	Mortar D
Hand	1830	1430	2300	1980
Dry spray	2100	1640	2110	2070
Wet spray	2120	1670	2370	2080

Table 3.4 *ISAT test results for mortars (Gordon, 1991, 1993)*

Application method	Time (min.)	Initial surface absorptions (ml/m^2/sec)			
		Mortar A	Mortar B	Mortar C	Mortar D
Hand	10	0.17	0.155	0.037	
	60	0.068	0.047	0.024	
Dry spray	10	0.029	0.026	0.034	0.004
	60	0.008	0.010	0.012	0
Wet spray	10	0.066	0.055	0.037	0.002
	60	0.024	0.019	0.024	0

mixes are given in Tables 3.2 to 3.4. Comparison of hand with spray application is difficult due to the test methods available. (Deykin *et al.*, 1993) and so all the results for the sprayed material are based on cores or prisms cut from sprayed material.

Compressive strengths are frequently used as a basis for comparison, and Table 3.2 shows the effect of applications method on the compressive strength of the four mortars. When wet sprayed, mortar A had a strength increase over the hand-applied value of 86%, mortar B 13%, mortar C 2% and mortar D 40%. The figures for

dry spray are different again, reflecting the different water/cement ratios achieved. Corresponding increases in fresh wet densities (Table 3.3) were 15%, 16%, 3% and 5%, respectively; so the increase in density due to the spraying cannot be used to explain the increases in strength. Mortar A is the closest in formulation to a standard sand/cement mix and changes reflect the removal of entrapped air and a measure of densification. Mortar B contains a large percentage of lightweight and light strength filler, and the compressive strength of the material is determined by the strength of this filler. Mortar C on the other hand is a dense, high cement content material and shows only a marginal increase in density and compressive strength. Mortar D shows a slight increase in density but a considerable increase in compressive strength. In formulating this mortar, specific attention was given to reducing the water/cement ratio, as the material is intended for both wet and dry spraying. The similarity in wet and dry spray properties of mortar D in Tables 3.2 and 3.3 is immediately apparent.

Table 3.4 shows the effect on surface absorption using the ISAT test method. This type of test gives an indication of gas and liquid permeability and possible resistance to carbon dioxide, chlorides and sulphates. Again, variations are apparent which do not specifically follow strength or density measurements. Grading of aggregates (including pore-blocking materials), cement content, polymers, plasticizers, rheology modifiers and application method can all affect the result. It is worth noting (Table 3.4), that the Concrete Society classification (1987) for low permeability is reflectd by ISAT values of less than 0.25 ml/m^2/sec at 10 minutes, and less than 0.1 ml/m^2/sec at 60 minutes.

It is because of the difficulty to predict the performance of a material from the raw material data that the preferred method of specifying materials for sprayed concrete applications should be on the basis of performance — relevant performance, not maximum performance!

3.7 Production methods

Production methods and technologies associated with pre-packaged material have, like everything else, advanced rapidly over the last few years. The manufacture of powder products can be divided into three stages: (a) raw material storage and handling, (b) mixing or blending, and (c) packout and storage.

Modern, efficient manufacturing plants normally include bulk storage silos for the base feed stock. Storage volumes are usually a minimum of 30 tonnes, and generally between 40 and 100 tonnes. Each individual material silo forms part of a central silo farm which serves a mixer or a number of mixers. Material delivered by road tanker is transferred pneumatically into the storage silos. It should be noted that when bulk silos are used it is essential to carry out quality control testing on incoming material before discharging it into the silo. For example, cement would be checked by sieve grading and surface area determination. There should also be a system of rigorous quality conformance with raw material suppliers.

Raw material can be transferred to the mixing area by mechanical or pneumatic conveyor. The material goes first to a computer-controlled batch weighing hopper where each raw material is weighed separately into the hopper to match the formulation and is then transferred to a mixer again by conveyor.

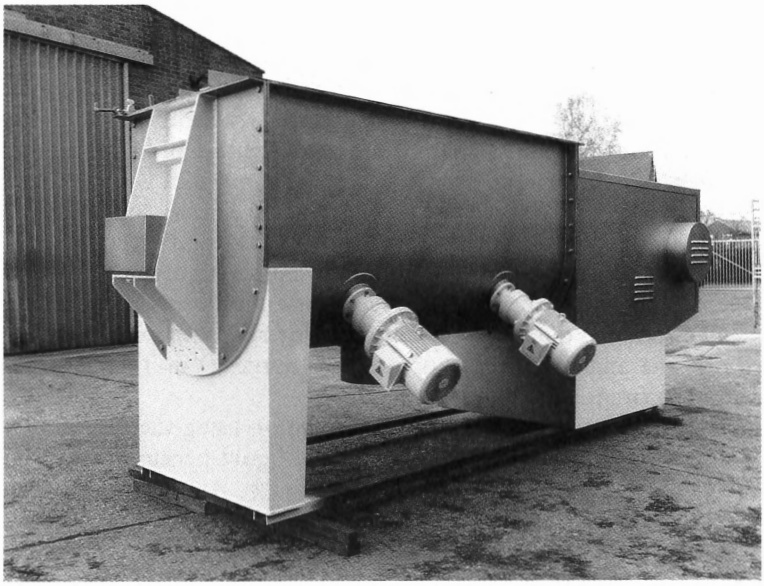

Figure 3.4 *Winkworth 2000 litre ribbon blender with high speed refiners (Winkworth Machinery Ltd.)*

There are essentially two forms of mixing and blending: distributive and dispersive. The distributive machines are of the drum or cone type where the shear forces are sufficient to achieve a satisfactory mixing quality after an adequate time. Typical drum mixers would hold between 2 500 and 4 000 litres and mixing is achieved by the material lifting and cascading from blades fixed to the inside of the rotating drum shell. Mixing time varies from 40 to 120 minutes depending upon formulation and material. Distributive mixers do not give good results when small quantities of ingredient are added to bulk material or when there are large differences in density and particle size. Discharge from these mixers tends to demix the product.

Dispersive mixers are the most effective type of powder mixer and can be of ribbon, paddle or ploughshare design (Figure 3.4). The high shear forces created by this type of mixer permits homogeneous mixing in a very short time and is extremely effective when liquids form part of the formulation. De-lumpers (refiners) can also be fitted to machines and are effective at de-agglomerating sand and distributing fibres. Rapid throughput requires the raw material to be introduced mechanically into the mixer from a batching station, with small volume components being added by hand. A mixing time of five minutes is typical. Discharge of the mixed product from a dispersive mixer is rapid and occurs with minimum segregation. These mixers offer the advantage of efficiency and quality and are the preferred equipment for mixing.

Following mixing, the product can be transferred directly to a packing station or discharged into holding bins to permit quality testing. With modern pre-packaged materials that are formulated to give specific and reproducible characteristics, quality control testing between mixing and packing is standard procedure. If qual-

ity control of raw material can be carried out to the requisite standard then only check quality control will be necessary after manufacture. Most of the pre-packaged spray materials contain cements, dried aggregates and natural materials; by nature these materials are variable and modifications to individual mixes may be necessary in all but the most simple of formulations. It is for this reason that storage in bins after blending is becoming more common. From a manufacturing standpoint a system that eliminates the need for intermediate storage is to be preferred.

After blending and quality control testing, the material is packaged. This will be in sacks, in disposable/reusable "big bags" or site silos. The latter two are becoming popular in countries where "green" legislation requires collection of the packaging by the supplier. They are also popular on large projects where material can be fed directly to the gun or mixer pump, or via an integral continuous mixer and then to the pump. If sacks are used, the powder is fed pneumatically or mechanically into "valve" sacks or fed under gravity into open-topped sacks. In both cases, the weight (in the case of the valve sack gross weight, and of the open top sack nett weight) will be determined with modern equipment to an accuracy of $\pm$ 0.5%.

In modern systems, the sacks are transferred to a sealing station for sewing, heat sealing or glueing in the case of open top sacks. Valve sacks with external valves are closed manually and with internal valves the bag is inverted to seal the valve. Sacks are then loaded onto pallets, shrink wrapped in polythene and despatched to stores. In a modern plant the whole process of blending and packaging is fully automated.

The production capabilities of modern powder production facilities are enormous. They can produce complicated and varied formulations to high levels of consistency, meeting exacting quality assurance standards required of modern materials. Such facilities also have correctly sized and designed dust control and extraction systems. These are needed for health reasons and also because under some circumstances powders can be explosive.

References

The Concrete Society (1987) Permeability Testing of Site Concrete. *Concrete Society Technical Report No. 31*

Concrete Society Working Party (1990) Assessment and Repair of Fire-Damaged Structures. *Concrete Society Technical Report No. 33,* The Concrete Society,

Deykin A., Gordon K. D., Humpreys M., and Decter M. (1993) Sprayed repairs - Properties and Testing of Cementitious Mortars. *Proc. Fifth International Conference on Structural Faults and Repair,* Edinburgh, UK, **2,** 283–289.

Emmons P. H., and Vaysburd A. M. (1992) Factors Affecting Durability of Concrete Repair, *Proc. Fifth International Conference on Structural Faults and Repair,* Edinburgh, UK, **2,** 253–267.

Fire Protection for Structural Steel in Buildings (1992) Association of Specialist Fire Protection Contractors and Manufacturers in conjunction with Fire Test Study Group and Steel Construction Institute, (2nd Edition - revised).

Gordon K. D. (1991) Wet Spraying of Pre-packaged Mortars for Concrete Repair. *Proc. Euro. Seminar and Workshop on Sprayed concrete,* Sprayed Concrete Association, Loughborough, UK.

Gordon K.D. (1993) Wet Spray Application of Polymer Modified Pre-packaged Repair Mortars. *Proc. Brazilian Workshop on Polymers in Concrete,* International Conference Polymers in Concrete, Salvador, Brazil.

King E. S. (1992) Sprayed Concrete as an Alternative Concrete Repair Material, *Proc. Euro.*

Seminar on Sprayed concrete, Sprayed Concrete Association, Loughborough UK.
Krantz, G. W. (1984) Selected Pneumatic Gunites for use in Underground Mining: A Comparative engineering analysis. *Bureau of Mines Information circular; 8984.* United States Department of the Interior,
Riley J.F., and Smith J.S. (1993) Changes in Continuous Casting Tunndish Lining Technology. *Proc Conference on Egyptian Steel Industry,* Cairo.

4 Production and Installation

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4.1 Introduction

This chapter introduces the processes, techniques and equipment involved in making and applying sprayed concrete. These activities can be divided as follows:

(a) production – the batching, mixing and delivery (pneumatically or by pump) of materials to the nozzle; and

(b) installation – the spraying of the concrete into place on a correctly prepared surface and its subsequent finishing and curing.

Production is largely equipment orientated and is quite different for the dry and wet processes. Conversely, installation is mainly labour orientated and highly dependent on the technique and skill of the operatives. The sections in this chapter are divided accordingly: one for dry and one for wet process production and a further three covering installation with both processes. The chapter is also linked to those on Equipment and Construction Practice (Chapters 9 and 10 respectively), in which more detailed information is presented.

Whilst the dry process represents the original application method ('guniting'), significant developments in wet process spraying technology over the last ten years have enabled it to compete or replace its dry counterpart in certain applications, particularly tunnelling which involves high volume output, and robot controlled installation. The dry process is still dominant in repairs, refractories and certain structural work.

4.2 Dry process production

In the dry process, cement, aggregates and possibly additives (dry) are batched, mixed and fed into the delivery equipment which is termed a 'gun'. The gun meters the dry materials into a pressurized air stream and conveys the mix pneumatically along a hose to the nozzle. Water is injected at the nozzle through a water ring and the wet concrete projected into place. Liquid additives, including silica fume slurry, may also be added at the nozzle. The complete process is illustrated in Figure 4.1 (a trial at the Dinorwig pumped storage scheme) and shown schematically in Figure 4.2.

Batching and mixing

The dry mix materials may be volume-batched (using gauging boxes) but are preferably weigh-batched. Materials can be mixed on site (Figure 4.3) in a transit mixer,



Figure 4.1 *Dry process spraying at Dinorwig, Wales.*

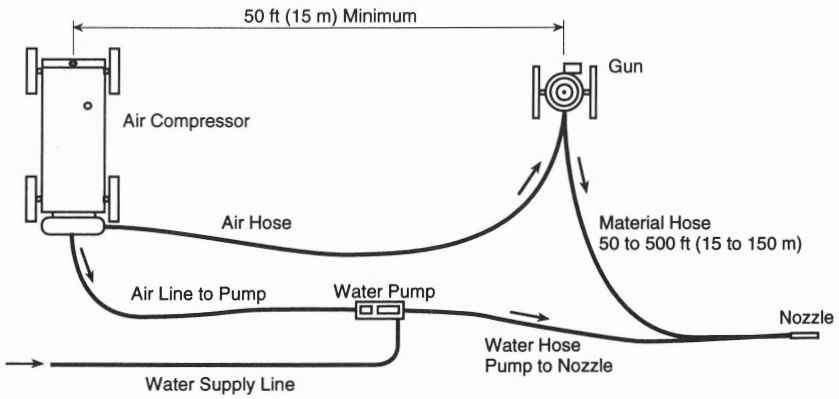

Figure 4.2 *Schematic arrangement of dry process.*

or pre-blended and bagged off site. A bag size of 25 kg is most common but large bags containing 0.5 to 1.5 tonnes have been used (Wallace, 1987). Whilst drop-weight mixers are most common on site, a forced-action paddle mixer gives superior mixing and should be used wherever possible, particularly when small quantities of additives (including fibres) are site batched.

If the mix contains fibres, it is important to ensure an uninterrupted flow of material to the nozzle with a reasonably uniform distribution of fibres at the specified fibre content. A suitable technique for dispensing fibres into the mix and getting the mix through the gun is essential and can be combined with either manual



Figure 4.3 *Typical dry process batching set-up.*

site batching, automated site batching, or pre-bagging (Robins and Austin, 1985). Manual site batching is the cheapest and also the most common method in the UK, with an output rate of 1 to 1.5 m^3/hour readily being achieved. The main disadvantage of manual site batching is the difficulty in controlling fibre content and fibre dispersion. Automated site batching involves conveying the cement/aggregate mix from a batching plant to the spraying site by a transit mixer. Fibre reinforcement can be added at the batching plant, directly into the transit mixer (*not* recommended), or at the conveyor to the gun (possibly using a fibre dispenser between the transit mixer and gun, as shown in Figure 4.4). With automated site batching, the output rate will usually be limited by the gun's capacity or the amount the nozzleman can handle (up to 10 m^3/hr may be possible).

However the dry mix is prepared, it is preferable to auger feed the material into the hopper of the gun, rather than lift it by hand. Auger feeding both agitates the mix (reducing segregation) and regulates the flow of material into the hopper which, when balanced with the outflow from the gun, minimizes the chance of blockages and provides a steady supply to the nozzle. An auger feed can also be fitted with sprinkler nozzles to dampen air-dry materials before they enter the gun. This reduces dust formation and is also thought to improve hydration of the mix. The moisture content should be a few per cent, any higher will cause clogging. The combined device is often referred to as a 'predampener' or 'pre-moisturizer'.

Delivery (pneumatic)

The gun meters material from the hopper at atmospheric pressure into the pressurized delivery line (typically at 3–6 bar, 50–100 psi). This is most commonly done by a barrel (rotor) containing vertical cylinders which rotates between two pressure plates, the upper with a hole linked to the hopper and the lower with one venting into the delivery line (see Figures 9.11 and 4.5). Rotating feed bowl guns have a

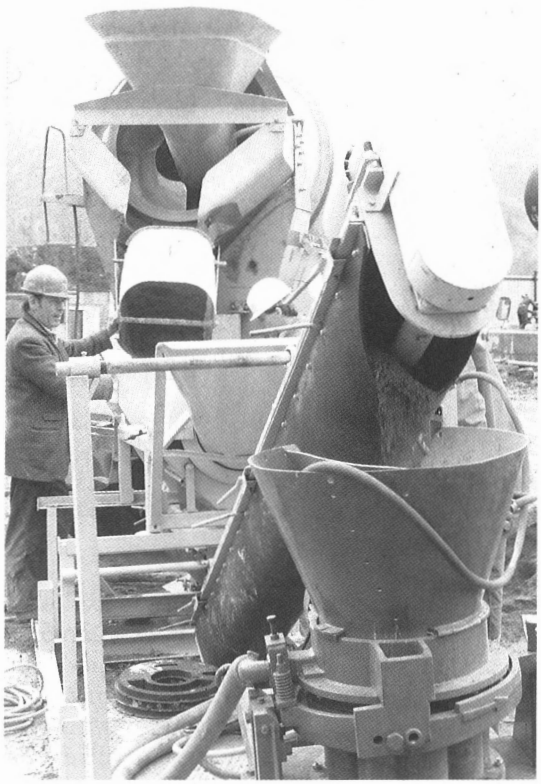

Figure 4.4 *Automated fibre dispenser adding steel fibres to 3:1 dry mix and auger feeding into gun.*

single, upper pressure plate and U-shaped cylinders. The output of these machines is typically 0.5–4 m^3/hr although capacities of up to 9 m^3/hr are available. They can be driven by diesel, electric or compressed air motors. Another method involves two chambers, the upper being alternately pressurized and then vented to receive the next batch of dry material. The original Cement Gun was of this type but double-chamber machines are not now common.

The air-suspended material is conveyed in a flexible hose, the diameter depending on aggregate size, air pressure and delivery rate; 25, 32, 38, 50 and 70 mm diameter are common sizes. The maximum conveyance distance depends on the machine output, air pressure and hose size but can be more than 300 m horizontally and 100 m vertically. Air supply pressures are typically 0.5–0.7 MPa (70–100 psi) producing an outlet pressure of around 0.3 MPa (40 psi) and a particle velocity of 30–60 m/s with a 50 mm diameter nozzle.

Nozzle designs vary, but consist of a water-ring or gate through which atomized water is injected into the mix. The water is supplied under pressure either by a pump or from a pressurized vessel; the latter gives a very even supply but needs refilling periodically. The rate of water addition is controlled by a valve which the nozzleman adjusts continually in response to the gun delivery (Figure 4.6). The



Figure 4.5 *A typical rotating barrel gun.*



Figure 4.6 *Nozzlemen adjusting water valve (dry process).*

water pressure should be similar to the air outlet pressure, 0.5 MPa (75 psi) being common. The nozzle itself can be straight, tapered or bubbled and is usually made from rubber or plastic; the shape is designed to obtain maximum wetting and uniform water dispersion during the brief time the mix is in the nozzle.

The method of water addition is crucial to this production technique. The water/cement ratio can be relatively low (typically 0.35–0.50, which leads to high strengths), because workability is not a requirement. However, water content con-

trol is in the hands of the nozzleman who must maintain sufficient water content to get good compaction and reinforcement encasement, but not excessive which may cause sloughing or sagging of the concrete away from the substrate. Within this range, decreasing the water content will generally improve strength and other hardened properties (unless it results in sand pockets or laminations). However, it also increases the rebound of material, which can be substantial (15–30% at a vertical surface, see Section 4.5). The lack of external control of the water/cement ratio has been one of the main drawbacks of the dry process, although excellent concrete can undoubtedly be produced by skilled operatives.

4.3 Wet process production

In the wet process, cement, aggregates, water and often additives are batched, mixed and fed into the delivery equipment (a pump or gun). Conventional wet-mix concrete is pumped hydraulically to the nozzle where air is injected (possibly with liquid admixtures) to project the mix into place (Figure 4.7). There is also another method, which is a hybrid of the wet and dry processes, in which wet concrete is conveyed pneumatically by a gun through the nozzle and into place. Admixtures may be injected at the nozzle but not water or air. To differentiate between the two, the former is termed hydraulic delivery and the latter pneumatic.

Batching and mixing

For low output applications (up to 3–5 m^3/hr), materials are usually weigh batched on site, sometimes in a mixer forming part of the pump (Figure 4.8). Fibres, if included, are simply batched with the other ingredients. For medium and large output applications (above 5 m^3/hr), materials will be premixed in a batching plant and transported by a transit mixer to site where it is then fed into the pump. Retarders and/or accelerators may be required, the latter being metered into the delivery hose or directly at the nozzle. Output rates for a single machine of 7–9 m^3/hr

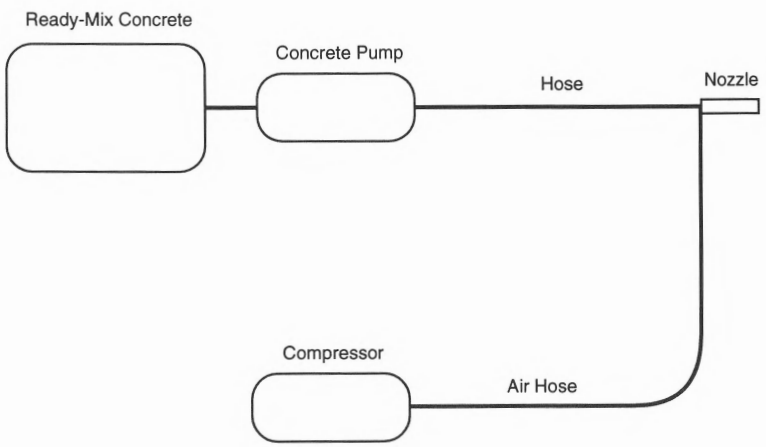

Figure 4.7 *Schematic arrangement of wet process (hydraulic).*

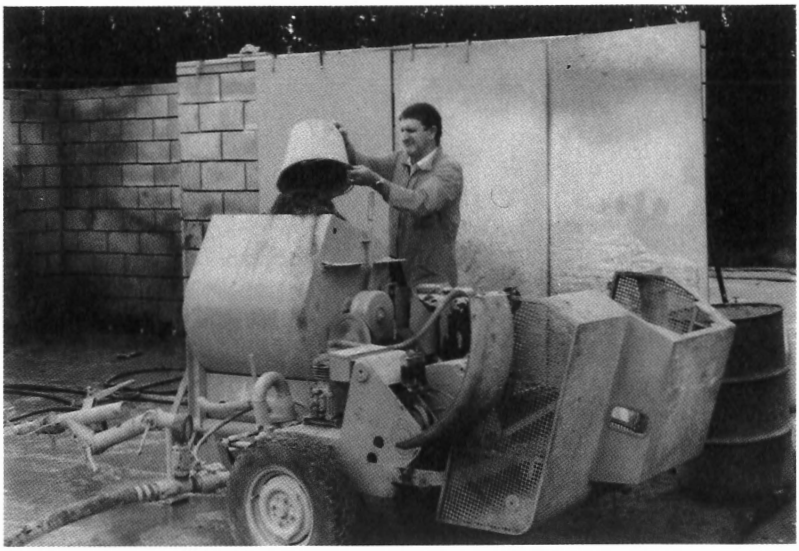

Figure 4.8 *Wet mix pump – steel fibres being added into the mixer.*

can be obtained, although automated systems with robot spraying arms and a mobile pump can achieve up to 20 m^3/hr.

Steel fibre reinforcement has been incorporated successfully on a large scale in Scandinavia (Opsahl & Buhre, 1985; Skatun, 1986; Holtmon *et al.*, 1993). Fibre contents of up to 5% by weight (120 kg/m^3 or 1.5% by volume) are reported with 50–70 kg/m^3 the most common, the fibres being batched with other dry materials. Littlejohn (1980) reported that fibres can be added through a dispenser into the plastic mix with the peristaltic Challange-Cook System. In the 1980's Besab developed a wet system in which steel fibres were added from a fibre dispenser through a separate hose into the wet concrete at a specially designed nozzle, allowing high aspect ratio fibres to be sprayed at 5% by weight (Sandel and Westerdahl, 1986). This method has not, however, found widespread acceptance.

Delivery (hydraulic)

In this method the wet concrete is placed in a concrete pump and pumped through the delivery hose to the nozzle. The pump may be of the worm (low volume, e.g. Figure 4.8), piston, or peristaltic type. Figures 4.9 and 4.10 show a small peristaltic pump, with separate mixer, spraying a mortar containing silica fume (10% by weight of cement) and 0.1% by volume of polypropylene fibres. The majority of pumps are of the piston type which have a wide range of outputs.

Whilst the pump itself may have a very high capacity (over 100 m^3/hr), the spraying rate is much lower with about 20 m^3/hr being the highest output with automated systems involving robot spraying.

The concrete is pumped down the hose (usually 50–100 mm diameter) to the nozzle at a pressure of about 6 MPa (900 psi) . Air is injected here, typically at 0.5–0.7 MPa (75-100 psi) to produce a particle velocity of 10–30 m/s although speeds

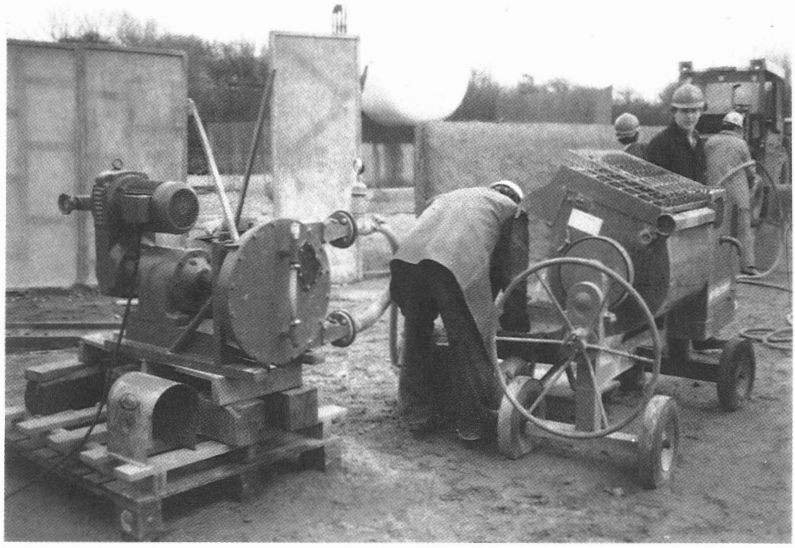

Figure 4.9 *Wet mix trial with peristaltic pump.*



Figure 4.10 *Spraying low volume wet mix mortar.*

approaching that of the dry process (60 m/s) are possible. There are numerous nozzle designs but they are usually quite short (less than 300 mm long), often tapered and have a ring of jets through which the compressed air is injected. An air valve may also be fitted. Maximum conveying distance depends on the pump capacity and operating pressure, but up to 150 m vertically and 500 m horizontally are possible.

Delivery (pneumatic)

This approach to delivering wet process sprayed concrete has been available for about 10 years. Rotating barrel machines are available which will spray either a dry or wet mix. The wet mix operating principle is similar to the dry process, except that compressed air assists gravity in discharging each rotor chamber into the delivery line where further air is added to convey the wet material to the nozzle. Outputs of 10–20 m^3/hr are claimed through hoses 60–80mm in diameter. Air consumption is high (10–20 m^3/min) and conveying distances limited to typically 30 m horizontally and vertically. Variable speed hydrostatic drives give an easily adjustable output.

A double chamber version of this type of system has been developed in Hungary (the 'Dogrogcrete' process) and trials undertaken by British Rail in the UK during the mid-1980s. A 14 mm down crushed limestone aggregate with a water/cement ratio of 0.38 produced 65 MPa at 28 days and up to 200 mm thick layers could be built up with a single pass on a vertical face (Long, 1990). Output was restricted to 2 m^3/hour.

There are occasional reports of two-stream systems, particularly from Japan. Matsuo and Kenmochi (1981), and Aihera and Yamamoto (1984) describe a system in which a pumped mortar and a dry process delivery aggregate (plus fibres and accelerator) are combined in a mixing pipe before the nozzle. A primary mortar comprising 'sand enveloped with cement' was prepared by first mixing sand with water and then adding cement to form a 'shell' around the sand particles. The complete system was either rail or truck mounted. Optimum composition is stated as a 1.75:1 sand/cement primary mortar, 450–570 kg/m^3 coarse aggregate, 350–380 kg/m^3 cement and 3% accelerator. Several advantages were claimed, including low rebound (8–12% including overhead work), low dust (3–10 mg/m^3), high output (6–10 m^3/hr) and high strength (50–70 MPa at 28 days, however only 15–38 MPa was achieved in trials on site).

4.4 Application

Spraying technique

Accepted good practice is to spray at right angles to the target surface at a distance of 0.5–2.0 metres, although around one metre is most common in order to get good compaction and minimum overspray, i.e. material that misses the target (see Figures 4.1 and 4.6). Low volume applications may have a lower particle velocity, in which case the nozzle is kept closer to the surface (Figure 4.10). Overhead spraying is also done at one metre or less because gravity reduces the velocity of the particle stream and increases rebound.

The nozzle tip should be gyrated so that the stream moves in loops across the surface. The spray should be kept as close to 90° to the surface as possible, although it should be recognised that the scope to do this is more limited with robot controlled nozzles. The benefits of correct nozzle movement have been demonstrated recently by Maidl (1991) who reports on an extensive laboratory and field study of robot-controlled dry process spraying. Figure 4.11 compares the effect of rigid,

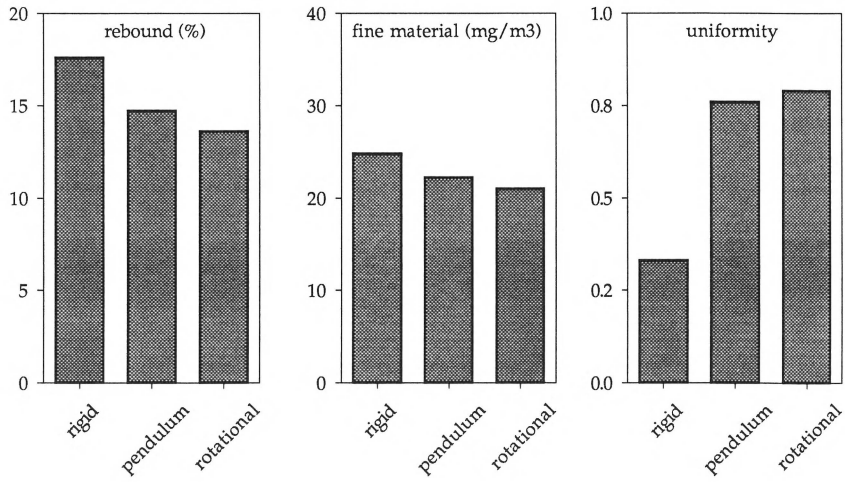

Figure 4.11 *Effect of nozzle movement on dry process spraying (Maidl, 1991).*

pendulum and rotational nozzle movement on rebound, dust generation and material uniformity. Gyratory movement was found to give the best performance by all three measures.

Material is built up from the bottom, with care being taken to fully encase reinforcement. This requires material to be built up behind the bars first to avoid inclusion of rebound, sandy material and large air pockets. This is vital to the durability of the concrete and requires a skilled nozzleman. The top edge is kept feathered (or 'benched') to allow rebound to fall clear and a second operative will often use a blowpipe just ahead of the nozzleman to clear the area that is about to be sprayed.

The water is continually adjusted in the dry process to obtain a well compacted concrete in situ, with acceptably low rebound. The air pressure and feed rate may also be occasionally adjusted at the gun. With the hydraulic wet process the delivery rate is adjusted at the pump and air pressure controlled at the nozzle.

Further discussion of good construction practice is given in Chapter 10 on Construction Practice and is also described by Ryan (1973), ACI Committee 506 (1990*a*, 1990*b*, 1983) and the Sprayed Concrete Association (1986).

Certification Schemes

Clearly the quality of the in-situ concrete is highly dependent on the skill and experience of the nozzleman. Poor quality installation has sometimes given sprayed concrete a bad reputation, particularly that applied by the dry process. This has led to training and certification schemes to demonstrate that qualified operatives are used by participating contractors. Such schemes have been used in the US following the introduction of the Guide to Certification of Shotcrete Nozzleman (ACI Committee 506, 1982) and an example is described by Crom (1986). In the UK the Sprayed Concrete Association has recently developed a registration scheme in conjunction with the Construction Industry Training Board (CITB) which administers

fourteen record schemes for diverse parts of the industry. Typically, these schemes consist of training programmes followed by tests that require the spraying of test panels including reinforcement encasement, visual inspection and testing of cores from the panels, and a written or oral examination of theory and knowledge. They may allow confirmation of grandfather rights on very experienced nozzlemen who are thus exempted from an examination. Some difficulty has been found in identifying suitable quantitative methods of assessment of both theory and practical tests, but these should be overcome as schemes become established.

Certification schemes must undoubtedly become an essential part of sprayed concrete construction in the future. Only by such measures will the industry be able to convince clients and engineers of the quality of the product. This in turn means that schemes must have the backing of an established independent organisation, such as the ACI or CITB, if they are to be authoritative and widely accepted.

4.5 Losses

Types

When spraying concrete, losses arise in a number of ways and can be defined as any material that is not part of the finished in-situ material. The three sources are:

(a) *overspray* – material missing the target surface;
(b) *rebound* – material which strikes the surface but does not adhere; and
(c) *cutback* – material which adheres but is subsequently removed whilst plastic to bring the surface to the correct profile.

Overspray should not be a significant portion of the total production losses. Cutback will only occur when a profiled finish is required and the layer is sprayed too thick initially. This loss can be minimised by use of guide wires, profile boards and a skilled nozzleman. It should be remembered that cutting back disturbs the concrete and should be avoided on thin layers where the bond to the substrate may be affected.

The biggest concern is losses due to rebound, which are the order of 20–30% with the dry process, but only 10–15% with the wet process. Not only is this an economic loss, but the individual constituents of the mix rebound by different amounts. This changes the in-situ proportions from those batched (particularly with the dry process) and can have a marked effect on performance. It is appropriate to deal separately with material rebound (largely aggregate and some cement) and fibre rebound (loss of steel or plastic fibres, when used).

Material rebound and in-situ proportions

In the dry process material rebound is influenced by many factors, including direction of spraying, spraying distance, aggregate grading, aggregate moisture content, water pressure, water-ring and nozzle design, additives and admixtures, layer thickness and surface conditions. The rebound of fibres is inextricably tied to material rebound but is also influenced by their size, shape, weight and possibly fibre content. The process is so complicated by these interrelated factors that no consensus has been (or seems likely to be) reached on ideal spraying set-up conditions. Nevertheless, there are general trends which can be identified and these are discussed be-

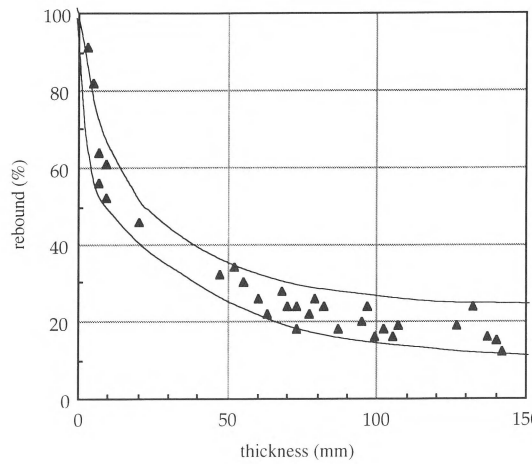

Figure 4.12 *Effect of layer thickness on material rebound (Parker et al., 1977).*

low. The increasing success of the wet-mix process in Scandinavia in producing acceptable in-situ properties at significantly lower rebounds has put pressure on the dry-mix industry, and manufacturers in particular, to improve the dry-mix process to reduce rebound and hence keep it competitive.

One of the few detailed examinations of material rebound was made by Parker *et al.* (1977) who observed the following characteristics of a 2.2 : 2.2 : 1 by weight dry-mix shotcrete (maximum aggregate size 13mm):

(i) rebound in producing the initial 13mm of a layer was around 60% compared with 10% for the rest of the layer;

(ii) rebound contained more than 60% coarse aggregate compared with 40% in situ, and very little cement; and

(iii) from high speed photography the particle velocity was found to be 30–60 m/s with an operating air pressure of 340 kN/m^2 (50 psi).

The effect of layer thickness is summarized in Figure 4.12 which demonstrates that it is much more economical to spray a single thick layer, say 100mm, than two separate 50 mm layers.

Three authors quote values of rebound illustrating the effect of the orientation of the target surface. The results of Ryan (1975), Gullan (1975) and Kobler (1966) are presented in Figure 4.13. The wide range in amounts of rebound illustrates how variable it is, although in each case the effect of surface orientation is very similar. Kobler also reports on the effect of nozzle-to-surface distance on rebound. The trend of the results showed a reduction in rebound as the nozzle-to-surface distance increased to 1.0 m, but an increase again at greater distances. Ryan states the nozzle should be kept in the 0.6–1.2 m range from the surface whilst Gullan recommends 1.0–1.5 metres.

Ward and Hills (1977) also carried out a detailed investigation of the dry-mix process at the Building Research Establishment. They looked at both coarse (12 mm down) shotcrete and fine (6 mm down) gunite mixes. A detailed discussion is given

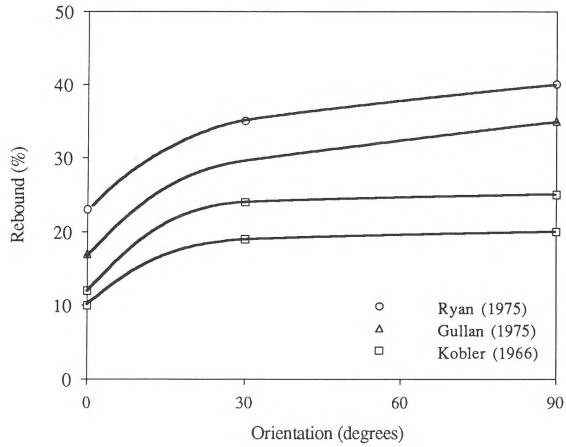

Figure 4.13 *Influence of surface orientation on material rebound.*

on the non-uniform distribution of the mix ingredients discharging from the nozzle which results in an inhomogeneous deposit. They also measured particle velocities using high speed photography, recording mean velocities of 15–35 m/s, with coarser particles moving more slowly, and noted that this gave a mixing time in a 200 mm long nozzle of 0.008 seconds. Experimentation with a water-ring 5 m before the nozzle tip produced higher quality in-situ concrete and this was attributed to the increased mixing time (0.2 s). They also observed, as did Parker *et al.* (1977) that many particles were spinning in the air stream, at up to 250 rpm for elongated particles, and this could be an important factor in the rebound mechanism. Increasing the air pressure was found to increase strength and density. The balance of in-situ performance and rebound was clearly demonstrated in one test where increasing the air pressure from 0.15 N/mm^2 to 0.43 N/mm^2 increased the compressive strength from 22 N/mm^2 to 40 N/mm^2 and rebound from 35% to 60%.

Ward and Hills sprayed 50 mm thick vertical panels and measured the grading and composition of the in-situ and rebound material and compared it with that of the dry mixes (Figure 4.14). It can be seen that most of the coarse particles (greater than 10 mm) rebound, along with some of the fine aggregate and a small amount of cement. Thus typical dry process sand/cement mixes (gunites), 3:1 or 4:1 by weight, have in-situ properties of 1.8:1 to 3.2:1, depending on the differential amounts of rebound, and water/cement ratios of 0.35 to 0.50. Not surprisingly these cement rich in-situ mixes can easily produce compressive strengths of 40–75 MPa. It is vital that the engineer appreciates that dry process spraying changes material proportions significantly and that the design is based on the anticipated in-situ mix.

The effect on material rebound of adding fibres is inconclusive. Some investigators have reported that sprayed fibre concrete rebounds less than an equivalent plain sprayed concrete mix, while others found no difference. Henager (1977) gives details of a 3.85:1 dry mix rebounding an estimated 31%, reducing to 10% with the addition of 4.4% by weight of 13 × 0.25 mm steel fibres. Ryan (1975) also found

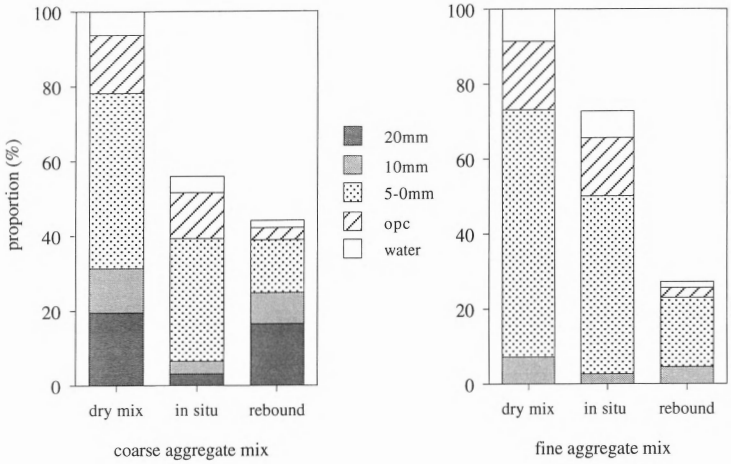

Figure 4.14 *Typical relative dry-mix, in-situ and rebound proportions (Ward and Hills, 1977).*

that the presence of fibres reduced material rebound by up to 45% but Ruffert (1974) and Mahar *et al.* (1975) report that fibres have no effect, the latter concluding that the reductions in material rebound found by Ryan were due to other factors in the spraying process (such as lower particle velocity or higher water/cement ratio). Our own experience is that steel fibres have little effect on material rebound which is usually in the range of 15–25% for vertical test panels sprayed to a thickness of around 100 mm. These values are in agreement with those reported by numerous other authors.

Material rebound with the wet process is low, typically 5–10% being reported for vertical surfaces (Opsahl and Buhre, 1985; and Shattuck, 1985). Little detailed information is available due to the lack of concern over such relatively small losses. The dosage of accelerator admixture may however be adjusted to take account of the orientation and hardness of the surface to be sprayed.

Fibre rebound

Researchers are almost unanimous in finding that steel fibres rebound more than the concrete material, values in the range 15–60% being reported. Fibre rebound, like material rebound, is influenced by layer thickness.

As part of a comprehensive investigation into dry-process sprayed steel fibre concrete, Parker *et al.* (1975) measured the rebound of 25 mm slit-sheet fibres, from the outer 50–100 mm of 150 mm thick vertical panels, as 12–56% (average 38%). As rebound is higher in the build up of the initial 13 mm of sprayed concrete these values are underestimates for a complete layer; the rebound for the complete 150 mm layer was put at 10–20% higher. Edgington (1977) quoted values of 15–45% rebound, measured from cores taken by British Rail during their investigations with wire fibres. Ryan (1975) suggested that figures of 40% when spraying horizontally and up to 60% for overhead work be assumed. More recently Morgan *et al.* (1987) reported values up to 50% and Banthia *et al.* (1992) 35–78%.

Care must be taken when interpreting reported values because fibre rebound (or the obverse, fibre retention) can be calculated in several ways. The most common method is:

$$\text{Fibre retention} = \frac{FC_i}{FC_{dm}} \times 100\% \text{ and}$$

$$\text{Relative fibre rebound} = \frac{FC_{dm} - FC_i}{FC_{dm}} \%$$

where FC_{dm} is the dry mix fibre content (% by weight)
and FC_i is the in-situ mix fibre content (% by weight)

Little (1985) calculated fibre retention in this manner to give figures of between 52 and 64%. Morgan (1991) gives in-situ fibre contents of 35–45 kg/m^3 corresponding to a dry mix fibre content of 60 kg/m^3 which equate to a fibre retention of between 58 and 75%. Armelin (1992) found the average fibre retention of six mixes containing two fibre types at three concentrations to be 75%.

Robins and Austin (1985) recognized that fibre retention and relative rebound calculated in this manner do not account for the material rebound of fibre mixes and underestimate the actual fibre losses. The in-situ fibre content, FC_i, as a percentage by weight of the dry material, and fibre rebound, R_f, were calculated from the expressions:

$$FC_i = WFC_i \frac{(1 + WCR + ACR_i)}{(1 + ACR_i)} \%$$

and

$$R_f = 100 - \frac{WFC_i (1 + WCR + ACR_i)}{FCR_{dm}} \%$$

where WFC_i is the in-situ fibre content (% by weight of wet material)
WCR is the water/cement ratio
ACR_i is the in-situ aggregate/cement ratio, and
FCR_{dm} is the dry mix fibre/cement ratio.

These equations assume that only the aggregate fraction rebounds. The in-situ proportion can be determined from a fresh concrete analysis, by washing a weighed sample cut from the sprayed concrete through a 150 mm sieve, then drying and weighing both the retained material (aggregate plus fibre) and the material passing through (cement plus a small proportion of sand).

Experience with steel fibres (wire, sheet and melt extract) in the dry process produces figures of around 40–60% rebound when spraying 100 mm thick onto vertical plywood panels (Robins and Austin, 1985) and this has been repeated consistently in more recent trials (Peaston, 1993). There is also a clear relation between fibre rebound and material rebound (Figure 4.15).

There is very little data available on the rebound of polypropylene fibres. However, on a repair contract involving the use of high-modulus fibrillated fibres to reinforce a 35 mm thick dry process mortar coating, the author recorded fibre rebound in the range 35–40%, which was of similar order to the material rebound (Austin and Robins, 1989).

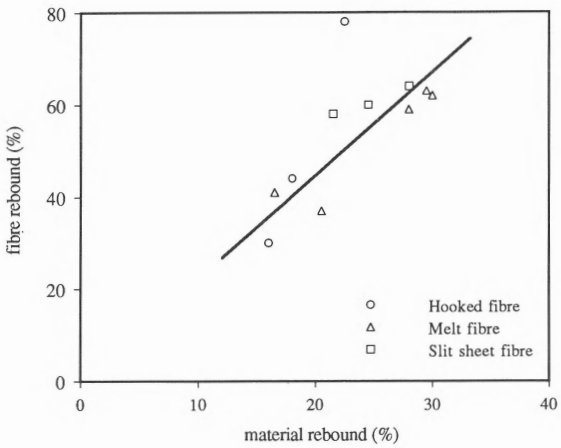

Figure 4.15 *Relationship between fibre and material rebound.*

In an attempt to relate fibre geometry to fibre rebound, Banthia *et al.* (1992) hypothesized that fibre rebound could be related to the fibre accelerations experienced during shooting: under a given air pressure fibre accelerations should be proportional to the fibre projected surface area and inversely proportional to fibre mass. In a trial conducted using five types of steel fibre with varying geometries the parameter fibre projected area/fibre mass, termed 'specific projected area', was found to be directly proportional to relative fibre rebound.

Reports of fibre rebound in wet process sprayed concrete are limited, but it is generally accepted that values are significantly less than with the dry process. This is because material rebound is lower and the mix is more plastic with the effect of binding fibres into the concrete. For example Kobayashi (1983) reports fibre retention figures of 60–90% for the wet process, compared with only 20–50% for the dry process.

Effect of silica fume

It has been reported that the inclusion of silica fume can significantly reduce material rebound. Morgan (1988) has described its extensive use in Canada including details on sixteen projects. When spraying a 50 mm layer overhead, incorporating silica fume in the mix was found to reduce rebound from 40% to 25%. He attributes this reduction to the greater cohesion and adhesion of silica fume concrete and also points out that the material is very resistant to wash out by water, making it particularly suitable for applying in running water or tidal conditions.

The author has conducted trials in the UK and found that additions of silica fume, in the range 5–15% by weight replacement of cement, reduced material rebound by up to 50% in both a 3:1mix and a 4:1mix. The data in Figure 4.16 is based on 37 different mixes both with and without fibre reinforcement. The inclusion of silica fume also significantly reduced fibre rebound. The use of 10% by weight cement replacement reduced fibre rebound from 56% to 40% in a 3:1 mix and from

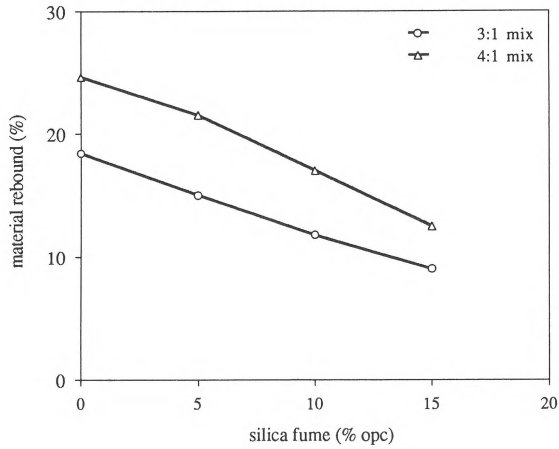

Figure 4.16 *Effect of silica fume on material rebound.*

65% to 50% in a 4:1 mix.

It is increasingly common to add silica fume at the nozzle as a slurry. Herfurth and Nilsen (1990) describe the success of this method in Europe and report lower rebound than with a powder form (5–10% compared with 15–25%) and more consistent cement content, avoiding increases during initial layer build-up,

4.6 Preparation, formwork and finishing

Many aspects of surface preparation, formwork, construction joint formation, finishing and curing of sprayed concrete are the same as those used in cast concrete construction. A quality product will result if skilled operatives follow established good practice and a knowledgeable engineer produces sound design, details and specification. The reader is again referred to documents produced by ACI Committee 506 (1990*a*, 1990*b*, 1983) and the Sprayed Concrete Association (1986) as well as further details in Chapter 10, Construction Practice and Quality Control.

Surface preparation

As with the repair of cast concrete, the integrity of sprayed concrete is totally dependent on the bond to the substrate. Without a sound bond the sprayed concrete layer will be ineffective and possibly dangerous. It is therefore vital that the target surface is prepared properly and the most important characteristics are roughness, soundness, cleanliness and moisture condition. Little work has been published on the effects of these parameters on sprayed concrete, but the author has recently reviewed the tensile bond of cementitious repair mortars (Austin *et al.*, 1994); these are similar in nature to sprayed concrete and the most important aspects are summarized below.

Roughness and soundness depend directly on the method of preparing the surface to be repaired. If the bond surface is produced by casting, saw-cutting, grit-blasting or water-jetting, it is likely to be sound, but the roughness will depend on

the size of grit or sand, the delivery pressure, and the operating time. If the bond surface is produced by a vigorous mechanical method, such as hammering or splitting, the surface will be very rough, but microcracks will be induced just beneath the prepared surface.

Tensile bond strength is sensitive to the existence of surface defects, such as microcracks in the substrate, because of a reduction in the effective bond area and the generation of stress concentration at the tips of microcracks, which will accelerate the development of defects. Tests carried out by Hindo (1990), Siffwerbrand (1990), Cleland *et al.* (1986) and the author (Austin *et al.*, 1995) clearly demonstrate that vigorous mechanical roughening produces an unsound surface and low bond strengths. Such methods should thus be avoided when preparing a surface for sprayed concrete. Water-jetting or grit-blasting should be used to obtain a rough, sound surface and potentially high bond between the substrate and sprayed concrete.

A bond surface should also be free of dust, oil, grease and other contaminants. Dust can be easily blown off but oil and grease require the application of a detergent. Little information is available on this issue. Generally, if sand-blasting or water-jetting is the means of preparing the surface, there should be no problem with the cleanliness.

The moisture condition of the substrate will determine the rate of movement of water from the sprayed concrete to the substrate concrete (or other material, e.g. rock or brick) due to the moisture imbalance between the two layers. Both the surface moisture condition and the moisture distribution inside the substrate are important. During the process of water movement, two things will occur: penetration of water from the sprayed concrete layer into the capillaries of the substrate concrete, and hydration of cement paste in the sprayed layer (limited rehydration of the substrate may also occur in a young concrete). To date, the published data on moisture condition is inconclusive but it appears that saturated or dried substrates may give lower bond strengths than air-dried surface wet or saturated surface dry conditions.

Formwork and reinforcement

Clearly one of the main advantages of sprayed concrete is the reduction or elimination of formwork. A back form may be required in new construction which can be removable or integral, the latter including rockwool and expanded mesh materials. In repair it is often necessary to form returns and corners, and this is done by temporary screed boards. These must be fitted a distance from the substrate to allow rebound to escape when spraying the first face and to form a clean joint. The screeds are then removed prior to spraying the adjacent face. Whatever the formwork, it is important that it is fixed rigidly, otherwise it will vibrate under the impact of the sprayed concrete and disturb the build-up of material.

Surface profiles can be produced by screeding to guide strips, although care should be taken to minimize disruption of the surface when cutting back. Ground (piano) wires can be used as a visual guide when spraying and for cutting back. Metal or plastic depth gauges are an alternative, provided they do not affect the integrity of the finished material. Also the layer can be checked by pushing in a steel depth probe. Careful consideration should always be given to the method of spraying, to the specified thickness (and tolerance), and to subsequent checking and measure-

ment. Overspraying is at best wasteful and underspraying may reduce load capacity and cover to reinforcement.

The size and spacing of reinforcing bars or mesh should be chosen to allow the sprayed concrete to fill behind and around the steel. Layers of bars or mesh should be staggered for similar reasons. In general, bars should be spaced at least 65 mm (2½ in.) apart and at least 12 mm (½ in.) or 2½ times the maximum aggregate size (whichever is the greater) away from the substrate. As with formwork it is essential that bars and mesh are held rigidly in position, by fixing to anchors and tying laps, in order that vibration is prevented and the specified cover maintained.

Finishing and curing

A natural or gunned finish is perhaps ideal for sprayed concrete, as the surface is not disturbed by finishing and the concrete will therefore be at its best in terms of bond to substrate and reinforcement, strength and durability. If, however, a textured finish is undesirable the surface can be finished by trowel, float or brush, but it should be understood that unlike cast concrete, it is stiff and therefore difficult to work.

Where a natural, textured finish is required the sprayed surface should be left untouched unless it has been cut back to obtain a profile. In this case a thin (up to 6 mm) fresh coat should be sprayed after screeding. It is preferable that this is done while the undercoat is still plastic to obtain a good bond, otherwise the substrate must be scarified to leave a good key for flash-coating later. Flash coats can also be used to cover fibres protruding form a fibre reinforced sprayed concrete, or to apply a different colour finish (obtained with different cements or colouring additives). Flash coats are applied with a higher water content than the main layer and are usually sprayed at greater distances, typically 2 to 3 m.

Smooth finishes are best achieved by a wooden or rubber-faced float, the latter giving a more closed texture. Brushing produces a sandy, fine-grained finish. A smooth closed surface can be obtained with a steel trowel. All concrete must be cured properly and sprayed concrete is no exception. In fact its relatively high cement content, low water/cement ratio and often thin section make it particularly prone to poor curing. Many engineers and most operatives still do not appreciate the dramatic effect that poor curing can have on concrete durability and strength, especially in adverse hot or windy conditions when evaporation rates are high.

The best curing method is to keep the surface moist by covering with wet hessian (burlap) which is kept damp for three to four days and ideally seven days. Polythene is ineffective as a barrier method because of lack of intimate contact with the surface, but spray or brush applied chemical curing membranes can provide good curing. They should not, however, be used when further concrete is to be applied; for example if a flash coat is to be sprayed onto a hardened layer a few days old, the latter should be moist cured, not sprayed with a membrane. Extra care should be taken with concretes containing supplementary cementing materials such as silica fume, slag and pulverized fuel ash (fly ash). These materials have a longer hydration period than Portland cement and therefore require longer curing, particularly in hot weather.

Precautions to be taken in cold weather or hot climates are the same as for conventionally cast concrete. For instance spraying should not take place below

5°C and in high temperatures materials may need shading and water cooling to prevent rapid setting and hardening.

References

ACI Committee 506 (1982) Guide to certification of shotcrete nozzlemen. American Concrete Institute. *Concrete International Design and Construction*, **14** (10) 69–79.

ACI Committee 506 (1983) Recommended practice for shotcreting. *ACI Standard 506-66*, American Concrete Institute, Detroit, 15.

ACI Committee 506 (1990*a*) Standard specification for materials, proportioning and application of shotcrete. *ACI Manual of Concrete Practice, Part 5*, American Concrete Institute, Detroit.

ACI Committee 506 (1990*b*) Guide to Shotcrete. *ACI Manual of Concrete Practice, Part 5*, American Concrete Institute, Detroit, 41.

Aihara, W. and Yamamoto, K. (1984) Cost down with the new shotcreting system. *Proceedings of International Symposium on Low Cost Road Tunnels*, Oslo, 563–577.

Armelin, H. (1992) Steel fibre reinforced dry-mix shotcrete: fibre orientation and its effect on mechanical properties. *Proceedings of International Conference on Fibre Reinforced Cement and Concrete*, Sheffield, RILEM, 266–276.

Austin, S.A. and Robins, P.J. (1989) A repair application of polypropylene fibre reinforced sprayed concrete. *Proceedings of International Conference on Recent Developments in Fibre Reinforced Cements and Concretes*, Cardiff, Elsevier Applied Science, London, 21–31.

Austin, S.A., Robins, P.J. and Pan, Y. (1995) Tensile bond testing of concrete repairs. *Materials and Structures*, in press.

Banthia, N., Trottier, J-F., Wood, D. and Beaupre, D. (1992) Influence of fibre geometry in steel fibre reinforced dry-mix shotcrete. *Concrete International*, **14** (2), 24-28.

Cleland, D.J., Naderi, M. and Long, A.E. (1986) Bond strength of patch repair mortars for concrete. Proceedings of RILEM *International Symposium on Adhesion between Polymers and Concrete*, Aix-en-Provence, Chapman and Hall, London, 225–244.

Crom, T.R. (1986) Shotcrete nozzlemen certification. *Concrete International*, **8** (2), 27–30.

Edgington, J. (1977) Economic fibrous concrete. *Proceedings of Fibre-reinforced materials: Design and engineering applications*, Institution of Civil Engineers, London, 115–126.

Gullan, G.T. (1975) Shotcrete for tunnel lining. *Tunnels and Tunnelling*, **7**(9), 37–47.

Herfurth, E.A. and Nilsen,T. (1990) Advances in dry shotcrete technology by means of microsilica. Proceedings of Engineering Foundation Conference *Shotcrete for Underground Support V*, Uppsala, Sweden, 251–64.

Henager, C.H. (1977) The technology and uses of steel fibrous shotcrete – A state-of-the-art report. *Report*, Batelle Development Corporation, Richland, Washington.

Hindo, K.R. (1990) In-plane bond testing and surface preparation of concrete. *Concrete International*, **12**(4), 46–48.

Holtmon, J.P., Lilleas, T. and Opsahl, O.A. (1993) Norwegian wet mix sprayed concrete – state-of-the-art and future developments. *Proceedings of International Symposium on Sprayed Concrete*, Fagernes, Norway, 28–91.

Kobayashi, I.K. (1983) Developments of fibre reinforced concrete in Japan. *Cement and Concrete Composites*, **5**(1), 27–40.

Kobler, H.G. (1966) Dry-mix coarse-aggregate shotcrete as underground support. *Shotcreting* (SP-14), American Concrete Institute, Detroit, 33–58.

Little, T.E. (1985) An evaluation of steel fibre reinforced shotcrete for underground support. *Canadian Geotechnical Journal,* **22**(4), 501–507.

Littlejohn, G.S. (1980) Wet process shotcrete. *Proceedings of Symposium on Sprayed Concrete (CI80)*, Concrete Society, London, 18–32.

Long, W.B. (1990) Sprayed Concrete. *The maintenance of brick and stone masonry structures*, ed. Sowden A.M., E & F N Spon, London, 239–252.

Mahar, J.W., Parker, H.W. and Wuellher, W.W. (1975) Shotcrete practice in underground construction. *Report* No. FRA-OR & D 75-90, Federal Railroad Administration, Washington D.C.

Maidl, B. (1991) Shotcrete robot for improving working conditions, quality and economy in civil engineering and tunnelling. *Proceedings of 8th International Symposium on Automation and Robotics in Construction*, Stuttgart, 85–94.

Matsuo, S. and Kenmochi, S. (1981) Improvements in shotcreting. *Water Power & Dam Construction*, December, 42–46.

Morgan, D.R. (1988) Dry-mix silica fume shotcrete in Western Canada. *Concrete International*, **10**(1), 24–32.

Morgan, D.R. (1991) Steel fiber reinforced shotcrete for support of underground openings in Canada. *Concrete International*, **13**(11), 56–64.

Morgan, D.R., McAskill, N., Neill, J. and Duke, N.F. (1987) Evaluation of silica fume shotcretes. *Proceedings of CANMET/ACI workshop on condensed silica fume in concrete*, Montreal, 34.

Opsahl, O.A. and Buhre, K.E. (1985) Why wet process steel fibre reinforced shotcrete? *Proceedings of US-Sweden Joint Seminar on Steel Fibre Concrete*, Stockholm, 51–65.

Parker, H.W., Fernandez, G. and Lorig, L.J. (1975) Field-orientated investigation of conventional and experimental shotcrete for tunnels. *Report* No. FRA-OR & D 76-06. Federal Railroad Administration, Washington D.C.

Parker, H.W., Fernandez-Delgado, G. and Lorig, L.J. (1977) A practical new approach to rebound losses. *Shotcrete for Ground Support* (SP-54), American Concrete Institute, Detroit, 149–187.

Peaston, C.H. (1993) *Production, properties and design of sprayed fibre concrete*, PhD thesis, Loughborough University of Technology, UK.

Robins, P.J. and Austin, S.A. (1985) Sprayed steel fibre concrete, Part 1 - production and installation. *Concrete*, **19**(3), 17–19.

Ruffert, G. (1974) Erfahrungen mit stahlfasersprifzbeton, *Tiefbau*.

Ryan, T.F. (1975) Steel fibres in gunite: an appraisal. *Tunnels and Tunnelling*, **7**(7), 74–75.

Ryan, T.F. (1973) *Gunite: A Handbook for Engineers*, Eyre and Spottiswoode, Leatherhead, UK.

Sandell, N. and Westerdahl, B. (1985) System Besab for high strength steel fibre reinforced shotcrete. *Proc. of US-Sweden Joint Seminar on Steel Fibre Concrete*, Stockholm, 25–40.

Shattuck, D.W. (1985) The new zoological gardens, Riyadh. *Civil Engineering*, Nov/Dec, 20–21.

Siffwerbrand, J. (1990) Improving concrete bond in repair bridge decks. *Concrete International*, **12**(9), 61–66.

Skatun, O. (1986) Applications of wet process steel fibre reinforced shotcrete in Scandinavia. *Proceedings of the 3rd International Symposium on Developments in Fibre Reinforced Cement and Concrete*, Sheffield, July, Paper 9.6.

Sprayed Concrete Association (1986) *Code of Good Practice*, SCA, Aldershot, UK, reprinted 1990.

Wallace, M. (1987) For reinforcing Canadians prefer steel fibres. *Concrete Construction*, **32**(9), 775–776.

Ward, W.H. and Hills, D.L. (1977) Sprayed concrete – tunnel support requirements and the dry mix process. *Shotcrete for Ground Support (SP-54)*, American Concrete Institute, Detroit, 475–532.

5 Physical Properties

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5.1 Introduction

There is in the published literature a considerable amount of information relating to the strength and other physical properties of sprayed concrete; this was not the case 10–15 years ago, and is perhaps a direct result of the increased usage of sprayed concrete as a construction material, particularly for rock support and tunnelling.

This chapter presents information on many of the physical properties of sprayed concrete. Throughout, the reader should bear in mind that in many instances sprayed concrete (and therefore its properties) differs only from more conventional concrete because of its method of mixing, conveying and placing (compaction). Not all the properties discussed will be of relevance to every application of sprayed concrete, and the designer/specifier must judge which properties are important before including them in a performance type specification.

Where appropriate, comparisons of wet-mix and dry-mix are made, and where their effect is likely to be important the influence of fibres on the properties of sprayed concrete is discussed (for example, in flexural strength and toughness). Where possible, appropriate standard test methods are referred to.

5.2 Plastic properties

Samples can be taken from freshly sprayed concrete and used to determine the mix parameters such as water/cement ratio, or cement content. Where fibres are included in a mix, then simple wash-out tests on samples of fresh concrete are often used to determine the resulting in-situ fibre content; such testing is of particular importance in the dry-mix process where the differential effects of rebound have a major influence on the resulting in-situ fibre content.

With the wet-mix process, samples of freshly mixed concrete are readily available before pumping and spraying, and can if required be tested for workability, air content, or composition. However, it must be remembered that the air content is drastically reduced by the pumping and spraying processes (Section 5.11).

Beaupré (Beaupré *et al.*, 1994*a*, Beaupré and Mindness, 1993) has recently suggested that the existence of flow resistance might be a good explanation for the 'shootability' (that is, the greater the thickness that can be built up) of a wet-mix sprayed concrete. In a series of tests on wet-mix asbestos-fibre reinforced sprayed concrete, Beaupré *et al.* (1991) found that the best way to incorporate high volumes of asbestos fibre in the mix was to increase the paste volume by making mixes with

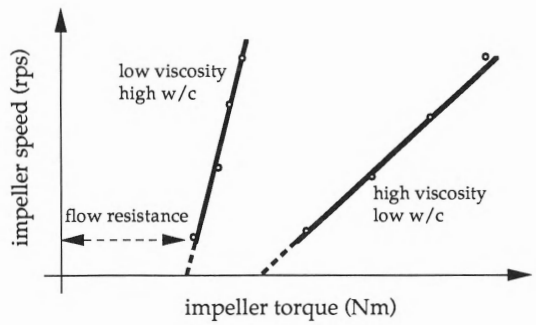

Figure 5.1 *Fresh concrete behaviour (Tattershall and Banfill, 1983).*

high air content. Sprayed concretes with initial air contents as high as 20% could be pumped and shot with very little rebound. They noted that the loss of air during pumping and shooting was very high, about 15% (leaving about 5% air content in the hardened sprayed concrete). They also noted an almost complete absence of rebound: 0.2% on walls and 0.5% overhead.

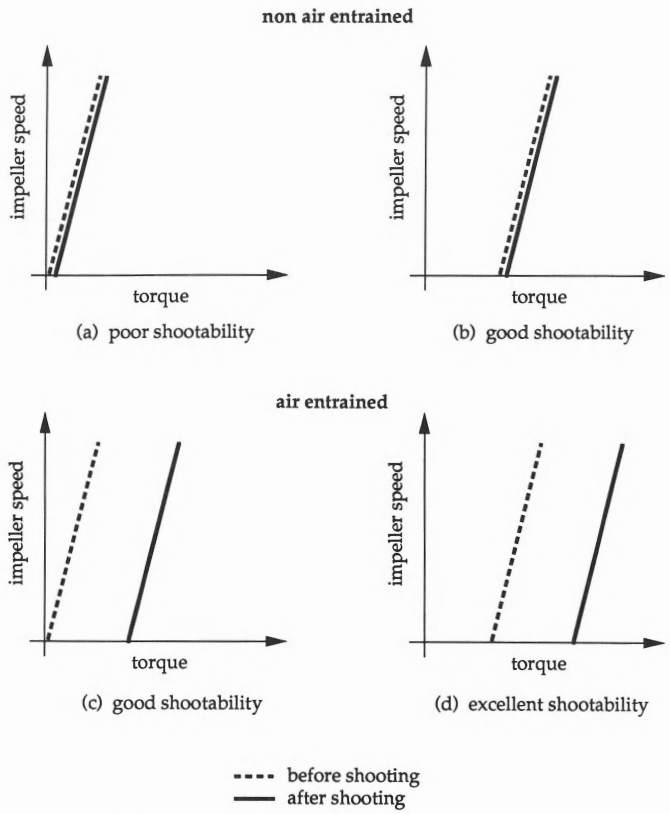

Figure 5.2 *Possible relationships between flow resistance and compaction (Beaupré et al., 1991).*

An explanation of what was observed comes from a consideration of the rheology of the concrete. Fresh concrete can be represented as a Bingham material (Tattershall and Banfill, 1983), where behaviour can be modelled as in Figure 5.1. The work of Beaupré *et al.* (1991) showed that compaction causes an increase in the flow resistance of the in-place sprayed concrete. From this, four types of behaviour relating to compaction and shootability can be proposed (Figure 5.2).

Figure 5.2*a* represents a very workable, easy to pump mix with a low flow resistance and no entrained air. There will be little compaction and the build-up thickness will be small, resulting in a poor shootability. Figure 5.2*b* represents a workable, pumpable mix with an acceptable flow resistance and no entrained air. Because there will be little compaction the flow resistance should be approximately the same before and after shooting. Also, because the in-place sprayed concrete has an acceptable flow resistance, the build-up thickness should be sufficient to ensure good shootability. Many sprayed concrete applications are probably well represented by this case. Figure 5.2*c* represents a very workable, easy to pump mix with a low flow resistance and a reasonable amount of entrained air. The in-place concrete, because of a high flow resistance, would have a high build-up thickness resulting in a good shootability. Finally, Figure 5.2*d* represents a workable, pumpable mix with an acceptable flow resistance and a high amount of entrained air. Because this concrete possesses entrained air, there will be compaction resulting in a higher flow resistance after shooting. The in-place concrete, because of a very high flow resistance, would have a very high build-up thickness resulting in excellent shootability.

Beaupré's work shows that the high initial air content is a good way of reducing the yield stress of the wet-mix concrete, hence enhancing its 'pumpability'. On impact with the receiving surface, air is lost during compaction which in turn increases the yield stress and hence the 'shootability'. This seems to address directly the conflicting requirements of pumpability versus shootability. Beaupré and Mindness (1993) also conclude that this temporary high air content approach may be used effectively in the production of high performance sprayed concrete, avoiding the harmful effects (crew health and concrete properties) of using accelerators.

5.3 Compressive strength

Plain sprayed concrete

The compressive strength of sprayed concrete is generally measured by compression testing of cores (to BS1881 Part 120, 1983*a*, ASTM C42, 1990 or similar) extracted from either test panels or the in-situ sprayed concrete.

The compressive strengths of dry process sprayed concrete reported in the literature are typically in the range 30–60+ MPa at 28 days, obtained with aggregate/cement ratios between 4:1 and 2.5:1 and unspecified water/cement ratios. Reported values for conventional opc wet process sprayed concrete are generally in the range 20–45 MPa for water-cement ratios 0.7 to 0.45. The use of silica fume and a water-reducer or plasticizer can produce strengths comparable with dry process sprayed concretes, 60 MPa being readily achievable. In a comparison of sprayed and cast site-produced concretes, Hills (1982) demonstrated that the compressive strength of

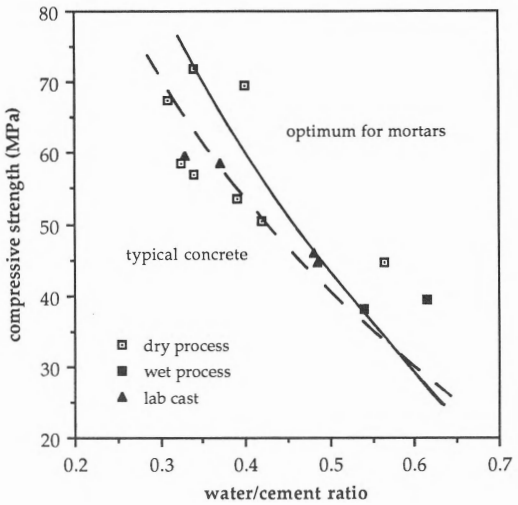

Figure 5.3 *Relationship between 28 day compressive strength and water/cement ratio (Hills, 1982)*

both dry and wet process sprayed concrete broadly follows the relationship with water/cement ratio for cast concretes and mortars (Figure 5.3). He obtained strengths between 37 and 72 MPa with water/cement ratios between 0.61 and 0.31.

Sprayed fibre concrete

The compressive strength of sprayed concrete is only marginally affected by fibre addition at rates commonly used in sprayed concrete (i.e. 60 to 80 kg/m^3 for steel fibres), and depends on the orientation of the roughly two-dimensional fibre plane relative to the direction of compressive loading. Figure 5.4 (Robins and Austin, 1989) shows the effect of in-situ fibre content of melt extract (25 mm long), hooked-end drawn wire (25 mm), and enlarged end slit-sheet fibres (18 mm) on the core compressive strength of a dry process sprayed concrete.

Recently, Banthia *et al.* (1994*a*) have presented the results of a comparative study of different steel fibre types in sprayed concrete. The investigation covered both dry-mix (Banthia *et al.*, 1992) and wet-mix (Banthia *et al.*, 1994*b*) methods and used five different steel fibre types readily available in the North American market. All fibre types were deformed, and included cold drawn wire, sheet steel and block steel. Fibre lengths varied from 25 to 32 mm, and the fibre content of the mixes (before spraying) was 60 kg/m^3. Silica fume was used in both dry-mix and wet-mix programmes, and the water-cementitious ratios for dry (estimated) and wet were 0.3 and 0.41, respectively. The addition of fibres to plain sprayed concrete gave increases in 7-day core compressive strengths of 7 to 15% for the dry mix and 5 to 21% for the wet mix. Because of fibre rebound (estimated $>50\%$ in dry mix and $<20\%$ for wet mix) there will have been more fibres in situ in the wet process sprayed concrete than in the dry one.

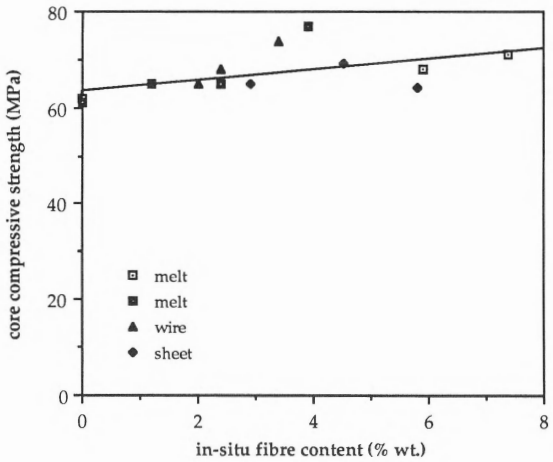

Figure 5.4 *Effect of fibre content on compressive strength (dry process)*

Nowadays, particularly with the wet-mix process, fibres are often used together with silica fume, and it is the latter that is more likely to have a significant effect on compressive strength (Swannell, 1993). Wet-mix sprayed concrete with compressive strengths in excess of 100 MPa can be produced, using appropriate combinations of water reducers, superplasticizers, silica fume and fibres (Morgan, 1991*b*).

Early age strength

Perhaps of equal (or even greater) interest than ultimate compressive strength are the rate of strength gain and the potential for very early age strength (i.e. hours rather than days). These are obviously of particular significance for sprayed concrete used in tunnelling applications. The strength development shown in Table 5.1 can be considered typical of the minimum requirements of a modern sprayed concrete mix (Swannell, 1993).

Table 5.1 *Compressive strength development*

Time	Strength
1–10 mins	initial set
3–30 mins	final set
1–3 hrs	1–4 MPa
8 hrs	5 MPa
1 day	10 MPa
3 days	20 MPa
7 days	30 MPa
28 days	40 MPa

Where accelerators are used to increase rates of setting strength gain, due consideration must be given to their long-term effect on physical properties. However, as the technology has developed over recent years, the percentage reduction in long-term strength effect has reduced significantly. Eight-hour compressive strengths of 5 to 7 MPa are frequently specified in tunnelling and mining applications and in deep excavations in unstable ground. When using normal Portland cements, such high early strengths can normally only be achieved by using an accelerator in the sprayed concrete. Morgan (1991*a*) has evaluated a wet-mix blended-cement sprayed concrete mixture without accelerators which produced early age strengths of 17 MPa at 4 hours and 22 MPa and 8 hours. Late-age compressive strength was also impressive, with field-cured sprayed concrete reaching 67 MPa at 28 days.

5.4 Flexural strength

Introduction

Sprayed concrete is often subjected to flexural loading in service, and so flexural strengths of sprayed concretes are frequently determined by performing standard beam tests on specimens cut from a test panel, e.g. ASTM C78 (1984), BS1881 Part 118 (1983*b*). Flexural strength is an indirect measurement of a concrete's tensile strength. Direct measurement of a concrete's tensile strength is difficult, though EFNARC's (1993) draft specification for sprayed concrete does describe a laboratory procedure, and a core pull-off test (such as that of Long and Murray, 1984) can be used for in-situ measurement. The cylinder splitting test is an indirect tensile test, and could be viewed as an alternative to a beam flexure test for determining a sprayed concrete's tensile strength properties. An advantage of the cylinder splitting test is that it can be used on cores taken directly from the in-situ concrete (Robins and Austin, 1985*a*), avoiding the need for spraying of test panels. Point-load testing of cores (Robins, 1984 and Robins and Austin, 1985*b*) is another indirect tensile test method available, and is discussed in more detail later in this section.

Plain and mesh reinforced sprayed concrete

Plain matrix flexural strengths are similar to cast concrete strengths and typically in the range 3 to 5 MPa at 28 days, depending on mix proportions and layer thickness. It is important to remember that flexural strength values do vary with specimen size (particularly depth), span and loading geometry. Whilst most authors quote strengths for 100 mm deep specimens, this is not always the case. Figure 5.5 compares flexural strengths of different layer thicknesses of dry-mix sprayed concretes (Robins and Austin, 1985*a*).

Light mesh is commonly used to reinforce sprayed concrete, but it is often located near the mid-depth of the section where it provides little or no flexural strengthening. More heavily reinforced sections will have significantly higher moment capacity, which can be calculated using reinforced concrete theory (*see* Section 6.3).

Improved flexural strength is a widely perceived reason for using sprayed fibre concrete. However, the improvements in flexural strengths due to steel fibre addition are relatively modest for the type and quantity commonly used in sprayed concrete. High flexural strengths, if required, can be more readily and economi-

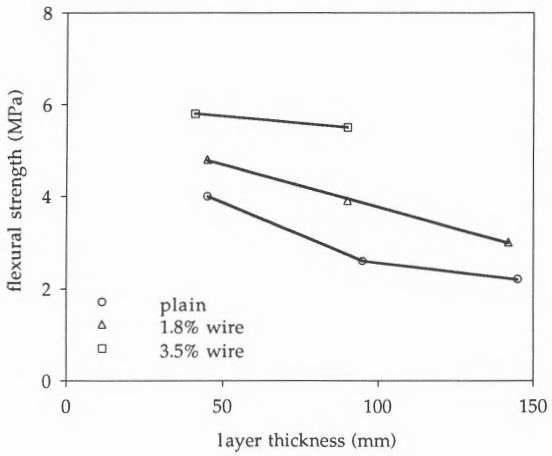

Figure 5.5 *Effect of layer thickness on flexural strength*

cally produced by increasing the matrix flexural strength, for example by reducing the water/cement ratio or through the use of materials such as silica fume and superplasticizers. Flexural strengths of 6 to 8 MPa at 28 days are quite common in high strength wet and dry-mix silica fume concretes. Morgan (1991*a*) has reported on high early strength blended-cement wet-mix sprayed concrete with flexural strengths of 4.1 MPa at 8 hours after batching and 7 MPa at 28 days. In a comparison of different forms of silica fume in both wet and dry-mix sprayed concretes, Wolsiefer and Morgan (1993) concluded that there were only small differences in flexural strength performance between the concretes made with the three different product forms; greatest improvement in flexural strength from the use of the silica fume occurred in the wet-mix sprayed concretes. For a water-cementitious ratio of 0.43, the average 28 day flexural strength of the silica fume wet-mix sprayed concretes was 6.4 MPa (compared with 5.3 MPa for the plain Portland cement control mix). Flexural strengths of similar dry-mix silica fume sprayed concretes (though with an estimated water/cementitious ratio of 0.39) were in the range 6.6 to 8.4 MPa.

Sprayed fibre concrete

Significant differences between the flexural performance of plain and fibre reinforced sprayed concrete are evident from the load-deflection curves produced from a beam flexural test. The fact that placing of sprayed concrete tends to orient the fibres in a plane parallel to the surface being sprayed is also beneficial to the flexural properties of the sprayed concrete, particularly when a thin layer is used.

For a sprayed fibre concrete, two values of flexural strength are significant: the so-called 'first-crack' flexural strength, determined as the strength at the point at which the load/deflection curve deviates from linearity (perhaps more correctly termed the limit of proportionality strength), and the ultimate flexural strength (or modulus of rupture) corresponding to the peak load. The former is only marginally influenced by fibres, but the latter increases with fibre volume as the fibre reinforcement delays formation of the first major flexural crack. This usually coin-

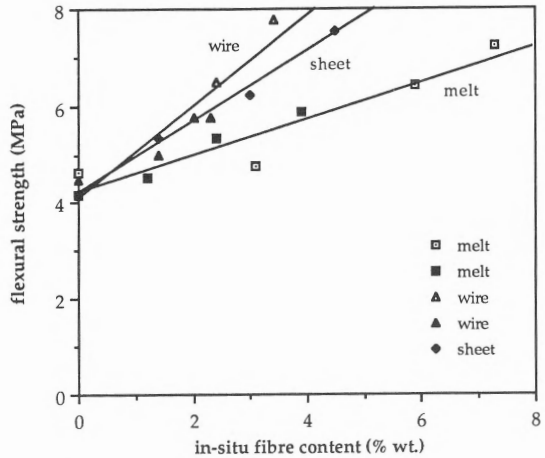

Figure 5.6 *Effect of fibre content on flexural strength (dry process)*

cides with peak load; however, above a critical fibre volume (where there are sufficient fibres to sustain the tensile load carried by the concrete prior to cracking), the composite is theoretically capable of carrying even more load and will sustain multiple cracking. Sprayed concrete in-situ fibre contents are such that this is unlikely to happen.

Flexural strengths of sprayed fibre concrete increase with increasing aspect ratio and volume concentration of fibres. Values reported for the dry process are generally in the range 5–10 MPa (ACI Committee 506, 1984; Ramakrishnan, 1981; Johnston, 1982*a*; Morgan, 1981; Vandewalle, 1986). Figure 5.6 gives typical results for three steel fibre types investigated by the authors (Robins and Austin, 1992). The effectiveness of hooked-end wire fibres for flexural strengthening is evident.

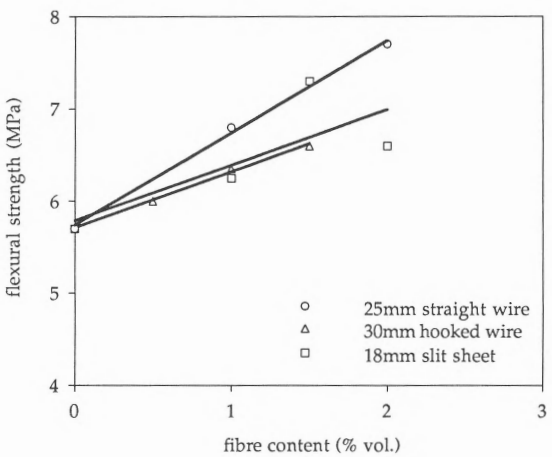

Figure 5.7 *Effect of fibre content on flexural strength (wet process)*

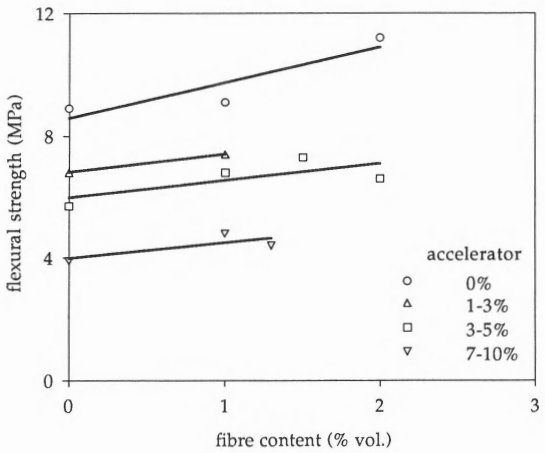

Figure 5.8 *Effect of accelerator dosage on flexural strength (wet process)*

For wet process sprayed fibre concrete, Vandewalle (1986) and Opsahl and Buhre (1985) quote flexural strengths up to around 10 MPa for fibre contents of 4.5 to 6% by weight of drawn wire or slit sheet fibres. Opsahl (1985) has presented quality control testing data from some twenty-five different wet-mix sprayed concrete tunnelling projects in Norway, with 28 day flexural strengths mostly in the range 5.5 to 11.0 MPa. The effect of fibres on flexural strengths of wet-mix sprayed concrete (Opsahl, 1985) is shown in Figure 5.7, which gives performances of three different fibres: a 25 mm straight wire fibre (aspect ratio 100), a 30 mm long hooked-end wire fibre (aspect ratio 60), and an 18 mm long enlarged end slit-sheet fibre (aspect ratio 38). The influence of accelerator (natrium-silicate based) dosage level on strengths of wet-mix sprayed concrete is evident from Figure 5.8.

Banthia *et al.* (1994*a*) compared the relative performance of five different commercially available steel fibre types in both wet and dry process sprayed concretes. Fibre lengths were all in the range 25 to 32.5 mm, and all fibres were deformed. A fibre content of 60 kg/m^3 (around 0.75% volume) was used in all mixes. Measurements of in-situ fibre contents revealed that in excess of 50% of the fibres added to the dry mix were lost in rebound, compared to less than 20% in the wet mix. The addition of the fibres to the plain sprayed concrete gave increases in flexural strengths of 13 to 24% for the dry mix and 6 to 24% for the wet mix sprayed concretes (Figure 5.9). Referring to Figure 5.9, fibre F1 was a 28 mm long hooked-end round fibre; F2, a 25 mm long hooked-end square section fibre;F3, a 32.5 mm long crimped fibre; F4, a 32.5 mm long hooked-end twisted fibre; and F5, a 25.5 mm long deformed fibre. Even though the dry-mix compressive strengths were consistently higher (on average 33%) than the wet-mix, the flexural strengths were consistently lower (on average 27%). The former is most likely a result of the lower water/cement ratio of the dry-mix sprayed concrete, while the latter may in part reflect the greater rebound of the dry-process spraying (and hence lower quantity of fibres in situ), but must also reflect the more variable nature of compaction achieved with the dry process in these trials. Any variations or flaws in the sprayed concrete are likely to

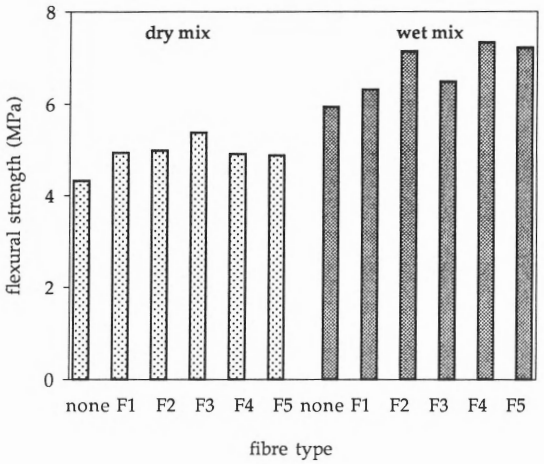

Figure 5.9 *Flexural strengths of sprayed concretes with different steel fibre types (Banthia et al., 1994a)*

have a greater effect on tensile strength than on compressive strength. Average in-place fibre volumes for the dry and wet-mix sprayed concretes were 0.3% and 0.7%, respectively.

Much less information is available on the properties of polypropylene fibre reinforced sprayed concrete. Austin and Robins (1989) measured limit of proportionality and ultimate flexural strengths of 3.9–4.7 MPa and 5.2–6.6 MPa for 40 mm thick specimens containing 0.25–0.7% by weight in situ of high-yield fibrillated polypropylene fibres, with lengths of 6 and 12 mm. Both Opsahl (1985) and Morgan *et al.* (1989) have reported reductions in flexural strength with high additions of polypropylene fibres (see Table 11.6).

The flexural strength of sprayed concrete is commonly determined from beam specimens sawn from test panels sprayed as part of the construction programme. The spraying of the test panels and the cutting and preparation of the beams is time-consuming and costly, and the samples so obtained are not necessarily representative of the in-situ sprayed concrete (see Section 6.5). Since cores are really the only test specimens that can be taken readily from the in-situ sprayed concrete, the potential of using a core point-load test (an indirect tensile splitting test) as an alternative to beam flexure for quality control testing has been investigated (Robins, 1984 and Robins and Austin, 1985*b*). In the point-load test a core is placed between two conical loading platens and the compressive load required to split the specimen is recorded. An index of strength is calculated from the failure load. The comparative effects of steel fibre quantities on flexural strength and point-load index are shown in Figure 5.10.

The relationship between beam flexural strength and point-load strength for sprayed concrete is shown in Figure 5.11, where it can be seen that over the practical range of sprayed concrete strengths there is an approximately linear variation. It should be noted that when testing an anisotropic material, such as sprayed fibre

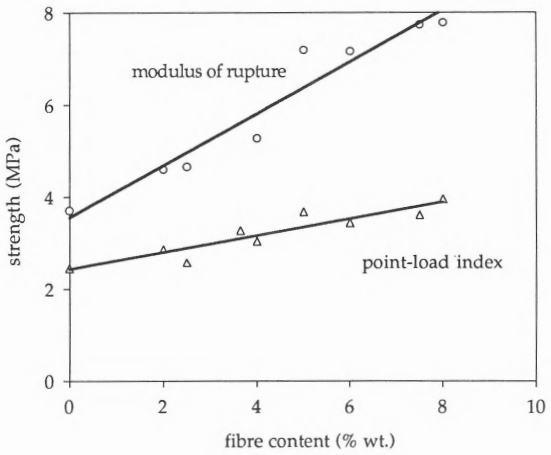

Figure 5.10 *Effect of fibre content on flexural and point-load strengths.*

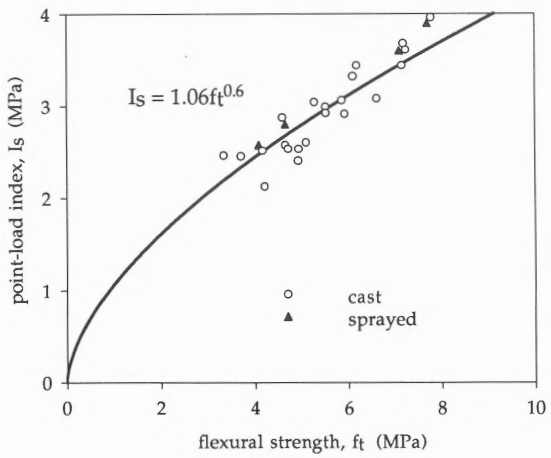

Figure 5.11 *Relationship between point-load index and flexural strength.*

concrete or even some plain sprayed concretes, the direction of testing is important. In order to measure the effect of the fibres on point-load strength of sprayed fibre concrete, axial testing of the cored samples is needed (Austin and Robins, 1993); diametral point-load testing can be used to obtain information on the concrete's matrix strength. The point-load test has been used by Ove Arup and Partners (Scott, 1994) as a quality control test for sprayed fibre concrete used in both slope stabilization and rock support applications.

Mesh and fibres compared

The relative flexural strengths of mesh reinforced and fibre reinforced sprayed con-

crete will clearly depend upon fibre type and volume, and the mesh size and its position in the section. A survey of published data reveals that typical fibre and mesh reinforced sections in the 50–150 mm thickness range have similar flexural strengths (see Section 6.3). So simple improvement of flexural strength alone is probably not a good enough reason for adding steel fibres to a sprayed concrete mix. It is the improved post-cracking resistance and ability to continue sustaining loads at increasing deflections (or toughness, see Section 5.5) that are more likely to be sound reasons for choosing fibre reinforcement.

The issue of comparative performance of mesh and fibre reinforcement for tunnel-support applications has been addressed by Kirsten and Labrum (1990) and Kirsten (1992) and summarized recently by Kirsten (1993). They carried out tests on mesh, hooked wire and melt-extract fibre reinforced sprayed concrete panels. Two-way spanning, 1.6m square panels with thicknesses of 50, 100 and 150 mm were tested under both distributed and point loading. Table 6.4 in Section 6 contains a summary of some of their data. They concluded that, with regard to strength and ductility, the performance of the mesh (a 75 × 75 × 3.1 mm diamond) reinforced panels was slightly better. However, they only achieved in-situ fibre contents of 1.3 to 2.5% by weight, and deduced that had they achieved their target of 3% in situ, the fibre reinforced sprayed concrete would have been capable of sustaining load at prolonged deformation to a similar extent and hence would have been equivalent in overall performance to the mesh-reinforced sprayed concrete of similar thickness. Maximum loads and effective loads at deflections of 50, 100 and 150 mm are shown in Table 6.4, and it can be seen that even with the relatively low in-situ fibre contents the peak flexural loads of the fibre panels compare reasonably favourably with those for the mesh panels.

5.5 Flexural toughness

Background

Toughness is generally recognized as the property most enhanced by the addition of fibre reinforcement to concrete. Prior to the use of fibres to reinforce concrete, there was no requirement for any standard concrete tests to assess toughness or its associated properties of post-cracking strength and ductility. The first formal definition of a toughness index was provided by Henager (1978) and later adopted by ACI Committee 544 (1978). Using load-deflection curves produced from modulus of rupture tests on 102 × 102 mm beams over a 305 mm span in third point loading, toughness index was defined as the area up to a central deflection of 1.9 mm divided by that to first crack; first crack being defined as the limit of proportionality of the initial linear response, although in reality most low volume steel fibre concretes do not crack until the peak load is reached, the non-linearity being due to softening of the material caused by microcracking (Mangat *et al.*, 1987). The main disadvantage of this index is that the results are only reproducible if the same sized specimens and testing machines are used.

Johnston (1982*b*) proposed a toughness index with the denominator based on the area to first crack as with the ACI index, but with the numerator based on the area up to certain multiples of the first crack deflection. The precise multiple of

Table 5.2 *Some test specifications for toughness measurement*

Source	Specimen and loading	Specimen dimensions[1]	Parameters monitored[2]
ACI 544 (1988)	Beam Third-point loading	$b=d=100$ mm $\ell=300$ mm $s=350$ mm	Total load Net-deflection midspan
ASTM C 1018 (1992)	Beam Third-point loading	100 mm × 100 mm × 350 mm preferred Variations permitted	Total load Net deflection at midspan or net deflection at load points
EFNARC Specification Draft (1993)	Beam Third-point loading	$b=125$ mm $d=75$ mm $\ell=450$ mm $s=600$ mm	Total load Net-deflection at midspan
	Plate. All edges simply supported Centre punch load	600 mm × 600 mm 100 mm thick Punch 100 mm × 100 mm	Load Deflection at the centre of the plate
Japan Concrete Institute Standard JCI-SF4 (1983)	Beam Third-point loading	$b=d$ 100 mm for $\ell_f < 40$ mm $b=d$ 150 mm for $\ell_f > 40$ mm $\ell=3d + 80$ mm	Total load Net-deflection at midspan or Net-deflection at load-points
Norwegian Concrete Association NCA (1993)	Beam Third-point loading	$b=125$ mm $d=75$ mm $\ell=450$ mm $s=550$ mm	Total load Net-deflection at midspan

1 – Depth = d; thickness = b; span = ℓ; overall length = s; fibre length = ℓ_f.
2 – Continuous record of load-deflection response required in all standards except ASTM (use of old dial gauge and discrete load-deflection monitoring is permitted).
3 – Deflection limit for test = δ_ℓ; δ_f = deflection at first crack.

first crack deflection can be chosen to suit service conditions. This new index also introduced the idea of perfectly elastic-plastic behaviour where the load would hold constant after first crack. The index value corresponding to such behaviour can be calculated at any deflection and used as a reference when analysing toughness indices. Johnston suggested using cut-off deflections of 3, 5.5 and 15.5 times the first crack deflection; corresponding to these cut-offs a perfectly plastic beam would have toughness index values of 5, 10 and 30 respectively. Johnston (1982*c*) showed these new indices to be considerably less variable than the ACI definition, and his system of indices was eventually to be incorporated into ASTM Standard C1018 (1984) though this was not published until 1984, and has recently been updated (ASTM C1018, 1992) to include residual strength factors.

Table 5.2 *continued*

Deflection rate and test limit[3]	Toughness measures	Other quantities defined
0.05–0.10 mm/min $\delta_\ell > 1.9$ mm	Ratio of energy absorbed up to deflection of 1.9 mm to that absorbed at δ_f	First-crack strength
0.05–0.10 mm/min $\delta_\ell > 5.5\delta_f$ or higher limits as required	Ratio of energy absorbed up to $n\delta_f$ to that absorbed up to δ_f (n = 3, 5.5, 10.5, 15.5). Residual strength factor(s)	First-crack strength First-crack deflection
0.25 ± 0.05 mm/min $\delta_\ell = 5$ mm	Residual strength at deflections of 1 mm and 3mm. ASTM C 1018 parameters I_{10}, I_{20}, I_{50} and $R_{10\text{-}20}$, $R_{20\text{-}50}$.	Toughness classification based on residual strength First-crack strength Flexural strength
1.5 mm/min $\delta_\ell = 25$ mm	Energy absorption capacity until deflection of 25 mm	First-crack and maximum load Energy deformation curve Toughness classification based on energy absorption
ℓ/1500-ℓ/3000/min	Energy absorbed up to deflection of ℓ/150 Equivalent flexural strength up to deflection of ℓ/150	Flexural strength
0.25 ± 0.05 mm/min $\delta_\ell = 5$ mm	Residual flexural strength at deflections of 1 mm and 3 mm	Toughness classification based on residual flexural strength Flexural strength

An alternative approach to toughness definition has been proposed by the Japanese Concrete Institute (1983). In their test method, beams are tested under third-point loading and flexural toughness is taken simply as the total area under the load deflection curve up to a deflection of 1/150th of the span, expressed in absolute units of energy. An 'equivalent' flexural strength can also be calculated. This method has also been adopted by the Japan Society of Civil Engineers (JSCE, 1984). Definitions of the toughness parameters calculated from the ASTM (1992) and JSCE (1984) methods are given in Chapter 11, Figures 11.10 and 11.11.

Gopalaratnam and Gettu (1994) present a summary of some eleven different national test specifications, and give a critical overview of most of the methods available for toughness characterization of fibre reinforced concrete. A selection of the different standards is summarized in Table 5.2.

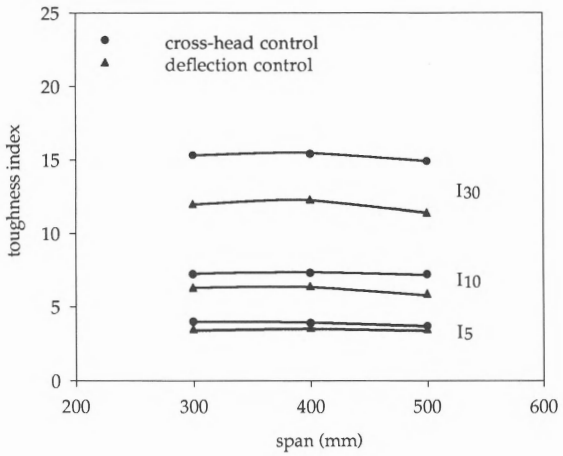

Figure 5.12 *Influence of span and method of test control on toughness index*

Toughness characterization issues

One of the major restrictions on the use of both the ACI (1978) and JCI (1983) test methods is their inability to be adapted to suit varying test conditions. Both indices specify an arbitrarily prescribed end-point deflection which relates to a particular specimen geometry, and the results are therefore only reproducible if the same sized specimen and geometry are used. The ASTM (1992) indices do not suffer from the same restriction. As they are defined in terms of multiples of first crack deflection, they are potentially applicable to any test from which a load-deflection plot can be produced. However, the indices are critically dependent on the location of the first crack position on the load/deflection curve, any error here being magnified when the cut-off deflection is calculated.

Much of the toughness characterization of fibre reinforced sprayed concretes reported in the literature is based on the ASTM C1018 test. However there has recently been considerable debate over the reliability and reproducibility of the toughness index approach (Gopalaratnam *et al.*, 1991; Vandewalle, 1993; Austin and Robins, 1993; Ramakrishnan *et al.*, 1994; Trottier and Banthia, 1994; Gopalaratnam and Gettu, 1994; and Banthia *et al.*, 1994*a*). In Chapter 11, Morgan presents a discussion on some of the key issues involved in the current toughness debate.

Amongst these issues is the testing arrangement, including the geometry of the specimen (including span), the method of load control and the measurement of deflection. Work by Johnston (1982*b*,*c*) and the authors (Robins *et al.*, 1989) has shown that toughness index is relatively insensitive to modest changes in the span/depth ratio. Figure 5.12 demonstrates this point for 100 × 100mm cross-section beams with 4% by weight of steel fibres tested in four-point loading. Gopalaratnam and Gettu (1994) have suggested that using shallow beams ($l/d > 5$) will help improve toughness characterizations based on four-point bend tests. Both the Norwegian Concrete Association (1993) and EFNARC (1993) specify a span/depth ratio of 6.0, as opposed to the 3.0 of the ASTM (1992) and JCI (1983) procedures.

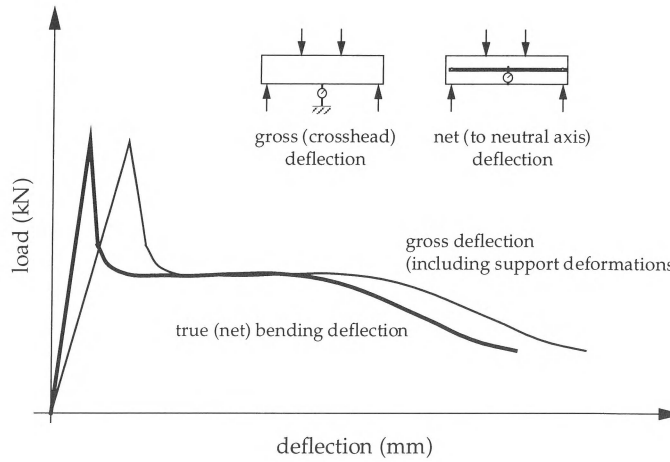

Figure 5.13 *Effect of deflection measurement method on load/deflection curves (Golpalaratnam et al., 1991)*

Most toughness measurement procedures require the specimen to be loaded at a constant rate of central bending deflection of the beams, which requires a feedback loop in the control system. It is important that this is adhered to because if crosshead control (as opposed to central deflection control) is used, the machine is able to dissipate stored strain energy into the specimen as it freely cracks and deflects, and so the shape of the load deflection curve is dependent on machine stiffness (Austin and Robins, 1993). Figure 5.12 contrasts I_5, I_{10} and I_{30} toughness indices determined from load/deflection curves produced from both crosshead and deflection control. The method of measuring beam deflection can also affect the shape of the load/deflection curve. If the settlement and twisting of the beam on its supports is not eliminated from the central deflection measurement the initial position of the load/deflection curve is shallower, which affects both the denominator (area up to first crack) and numerator of toughness index calculations (Figure 5.13). Gopalaratnam *et al.* (1991), in contrasting the ACI, ASTM and JCI standards, have shown that whilst these two effects can counteract each other to a certain extent, the effect is not constant and depends upon the post-cracking shape of the load/deflection curve. The proposed method in the draft EFNARC specification (1993) involves cutting 75 × 125 × 600 mm beams from a test panel and testing these under third point loading on a 450 mm span. The high span/depth ratio (6.0) was proposed to give a large bending deflection, with the view that if this occurs the settlement deflections become less significant.

The draft specification makes reference to the two issues of deflection measurement and load control. It states that the testing arrangement "... shall be so that it is possible to measure net deflection on the midpoint of the beam", and that "the stiffness of the testing machine shall be such that tests shall be real deflection controlled". As it stands, it is unclear whether net deflection measurement is optional or mandatory. From the beam flexural test load/deflection curve the EFNARC specification allows for residual strength values (determined from loads at 1 mm

Table 5.3 *Residual flexural strength requirements for EFNARC (1993)*

Toughness Classification	Residual strength value (MPa)	
	at 1 mm deflection	at 3 mm deflection
0	*Unreinforced*	
1	Fibre type and amount specified	
2	2.0	1.5
3	3.5	3.0

and 3 mm central deflection), and ASTM C1018 toughness indices (I_{10}, I_{20} and I_{50}) and residual strength factors (R_{10-20}, R_{20-50}) to be calculated. A toughness classification based on the residual strength values is suggested (Table 5.3), and there are also suggested values for the ASTM residual strength factors, based on concrete grade (EFNARC, 1993) for both rock support and other sprayed concrete applications.

The EFNARC draft specification also contains a 600 × 600 × 100 mm plate test, in which a sprayed concrete panel is simply supported on all four edges and loaded at its central point. The absorbed energy is determined from the load/deformation curve of the plate test, and again a toughness classification is suggested. One advantage of this test, over a beam test, is that it does allow a comparison of mesh-reinforced and fibre-reinforced sprayed concretes.

There is a definite tide of opinion in recent literature away from the toughness index approach to toughness characterization. Skjolsvold and Hammer (1993) describe a Nordic inter-laboratory test programme carried out to examine the reproducibility of the ASTM C1018 results for sprayed concrete. The test programme concluded that the development of the first part of a beam's load/deflection curve, including the first crack deflection, is very dependent on the test equipment. In order to reduce the test equipment dependency, the new Norwegian guidelines (NCA, 1993) base toughness evaluation on a load/deflection curve, but 'first crack' deflections are ignored and the loads at fixed deflections are used to calculate residual flexural strengths. (This approach was subsequently adopted by EFNARC as one of their methods of toughness classification).

Gopalaratnam *et al.* (1991) conclude that the I_5, I_{10} and I_{30} toughness indices of ASTM C1018 do not appear to be sensitive to fibre type or dosage, and Vandewalle (1993) reports that the effect of different fibre types is only found at higher toughness indices (I_{20}, I_{30}, I_{50}). Vandewalle also commented on a good correlation between the residual strength factors of the ASTM method and the toughness factors (or equivalent flexural strengths) of the Japanese standard.

Ramakrishnan *et al.* (1994) are also of the opinion that the ASTM C1018 toughness index procedure to derive I_5, I_{10}, I_{30} is an unsatisfactory method of determining toughness since it is not sensitive to fibre type or fibre content. They found the Japanese method (JCI, 1983 and JSCE, 1984) was more sensitive to both fibre type and content, and is therefore a better basis for comparing fracture toughness of different fibre reinforced concretes.

Trottier and Banthia (1994) question many aspects of both the JSCE (1984) and

Table 5.4 *Typical performance specification for steel fibre reinforced sprayed concrete (Morgan, 1991b)*

Property	Test method	Minimum requirements
Accelerated setting time	ASTM C-403	
initial set		10 minutes
final set		30 minutes
Compressive strength, MPa	ASTM C-42	
8 hour (accelerated)		5
1 day		10
7 days		30
28 days		40
Flexural strength, MPa	ASTM C-78	
7 days		4
28 days		6
Toughness index	ASTM C-1018	
I_5		3.5
I_{10}		5.0
I_{30}		14.0
Boiled absorption	ASTM C-642	8% maximum
Volume of permeable voids		17% maximum

ASTM (1992) methods, concluding that both techniques are only capable of capturing the trends of the effect of fibre geometry and matrix strengths at large deflections. (Their tests were done at a constant fibre dosage of 40 kg/m^3). They propose a new technique for toughness characterization which calculates post crack equivalent strengths at appropriate deflection values in the post-peak region of the load/deflection curve.

A 'notched' beam has been proposed as an alternative test specimen for toughness evaluation (Barr *et al.*, 1982, 1985; and Gopalaratnam *et al.*, 1991). Testing of a notched beam can be controlled by the crack mouth opening displacement (CMOD) in place of the midspan deflection. However, Gopalaratnam *et al.* (1991) have shown that the sensitivity of CMOD-based toughness indices (analogous to ASTM C1018 using CMOD instead of deflection) is unaltered though the scatter of results is lower. Ramakrishnan *et al.* (1994) and Gopalaratnam and Gettu (1994) conclude that the notched beam test using CMOD control offers a promising alternative to characterize toughness of fibre reinforced concrete.

Given the current doubts and debate concerning the toughness index approach, and until there is a proper rationale behind the inclusion of toughness properties in structural design, it seems that a pseudo-toughness approach based on equivalent flexural strength (as done in JSCE (1984) or in Trottier and Banthia's (1994) post-peak equivalent strength approach) seems to offer the most promising way of evaluating the post-cracking response of a fibre reinforced sprayed concrete. Limits for deflection (or crack widths if CMOD is used) which are application specific and serviceability related can sensibly be used in conjunction with this approach.

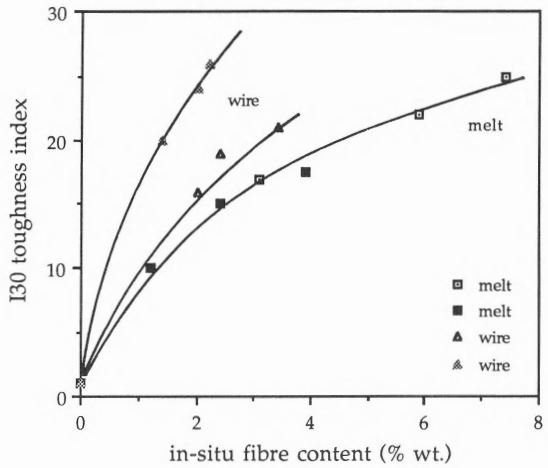

Figure 5.14 *Effect of fibre content on flexural toughness (dry process)*

Sprayed fibre concrete

Many of the toughness values of fibre reinforced sprayed concrete to be found in published literature are based on the ASTM C1018 test method. Morgan (Chapter 11) reports that toughness index values have been used for specification purposes in numerous sprayed fibre reinforced concrete projects in North America (mainly in tunnel lining applications) Morgan (1991*b*) quotes a typical performance specification used in civil engineering works, which includes minimum requirements for I_5, I_{10}, I_{30} toughness indices (Table 5.4).

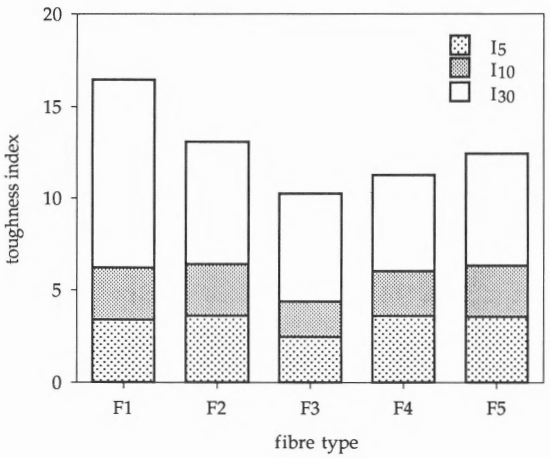

Figure 5.15 *Toughness indices of wet-mix sprayed concretes reinforced with different fibre types (Banthia et al., 1994a)*

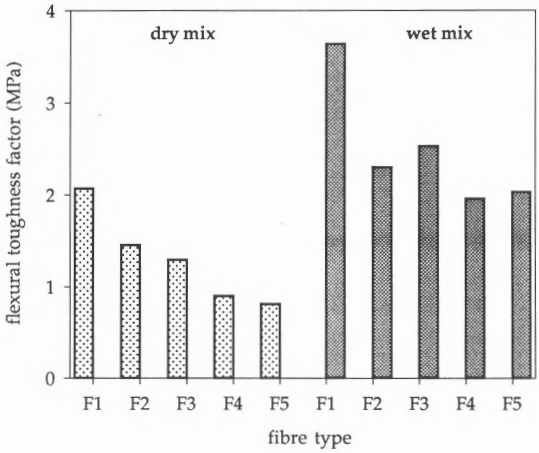

Figure 5.16 *Flexural toughness factors (JSCE, 1984) of dry and wet-mix sprayed concretes (Banthia et al., 1994a)*

Some I_{30} toughness index results for varying quantities of both wire and melt-extract fibres obtained by the authors at a series of dry process sprayed concrete trials (Robins and Austin, 1989) are shown in Figure 5.14. A general trend of increasing I_{30} index with increasing in-situ fibre content is evident. The efficiency of hooked-end fibre for toughening is evident.

Banthia *et al.* (1994*a*) compared the relative toughness performance of both dry-mix (Banthia *et al.*, 1992) and wet-mix (Banthia *et al.*, 1994*b*) sprayed concretes containing five different commercially available steel fibre types, at a constant fibre content of 60 kg/m^3. The five fibre types they used (F1 to F5) are described in Section 5.4. The ASTM C1018 I_5, I_{10}, I_{30} toughness indices of their wet-mix sprayed concretes are shown in Figure 5.15. Note that the lower indices do not appear sensitive to the variations in the fibre geometry, significant differences only occurring in the I_{30} values. Flexural toughness factors from the JSCE (1984) method for both dry and wet-mix concretes are compared in Figure 5.16. In both cases, the toughness factor (or equivalent flexural strength) appears to permit distinction to be made between the various fibre geometries. The lower toughness factors of the dry-mix concretes are in the main due to their lower flexural strengths (27% on average).

Skjøksvold and Hammer (1993) concluded that an increase in fibre length leads to improved toughness of a sprayed fibre concrete. They reported only minor differences in I_{20} toughness index between a 25 mm enlarged end slit-sheet fibre and a 30 mm long hooked-end wire fibre, but a significant difference between 30 mm and 40 mm long hooked-end fibres.

Published information on toughness values measured as part of quality control programmes on construction projects is relatively sparse. For wet-process sprayed fibre concrete used in the Mälmsjö tunnel in Sweden, Bylund (1993) reports flexural toughnesses based on the residual strength factors $R_{10,30}$ (ASTM, 1992) in the range 2.3 to 4.5 MPa.

5.6 Impact resistance

Impact resistance, or toughness under dynamic loading, is also significantly increased by the presence of fibres. ACI Committee 544 (1982) published a test procedure for measuring impact resistance in which the number of blows of a standard compaction hammer necessary to crack and separate a disc specimen (38 × 152 mm diameter) is recorded. Two measurements are recorded: the number of blows required to cause the first visible crack, and the number of blows required to cause the cracks to open up sufficiently to make the specimen touch three of the four positioning lugs in the apparatus. ACI Committee 506 (1984) report that plain sprayed concrete specimens normally fail at from 10 to 40 blows, whereas the number of blows required to crack and separate fibre reinforced specimens at 28 days ranges from about 100 to 500 or more depending upon the fibre content, fibre length, and type.

Figure 5.17 shows impact test results from Ramakrishnan (1985) for dry-mix sprayed concrete reinforced with a hooked-end drawn wire fibre, 30 mm long and 0.5 mm in diameter. Ramakrishnan concluded that the hooked-end fibre sprayed concrete had a great ability to absorb impact load, and that this ability increased as the fibre content increased. It was noted during testing that specimens with obvious laminations in them tended to rupture at the laminations under repeated impact loading, which reduced the effective thickness of the test specimens, causing failure at a lower number of blows.

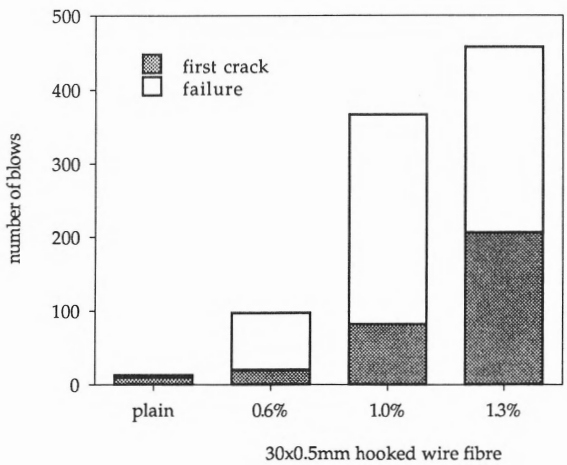

Figure 5.17 *Impact resistance of steel fibre sprayed concretes (Ramakrishnan, 1985)*

5.7 Bond to substrate

Published information on the bond strength between sprayed concrete and the substrates to which it is applied is relatively sparse. This is somewhat surprising, since it would seem to be a fundamentally important property of any construction material which is used to overlay another.

A common technique used for measuring the bond strength between a sprayed concrete and the substrate below is to apply a tensile load to pull off a core which has been drilled down through the concrete into the substrate below. Several suitable test apparatus are available, e.g. the 'Limpet' core pull-off test (Long and Murray, 1984). This test was originally developed for repair materials, but can equally well be used for sprayed concrete. CIRIA have published guidance on standard tests for repair materials, including one for pull-off tests (McLeish, 1993). When a pull-off test is carried out, three failure modes are possible: failure in the substrate; failure at the bonding surface; and failure in the sprayed concrete layer. Strictly, it is only failure at the bond surface which gives information on bond strength. Unfortunately, average bond strengths reported in the literature seem to include the other failure modes (particularly substrate failure), making meaningful comparison of different authors' test results even more difficult.

Schrader and Kaden (1987) state that the bond between sprayed concrete and an old sound concrete is generally very good, probably due to the sprayed concrete compaction surface and the normally low water/cement ratio of the material, particularly in dry-mix sprayed concretes. Parker (1977) mentions that when sprayed concrete first impacts on the receiving surface only the cement paste bonds to the surface, and the other components rebound until a sufficient thickness of paste is obtained. A well-compacted layer of cement paste with a low water/cement ratio is thus formed at the bond interface and acts rather like a bonding agent.

Tynes and McCleese (1974) evaluated the use of bonding agents with sprayed concrete and concluded that, in general, epoxy coating did not increase the bond strength of sprayed concrete to old sprayed concrete or cast concrete. It seems also that the use of latex emulsions in sprayed concrete can be detrimental to bond rather than improving it. This has been attributed to the presence of a polymer-rich non-absorptive film on an interface surface of a sprayed concrete layer providing a poor surface for a fresh concrete layer (Marusin, 1990), and to the polymer coating not allowing moisture to escape from the concrete substrate below (Schrader, 1992), hence causing problems of hydraulic pressure and/or ice pressures.

For wet process sprayed concretes applied to both rock and concretes, Opsahl (1985) concluded that the quality of the bond depended on the sprayed concrete, but was also greatly influenced by the substrate. Bond strength to rock is largely determined by the mineralogy, the physical properties of rock, and the presence of water leakage. Average bond strength to granite and syenite varied from 0.6 to 1.2 MPa; laboratory tests tended to yield higher results than field tests. Bond strengths to partly decomposed rock and schists were normally 0.4 to 0.5 MPa, while bond to slate, phyllite and rock with clay in the joints produced results between 0 and 0.4 MPa.

Reporting on the use of wet-process steel fibre sprayed concrete in tunnel linings, Opsahl (1984) states that as early as 24 hours after spraying, 70–80% of the final bond strength to a hard rock underlay can be developed. Bond strengths to hard rocks were found to be in the range 0.5 to 2.0 MPa. ACI Committee 506 (1984) report in-situ bond strengths of 3.7 MPa to a rough surfaced granitic gneiss but only 0.9 MPa in the laboratory, obtained by pulling off a 610 × 610 mm embedded steel plate. Core pull-off tests on the same material gave strengths of 1.5–2.6 MPa for plain and fibre reinforced materials, respectively. Bond strengths of about 1.0 MPa

are also reported for steel fibre reinforced sprayed concrete applied to granite by the wet process.

Opsahl (1982) quotes bond strengths for mesh and fibre reinforced wet process sprayed concrete of 0–1.0 MPa and 0.8–2.5 MPa, respectively, measured from 60 mm diameter core pull-off tests. It might be expected that the presence of mesh can reduce the bond of sprayed concrete to a substrate by obstructing the jet of material being shot at the surface and also by allowing the formation of sand pockets behind the bars. Opsahl (1985) has also reported bond strengths of a wet-mix sprayed concrete to a concrete substrate in the rang 0.4 to 2.2 MPa, the lowest values being obtained when shotcreting on deteriorated concrete or when using high dosages of accelerator in the wet-mix sprayed concrete.

For wet-process sprayed fibre concrete used in underground applications in Sweden, Bylund (1993) writes that for every 1000 m^2 of sprayed concrete, bond strength should be tested by pull-out tests, a general demand being 0.5 MPa. Bond tests on the Skarpnäck tunnel project in Stockholm produced values between 0.5 and 2.5 MPa, with a mean around 1.0 MPa. The variable nature of bond strength to rock is evident. Myrvang and Stjern (1993) report an average bond strength of 0.85 MPa for the wet-mix sprayed fibre concrete lining on the roof of the Gjøvik Olympic Ice Hockey Hall in Norway, this figure being an average of seventeen readings.

Influence of surface preparation

Talbot *et al.* (1994) report on an extensive investigation to evaluate the capacity of different sprayed concretes to provide a good and durable bond with concrete surfaces prepared for repair in different ways, including sandblasting, jackhammering and hydrodemolition. Seven dry-mix and three wet-mix sprayed concretes were used on six different surface preparations. Silica fume and steel fibres were used in some of the mixes. Bond testing was performed after 2 and 6 months.

They conclude that the type of surface preparation has a strong influence on the strength and durability of bonding, and that hydrodemolition or chipping with light jackhammers followed by sandblasting are generally the best types of surface preparation. The sprayed concrete mix composition was found to have relatively little influence on bonding, though the combined use of silica fume and steel fibres enhanced the bonding strength. No significant difference was observed between the bond strength of dry or wet process sprayed concrete to a hydrodemolished surface.

Average bond strengths at 2 and 6 months obtained by Talbot *et al.* (*ibid*) are summarized in Figure 5.18 for two of their dry mix sprayed concretes, one plain and one which included silica fume (10% replacement) and steel fibres (48 kg/m^3). Both were air entrained (around 10% air) and their compressive strengths were 31.3 and 51.5 MPa, respectively. In terms of bonding strength, sandblasting produced the highest values, though a significant loss of bond between 2 and 6 months was observed. The use of jackhammers alone yielded relatively low bond strengths, probably because the surface was not well cleaned before spraying. It can be seen from Figure 5.18 that the most consistent results were obtained with clean and relatively rough surfaces (prepared by hydrodemolition or by chipping with jackhammers followed by sandblasting). With these techniques bond strengths to a sound concrete substrate were in the range 1.7–2.1 MPa.

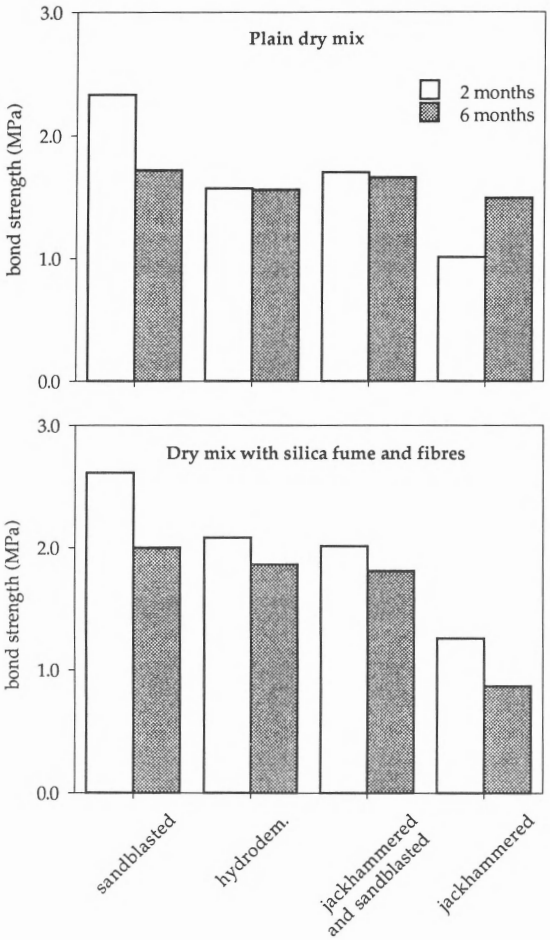

Figure 5.18 *Influence of surface preparation on bond strength (Talbot et al., 1993)*

5.8 Shrinkage

A knowledge of drying shrinkage strains is important, particularly when sprayed concrete is used in repair work, though reported information on shrinkage is limited. Although dry process sprayed concrete has a relatively low water/cement ratio, it can still shrink significantly. Shrinkage of concrete is directly proportional to the water/cement ratio and inversely proportional to the aggregate/cement ratio (largely a result of the restraining effects of the aggregate). For a given water/cement ratio, shrinkage increases with cement content. Because of the interaction of the effects of aggregate/cement and water/cement ratios, it is possible to have a rich mix with a low water/cement ratio (typical of a dry process sprayed concrete), giving a higher shrinkage than a leaner mix with a higher water/cement ratio.

Schrader and Kaden (1987) quote typical shrinkage values of 900 × 10^{-6} for dry process sprayed concrete (w/c = 0.37 and cement content 505 kg/m^3) and 600 × 10^{-6} for wet-mix (w/c = 0.42 and cement content 415 kg/m^3). These different shrinkage values quoted for dry and wet process concretes are more likely a result of the different amounts and proportions of mix constituents, rather than an inherent difference between the shrinkage properties of dry and wet process sprayed concretes. Wolsiefer and Morgan (1993) have reported on wet and dry-mix sprayed concretes, and concluded that the higher shrinkage displayed by the wet-mix concretes was attributable to the higher water demand of the wet-mix process, for a given cement content (see Figure 11.14). It is interesting to note that the silica fume mixes in Figure 11.14 exhibit lower drying shrinkage values than the conventional OPC sprayed concretes.

Hills (1982) concludes that shrinkage values for sprayed concretes lie broadly within the expected range for cast concretes. For the site-produced sprayed concrete mixes investigated (*ibid*), drying shrinkage at six months lay in the range 400–1000 × 10^{-6}; wet process sprayed concrete, with its higher water/cement ratio, showed generally the greatest shrinkage. Wetting expansion was in the range 0–100 × 10^{-6}. Neubert and Manns (1993) investigated the drying shrinkage of both wet and dry-mix sprayed concretes with 'normal' and 'high' doses of accelerating admixtures (alkali aluminates and alkali carbonates). They concluded that the shrinkage of dry-mix and wet-mix normally accelerated concretes were 20 and 50% higher, respectively, than that of non-accelerated concrete, whilst wet-mix sprayed concrete with high doses of accelerator showed a doubling of the shrinkage. Shrinkage/time curves for the accelerated sprayed concretes of Neubert and Manns (1993) are shown in Figure 5.19.

Drying shrinkage values for fibre reinforced sprayed concrete have only occasionally been reported. Ramakrishnan (1985) found that shrinkage was reduced by about 30% with the inclusion in the dry mix of 1.0% by volume (about 80 kg/m^3)

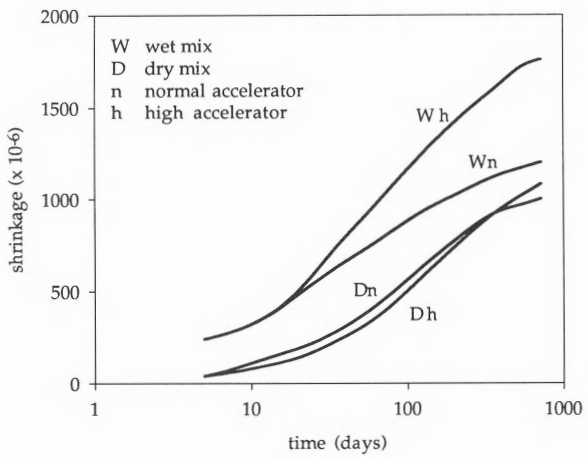

Figure 5.19 *Shrinkage of sprayed concretes with accelerators (Neubert and Manns, 1993)*

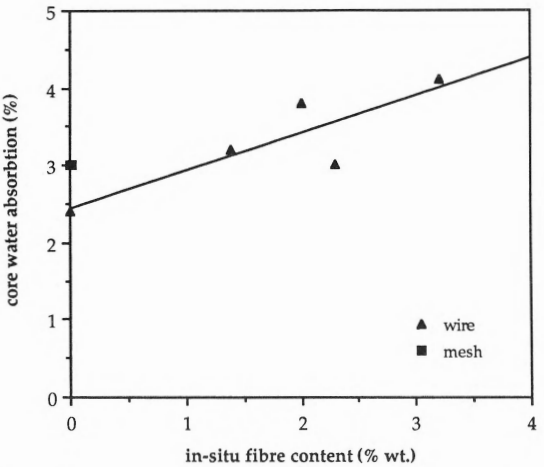

Figure 5.20 *Effect of fibre content on water absorption (dry process)*

of 30 mm long hooked-end wire fibres. Fibres can also be effective in distributing the cracking and in restricting the crack widths that occur in a restrained shrinkage situation (see Figures 11.15 and 11.16). In a study of wet-process sprayed concrete containing accelerators, silica fume and steel fibres, Opsahl (1985) concluded that the shrinkage was not significantly influenced by the steel fibre reinforcement.

In summary, sprayed concretes have higher drying shrinkages than some conventional cast concretes, but this is a result of their typically lower aggregate-cement ratios and higher cement contents, rather than an effect of the spraying process itself.

5.9 Water absorption

Properly applied, dry process mix sprayed concrete is a relatively dense, well compacted material and consequently its water absorption is quite low. Hills (1982) recorded 30 minute water absorptions (to BS 1881 Part 122, 1983*c*) in the range 2.3–3.6% with the dry process and 3.5–4.7% for the wet process, the latter reflecting the higher water content of these mixes. These results were within the range of 2.6–4.0% for equivalent cast concretes.

The authors (Robins and Austin, 1989) have found that the inclusion of steel fibres in the mix produces small increases in absorption values (Figure 5.20). Little (1985) also found that the presence of drawn wire fibres increased the boiled absorption from 7.0% for plain sprayed concrete to 8.1% with fibres. Jones (1987) quotes boiled absorptions in the range 4–8% for steel fibre sprayed concrete containing silica fume.

In North America, the ASTM C642 (1990) test for determination of boiled absorption and volume of permeable voids is quite commonly used in sprayed concrete specifications and quality control testing. Morgan (1992) points out that the test is particularly useful in identifying sprayed concrete that is less than adequately

Table 5.5 *Suggested indicators of sprayed concrete quality (Morgan 1992)*

Sprayed Concrete quality	Boiled Absorption%	Permeable Voids, %
excellent	<6	<14
good	6–8	14–17
fair	8–9	17–19
marginal	>9	>19

consolidated, or which has been damaged by excessive use of accelerators. Morgan *et al.* (1987) suggest that boiled absorption and volume of permeable voids can be used as indicators of shotcrete quality (Table 5.5 and Figure 11.12).

In a study of both wet-mix and dry-mix sprayed concretes undertaken to evaluate the performance characteristics of three different silica fume product forms (uncompacted, low density compacted, and high density compacted), Wolsiefer and Morgan (1993) recorded 28 day boiled absorptions in the range 5.9 to 6.9% for the wet-mix concretes, and 2.7 to 4.9% for the dry-mix concretes. The corresponding ranges for permeable voids were 12.9 to 14.3% (wet-mix) and 6.3 to 11.2% (dry-mix). Under the classifications of Table 5.5, this puts all the wet-mix sprayed concretes in the 'good' or 'excellent' class, with all the dry-mix in the 'excellent' category. Compared with the plain sprayed concrete control mixes, silica fume addition was found to result in significant reductions in boiled absorption and permeable voids in dry-mix sprayed concrete, but not in the wet-mix sprayed concretes (where small increases were observed).

Beaupré *et al.* (1994*b*) report ASTM C642 immersed absorption values for dry-mix sprayed concretes in the range 3 to 10%, and for wet-mix sprayed concretes 6 to 8.5%. In all some twenty-five dry-mix and eleven wet-mix sprayed concretes were tested; the mixture variables included cement type, silica fume, polypropylene and steel fibres, accelerators and air entraining admixtures. They concluded that increases in air content generally increased the absorption values.

Banthia *et al.* (1992) compared the performance of five different steel fibre types in dry-mix sprayed concrete. All fibre mixes and the plain control mixes contained silica fume; the fibre content (in the dry mix) of all the fibre mixes was constant at 60 kg/m^3. The absorption, boiled absorption and permeable voids values were remarkably consistent across all the different mixes. Neither the inclusion of fibres nor the fibre type appears to have had a significant effect on any of these absorption properties. The range of the boiled absorptions (8–9%) and permeable voids (17–19%) puts all the fibre sprayed concretes in the 'fair' category proposed by Morgan *et al.* (1987). Immersed absorptions were also in the 8 to 9% range.

In a parallel study of fibre reinforced wet-mix sprayed concrete Banthia *et al.* (1994*b*) concluded that the wet-mix concrete produced was denser and had lower boiled absorption (7.5–8%) and permeable voids content (16–18%).

5.10 Permeability

Though permeability is one of the prime factors governing the durability of concrete, there is relatively little published information relating to sprayed concrete. Whilst a low permeability concrete matrix is generally desirable it should be appreciated that a mix with higher permeability that has not cracked can be more watertight than a low permeability mix which develops substantial microcracks due to drying shrinkage.

Values obtained from the initial surface absorption test (BS 1881 Part 5, 1970) for dry and wet process sprayed concrete have been found to be in the range for conventionally cast concretes (Hills, 1982), namely 0.14–0.35 ml/m^{2}s for dry and 0.35–0.41 ml/m^{2}s for wet-mix after 30 minutes. The Concrete Society (1985) suggest a range of 0.17–0.35 ml/m^{2}s for "average" quality concrete.

Schrader and Kaden (1987) quote permeabilities for dry process sprayed concrete in the range 3×10^{-10} to 3×10^{-13} m/s for moderately low to very high strength concrete. Opsahl and Buhre (1985) determined permeabilities of drilled cores of wet process silica fume modified sprayed concrete containing 1% by volume of slit-sheet fibres. Values quoted were between 2×10^{-14} and 1×10^{-13} m/s for a 45 MPa compressive strength mix and $< 10^{-15}$ for a 75 MPa mix. They also state that concrete may be considered watertight when the coefficient of permeability is less than 10^{-12} m/s.

Ramakrishnan (1985) reported the general conclusions from Krantz's (1984) permeability measurements on steel-fibre sprayed concrete, that the sprayed concrete specimens exhibited a general trend of increasing permeability with decreasing compressive strength, and permeability also increased with increasing water/cement ratio. These are trends that would be expected for normal concrete. Opsahl (1985) found evidence that increasing fibre contents gave reduced permeability, but pointed out that steel fibre reinforcement is no guarantee for watertight sprayed concrete. Opsahl concluded that curing condition was much more critical for permeability than for mechanical properties.

5.11 Freeze/thaw resistance

It is possible to produce both dry and wet-mix sprayed concrete that will resist highly aggressive freeze/thaw environments. One of the earliest systematic laboratory studies was carried out by Litvin and Shideler (1966), who evaluated 16 wet-mix and 22 dry-mix sprayed concretes. The majority of their dry-mix sprayed concretes and the wet-mix concretes with adequate air-entrainment exhibited excellent freeze-thaw durability.

Dry process sprayed concrete (with high strength and low water/cement ratio) is generally reported as being resistant to freeze/thaw conditions encountered in service. Schrader and Kaden (1987) discuss the subject in some depth, pointing out that the resistance of sprayed concrete to freeze/thaw damage is no different from an equivalent cast concrete, the entrained air content being the principal factor governing performance. Using the ASTM C666 (1992) test procedure, sprayed concrete samples without significant air contents will deteriorate progressively, although very high strength material (above 70 MPa) may resist freeze/thaw damage without

air entrainment. Johnston (1982) concluded from ASTM tests that a proper entrained air void system is just as necessary for steel fibre concrete as for plain concrete.

Air entrainment of sprayed concrete using the dry process has generally been found to be unsuccessful, and indeed unnecessary. Up to 5% air has been found to remain in sprayed concrete applied by the wet process, although less than half of the voids were of a sufficiently small size to be effective in providing durability (Schrader and Kaden, 1987). Opsahl and Buhre (1985) carried out ASTM C666 freeze/thaw tests on specimens of wet process silica fume sprayed concrete containing steel fibres, and concluded that good air-void characteristics were achieved without the use of air-entraining agents, durability factors in the range 60–80 being obtained for sprayed concrete of 60–70 MPa compressive strength.

Morgan *et al.* (1988) reported freeze/thaw durability studies made on both wet and dry-mix sprayed concretes, made with and without the addition of steel fibres and silica fume. In their studies, the compressive strengths of the concretes were high (42 to 66 MPa) and the water/cement ratios low. Wet-mix sprayed concretes were air entrained to 8 per cent before spraying, and measurements after spraying revealed that generally about one half of the as-batched air content was lost in the spraying process. The dry-mix sprayed concretes were not air entrained. Table 5.6 summarizes the mix proportions, air-void properties, and freeze/thaw durabilities. There is remarkable correspondence between the air contents and the air-void spacing factors in both the wet and dry-mix sprayed concretes. The specific surface values are nearly all within the range 16 to 32 mm^{-1}, suggested by Neville (1981) as being indicative of concrete with suitable air entrainment for freeze/thaw durability.

Most failures of sprayed concrete due to external exposure environments do not involve failure of the material itself, but are more often associated with the sound sprayed concrete coming away from the substrate to which it is applied. Causes of failures include: failure to adequately prepare the substrate; applying a thin layer of sprayed concrete to a base concrete of low durability (thus the base concrete continues to deteriorate beneath the sprayed layer); and failure to provide pressure relief and drainage for water build-up behind the sprayed layer. The application of a

Table 5.6 *Freeze/thaw durability (after Morgan et al., 1989)*

Spraying process	Mix quantities kg/m³			w/c ratio	Comp. strength MPa	Air void details			Durability rating
	cement	fume	fibres			content %	spacing factor mm	specific surface mm^{-1}	
dry	413	-	-	0.29	50	5.4	0.27	18	excellent
dry	361	52	-	0.29	52	6.0	0.29	17	excellent
dry	361	52	60	0.29	42	6.5	0.31	15	excellent
wet	465	-	-	0.35	56	5.6	0.17	27	excellent
wet	404	103	-	0.35	66	4.5	0.28	18	excellent
wet	404	103	60	0.35	65	5.2	0.27	19	excellent

relatively impermeable layer of sprayed concrete can aggravate a build-up of vapour or water pressure in the base concrete. If the sprayed concrete thickness is insufficient to prevent frost penetration, then the application of the sprayed concrete layer can actually accelerate deterioration of the structure, and the failure will often occur behind the bond plane in the base concrete.

In endeavouring to produce freeze/thaw durable sprayed concretes by the wet or dry process the following points should be borne in mind:

(i) do not use aggregates that themselves are susceptible to frost attack;

(ii) the quality of workmanship of the sprayed concrete is of great importance, particularly with the dry process. The in-place sprayed concrete must be homogeneous, well-consolidated and free of any voids or other defects that will produce excess capillary porosity;

(iii) the sprayed concrete should have an adequate cement content and a low water/cement ratio. Morgan (1989) suggests a cement content of at least 350 kg/m^3 (and preferably exceeding 400 kg/m^3) and a water-cement ratio below 0.5, and preferably below 0.4. Wet-mix sprayed concretes will require water-reducing admixtures;

(iv) Air entrainment is needed in wet-mix sprayed concretes and it should be remembered that as much as one half of the as-batched air content may be lost in the spraying process.

Suitable sprayed concrete for use in aggressive freeze/thaw applications will generally exhibit 28-day core compressive strengths in excess of 50 MPa. However, high compressive strength does in itself not guarantee freeze/thaw durability; it is the size and size distribution of air voids that are all-important.

5.12 Reinforcement corrosion

The corrosion of steel mesh within sprayed concrete is governed by the usual factors, principally the permeability of the matrix and the severity of the environment. Reference should be made to standard reinforced concrete practice (for example, BS 8110, 1985) where durability is controlled by the amount of cover and limitations on the mix proportions. Top cover and back spacer requirements (the latter to allow satisfactory bond and reinforcement encasement) effectively limit the thickness of mesh reinforced sprayed concrete to a minimum of 50 mm. Fibre-reinforced sprayed concrete does not generally suffer from these restrictions and can therefore be applied in thinner layers. Polypropylene and stainless steel fibres are naturally durable reinforcement materials.

Factors that are relevant to the corrosion resistance of a bar or mesh reinforced sprayed concrete are equally relevant to a steel-fibre reinforced sprayed concrete. Provided the concrete matrix remains uncracked and retains its alkalinity, steel fibre sprayed concrete will resist corrosion. Even when exposed to marine environments, deicing chemicals or other conditions likely to reduce alkalinity, carbonation in good quality steel fibre sprayed concrete may be restricted to a depth of just a few millimetres over a period of many years (Hoff, 1987). Provided the matrix remains uncracked, most of the fibres within remain protected (Hannant and Edgington, 1975). Carbon steel fibres at the surface will corrode rapidly leaving staining, though such staining is soon removed if the surface is subjected to wear or

abrasion. Fibres below the carbonated layer will remain protected provided the sprayed concrete remains uncracked. If surface staining and rusting of fibres is viewed as undesirable from an aesthetic viewpoint (or indeed if the presence of fibres on the surface is unacceptable for safety reasons) then a thin surface coating (flash coat) of plain sprayed concrete can be applied over the fibre reinforced material. Morgan (1991*b*) quotes the West Coast Rockscape around the whale pool at the Vancouver Public Aquarium as a successful example of this technique; after five years of exposure in a marine environment there was no rust staining or deterioration associated with the use of steel fibre reinforced sprayed concrete overlaid with a plain flash coat.

If the sprayed concrete does crack then any fibres bridging a crack may start to corrode. The continued effectiveness of the fibres in transferring load across a crack, and in restraining the crack growth, will depend upon such factors as the crack width, the diameter of the fibre, and the severity of the corrosive environment. Some studies (Schrader and Munch, 1976) have shown that if crack widths remain in the range 0.03–0.08 mm, carbon steel fibres will not oxidize even after several years of exposure. Other work (Hannant and Edgington, 1975) has shown that, although corrosion takes place in a moist marine environment when crack widths are in the range 0.1–0.3 mm, much of the composite strength may be retained because the fibres are not initially stressed to anywhere near their ultimate strength, and can therefore tolerate a considerable reduction in diameter by corrosion before failing and allowing the crack to open further.

One of the major advantages of steel fibre reinforcement over mesh reinforcement in sprayed concrete subjected to severe exposure environments is that the steel fibres, being small, non-continuous and protected by an alkaline matrix, do not appear to support the classic galvanic corrosion cells that are often the cause of corrosion and deterioration in mesh reinforced sprayed concrete. Schupack (1985), reporting on a series of investigations on the durability of steel fibre concrete exposed to severe environments, concluded that the corrosion of carbon steel fibres in concrete beams, after ten years exposure in a marine environment, seemed to be limited to the depth of carbonation (maximum around 3 mm). Even with chloride ion penetration, the fibre corrosion was limited to the concrete surface.

References

ACI Committee 506 (1984) State-of-the-art report on fibre reinforced shotcrete. *Concrete International*, **6**(12), 15–27.

ACI Committee 544 (1982) Measurement of properties of fibre reinforced concrete, *ACI Manual of Concrete Practice, Part 5*. American Concrete Institute, Detroit.

American Concrete Institute (1978) Measurement of properties of fibre reinforced concrete. ACI Journal, **75**(7), 283–289.

American Concrete Institute (1988) Measurement of Properties of Fibre Reinforced Concrete. *ACI Materials Journal*, **85**(6), 583–593.

American Society for Testing and Materials (1989) Standard test method for flexural toughness and first-crack strength of fibre reinforced concrete. *ASTM Standards for Concrete and Mineral Aggregates*, ASTM C1018.

American Society for Testing and Materials (1984) ASTM C78-84, *Standard test method for flexural strength of concrete.* ASTM, Philadelphia.

American Society for Testing and Materials (1986) ASTM C39-86, *Standard test method for*

compressive strength of cylindrical concrete specimens. ASTM, Philadelphia.
American Society for Testing and Materials (1990) ASTM C642-90, *Standard test method for specific gravity, absorption, and voids in hardened concrete*. ASTM, Philadelphia.
American Society for Testing and Materials (1992) ASTM C 1018-92, *Standard Test Method for Flexural Toughness and First-Crack Strength of Fiber-Reinforced Concrete*. ASTM, Philadelphia.
American Society for Testing and Materials (1992) ASTM C666-92, *Standard test method for resistance of concrete to rapid freezing and thawing*. ASTM, Philadelphia.
Austin, S.A. and Robins, P.J. (1989) A repair application of polypropylene fibre reinforced sprayed concrete. *Proc. Int. Conf. on Recent Developments in Fibre Reinforced Cements and Concretes*, Cardiff, Sept., 21–31.
Austin, S.A. and Robins, P.J. (1993) Test Methods for Strength and Toughness of Sprayed Fibre Concrete. *Procs. Int. Symp. on Sprayed Concrete*, Norwegian Concrete Association, Fagernes, Norway, 7–19.
Banthia, N., Trottier, J-F., Beaupré, D. and Wood, D. (1994*a*) Properties of steel fibre reinforced shotcrete. *Canadian Journal of Civil Engineering*, **21**, 564–575.
Banthia, N., Trottier, J-F., Beaupré, D. and Wood, D. (1994*b*) Influence of fibre geometry in steel fibre reinforced wet-mix shotcrete. *Concrete International: Des. and Constr.*, **16**(5), 27–32.
Banthia, N., Trottier, J-F., Wood, D. and Beaupré, D. (1992) Influence of fibre geometry in steel fibre reinforced dry-mix shotcrete. *Concrete International: Des. and Constr.*, **14**(5), 24–28.
Barr, B.I.G., and Hasso, E.B.D. (1985) A Study of Toughness Indices. *Magazine of Concrete Research*, **37**(132), 162–173.
Barr, B.I.G., Liu, K., and Dowers, R.C. (1982) A Toughness Index to Measure the Energy Absorption of Fibre Reinforced Concrete. *The International Journal of Cement Composites and Lightweight Concrete*, **4**(4), 221–227.
Beaupré, D. and Mindness, S. (1993) Compaction of wet shotcrete and its effect on rheological properties. *Proc. Int. Symp. on Sprayed Concrete*, Fagernes, Norway, October, 167–181.
Beaupré, D., Mindness, S. and Pigeon, M. (1994*a*) Rheology of fresh concrete. *Proc. Int. RILEM Workshop on Special Concrete - Workability and Mixing*, E. & F.N. Spon, March, 225–235.
Beaupré, D., Pigeon, M., Morgan, D.R. and McAskill, N. (1991) Le béton projeté de fibres d'amiante. *Proc. of First Canadian University - Industry Workshop on Fibre Reinforced Concrete*, Québec, October.
Beaupré, D., Talbot, C., Gendreau, M. and Pigeon, M. (1994*b*) Deicer salt sealing resistance of dry and wet process shotcrete. *ACI Materials Journal*, **91** (5), 487–94.
British Standards Institution (1970) BS 1881 : Part 5, Methods of testing hardened concrete for other than strength. BSI, Milton Keynes.
British Standards Institution (1983*a*) BS 1881: Part 120, Method for determination of the compressive strength of concrete cores. BSI, Milton Keynes.
British Standards Institution (1983*b*) BS 1881: Part 118, Method of determination of flexural strength. BSI, Milton Keynes.
British Standards Institution (1983*c*) BS 1881: Part 122, Method of determination of water absorption. BSI, Milton Keynes.
British Standards Institution (1992) BS 1881: Part 207, Recommendation for the assessment of concrete strength by near-to-surface tests. BSI, Milton Keynes.
Bylund, M. (1993) Case studies about wet shotcrete used in two different projects. *Proc. Int. Symp. on Sprayed Concrete*, Norwegian Concrete Association, Fagernes, Norway, October, 346–357.
Concrete Society Working Party on Permeability Testing (1985) Permeability testing of site concrete. *Proceedings of Conference on Permeability of Concrete and its Control*, London, 1–68.
EFNARC Technical Committee Sprayed Concrete (1993) *Draft specification for sprayed con-*

crete. European Federation of National Associations of Specialist Repair Contractors and Material Suppliers for the Construction Industry, Aldershot, U.K.

Gopalaratnam, V.S. and Gettu, R. (1994) On the characterization of flexural toughness in FRC. National Science Foundation (USA), *Proc. of Workshop on Fibre Reinforced Cement and Concrete*, Sheffield, July, 161–180.

Gopalaratnam,V.S., Shah,S.P., BATSON, G.B., CRISWELL, M.E., RAMAKRISHNAN, V., and WECHARATANA, M. (1991) Fracture Toughness of Fiber Reinforced Concrete. *ACI Materials Journal*, **88**(4), 339–353.

Hannant, D.J. and Edgington, J. (1975) Durability of steel fibre concrete. *RILEM Symposium on Fibre Reinforced Cement and Concrete*, Construction Press Ltd, 159–169.

Henager, C.H. (1978) A toughness index for fibre concrete. *Testing and Test Methods of Fibre Cement Composites,* RILEM Symposium, Construction Press, Lancaster, 79–86.

Hills, D.L. (1982) Site-produced sprayed concrete. *Concrete*, **16**(12), 44–50.

Hoff, G. (1987) Durability of fibre reinforced concrete in a severe marine environment. *Katherine and Bryant Mather Conference on Concrete Durability*, SP-100, American Concrete Institute, 997–1042.

Japan Concrete Institute (1983) Method of test for flexural strength and flexural toughness of fibre reinforced concrete. Standard SF4, *JCI Standards for Test Methods of Fibre Reinforced Concrete*, 45–51.

Japan Society of Civil Eengineers (1984) Method of test for flexural strength and flexural toughness of fibre reinforced concrete. Standard JSCE-SF4, *JSCE Standard for Test Methods of Fibre Reinforced Concrete*, June, 45–51.

Johnston, C.D. (1982*a*), Steel fibre-reinforced concrete - present and future in engineering construction. *Composites*, **13**(2), 113–121.

Johnston, C.D. (1982*b*) Definition and measurement of flexural toughness parameters for fibre reinforced concrete. *Cement, Concrete and Aggregates*, 4(2), 53–60.

Johnston, C.D. (1982*c*) Precision of flexural strength and toughness parameters for steel fibre reinforced concrete. *Cement, Concrete and Aggregates*, 4(2), 61–67.

Jones, M.B. (1987) Testing sprayed concrete's fibre. *Tunnels and Tunnelling*, **19**(7), 45–48.

Kirsten, H.A.D. (1992) Comparative efficiency and ultimate strength of mesh- and fibre-reinforced shotcrete as determined from full-scale bending tests. *J. S. Afr. Inst. Min. Metall.*, **92**(11/12), 303–323.

Kirsten, H.A.D. (1993) Equivalence of mesh- and fibre-reinforced shotcrete at large deflections. *Can. Geotechn. J.*, **30**, 418–440.

Kirsten, H.A.D. and Labrum, P.R. (1990) The equivalence of fibre and mesh reinforcement in the shotcrete used in tunnel-support systems. *J. S. Afr. Inst. Min. Metall.*, **90**(7), 153–171.

Krantz, G.W. (1984) Selected pneumatic gunite for use in underground mining. *Bureau of Mines Information Circular*, US Department of the Interior, IC 8984.

Little, T.E. (1985) An evaluation of steel fibre reinforced shotcrete for underground support. *Canadian Geotechnical Journal*, **22**(4), 501–507.

Litvin, A. and Shideler, J. (1966) Laboratory study of shotcrete. *ACI Special Publication*, SP-14, 165–184.

Long, A.E. and Murray, A.McC. (1984) The pull-off partially destructive test for concrete. *In Situ Nondestructive Testing of Concrete (SP-82)*, American Concrete Institute, Detroit, 327–350.

Mangat, P.S. and Gurusamy, K. (1987) Flexural strength of steel fibre reinforced cement composites. *Journal of Materials Science*, **22**(9), Sept., 3103–3110.

Marusin, S.L. (1990) Failure of latex modified shotcrete. *Concrete International*, **12**(10), 39–42.

McLeish, A. (1993) *Standard tests for repair materials and coatings for concrete*. CIRIA Technical Note 139, Construction Industry Research and Information Association, London.

Morgan, D.R. (1981) Steel fibre shotcrete - a laboratory study. *Concrete International*, **3**(1), 70–74.

Morgan, D.R. (1989) Freeze-thaw durability of shotcrete. *Concrete International: Design and Construction*, **11**(8), 86–93.

Morgan, D.R. (1991*a*), High early strength blended-cement wet-mix shotcrete. *Concrete International,* **13**(5), 35–39.

Morgan, D.R. (1991*b*), Steel fibre shotcrete for support of underground openings in Canada. *Concrete International*, **13**(11), 56–64.

Morgan, D.R. (1992) New developments in shotcrete for repairs and rehabilitation. *Proc. of Int. Conf. on Advances in Concrete Technology*, Athens, 699–739.

Morgan, D.R. and McAskill, N., Richardson, B.W. and Zellers, R.C. (1989) A Comparative Evaluation of Plain, Polypropylene Fibre, Steel Fibre and Wire Mesh Reinforced Shotcretes. *Transportation Research Record 1226*, Washington, D.C., 78–87.

Morgan, D.R., Kirkness, A.J., McAskill, N. and Duke, N. (1988) Freeze-thaw durability of wet-mix and dry-mix shotcretes with silica fume and steel fibres. *Cement, Concrete and Aggregates*, **10**(2), 96–102.

Morgan, D.R., McAskill, N., Neill, J. and Duke, N.F. (1987) Evaluation of silica fume shotcretes. *Proc. CANMET/CSCE International Workshop on Condensed Silica Fume in Concrete*, Montreal, May, 34 pp.

Myrvang, A. and Stjern, G. (1993) Determination of in-situ stress and adhesivity of sprayed concrete. *Proc. Int. Symp. on Sprayed Concrete*, Norwegian Concrete Association, Fagernes, Norway, October, 424–438.

Neubert, B. and Manns, W. (1993) Mechanical-technological properties of shotcrete with accelerating admixtures. *Int. Symp. on Sprayed Concrete*, Norwegian Concrete Association, Fagernes, Oct., 258–270.

Neville, A.M. (1981) *Properties of Concrete*. 3rd Edition, Pitman.

Norwegian Concrete Association (1993) *Sprayed Concrete for Rock Support - Technical Specification and Guidelines*. (NB, Norsk Betongforening), Publication No. 7, June, 74 pp.

Opsahl, O.A. (1982) Steel fibre reinforced shotcrete for rock support. Report for Royal Norwegian Council for Scientific and Industrial Research, *NTNF Project 1053.09511*, 33.

Opsahl, O.A. (1984) Use of wet-process steel-fibrous shotcrete in tunnel linings. *Proc. of Int. Symp. on Low Cost Road Tunnels*, Oslo, June, 305–315.

Opsahl, O.A. (1985) *Study of a wet-process shotcreting method - Volume 1*. Division of Building Materials, University of Trondheim, Report No. BML 85.101, November.

Opsahl, O.A. and Buhre, K.E. (1985) Why wet process steel fibre reinforced shotcrete? *Proceedings of US-Sweden Joint Seminar on Steel Fibre Concrete*, Stockholm, 51–65.

Parker, H.W. (1977) A practical new approach to shotcrete for rebound losses. *ASCE and ACI SP54, Shotcrete for Ground Support*, Detroit, 149–187.

Ramakrishnan, V. (1985) Steel fibre reinforced shotcrete - a state of the art report. *Proceedings of US-Sweden Joint Seminar on Steel Fibre Concrete*, Stockholm, 7–24.

Ramakrishnan, V. et al. (1981) Comparative evaluation of fibre shotcretes, *Concrete International*, **3**(1), 56–69.

Ramakrishnan, V., Yalamanchi, S.S. and Kakodkar, S. (1994) National Science Foundation (USA), *Proc. of Workshop on Fibre Reinforced Cement and Concrete*, Sheffield, July, 181–193.

Robins, P.J. (1984) Point-load test for tensile strength estimation of plain and fibrous concretes. *In Situ Nondestructive Testing of Concrete (SP-82)*, American Concrete Institute, Detroit, 309–325.

Robins, P.J. and Austin, S.A. (1985*a*) Melt extract fibre reinforced sprayed concrete. *Composite Structures 3: Procs. of the 3rd Int. Conf. on Composite Structures*, Elsevier Applied Science, London, 242–253.

Robins, P.J. and Austin, S.A. (1985*b*) Core point-load test for steel fibre reinforced concrete, *Magazine of Concrete Research*, **37**(133), 238–242.

Robins, P.J. and Austin, S.A. (1989) Repair using sprayed fibre concrete. *Int. Conf. on Case Histories in Structural Failures*, Singapore, March, K67-79.

Robins, P.J. and Austin, S.A. (1992) *Sprayed and sprayed fibre concrete*, Chapter 24 of Construction Materials Reference Book, Butterworth-Heinemann.

Robins, P.J., Austin, S.A. and Peaston, C.H. (1989) Toughness testing of fibre reinforced concrete. *Composite Structures*, Elsevier Applied Science, London, July, 729–742.

Schrader, E.K. (1992) Mistakes, misconceptions, and controversial issues concerning concrete and concrete repairs. *Concrete International*, **14**(11), 54–59.

Schrader, E.K. and Kaden, R.A. (1987) Durability of shotcrete. *Concrete Durability (SP-100)*, American Concrete Institute, Detroit, 1071–1101.

Schrader, E.K. and Munch, A.V. (1976) Dock slab repair by fibrous concrete overlay, *Proc. ASCE Journal of the Construction Division*, **102**(CO-1), 179–196.

Schupack, M. (1985) Durability of steel fibre reinforced concrete exposed to severe environments, *Proc. of US-Sweden Joint Seminar on Steel Fibre Concrete*, Stockholm, June, 479–496.

Scott, M. (1994) Private communication relating to reported use of point-load test for quality control on construction projects.

Skjølsvold, O. and Hammer, T.A. (1993) Toughness testing of fibre reinforced shotcrete. *Int. Symp. on Sprayed Concrete*, Norwegian Concrete Association, Fagernes, Oct., 67–77.

Swannell, N.G. (1993) An evaluation of fibre reinforced sprayed concrete as a permanent tunnel lining material. *Int. Symp. on Sprayed Concrete*, Norwegian Concrete Association, Fagernes, Oct., 295–309.

Talbot, C., Pigeon, M., Beaupré, D. and Morgan, D.R. (1994) Influence of surface preparation on long term bonding of shotcrete. *Materials Journal*, **91** (6), 560-66.

Tattershall, G.H. and Banfill, P.F.G. (1983), *The Rheology of Fresh Concrete*. Pitman, London.

Trottier, J-F. and Banthia, N. (1994) Concrete reinforced with deformed steel fibres: toughness characterization and bond-slip mechanisms. National Science Foundation (USA), *Proc. of Workshop on Fibre Reinforced Cement and Concrete*, Sheffield, July, 212–236.

Tynes, W.O. and McCleese, W.F. (1974) Investigation of shotcrete. *US Army Engineer Waterways Experiment Station, Technical Report C-74-5*, 48 pp.

Vandewalle, M. (1985). The use of steel fibre reinforced shotcrete. *Proc. Int. Symp. on Low Cost Road Tunnels*, Oslo, June, 291–303.

Vandewalle, M. (1993) Steel fiber reinforced shotcrete design requires a uniform toughness criterion. *Int. Symp. on Sprayed Concrete*, Norwegian Concrete Association, Fagernes, Oct., 455–464.

Vandewalle, M. (1986) Steel fibre reinforced shotcrete. *Proceedings of the 3rd International Symposium on Developments in Fibre Reinforced Cement and Concrete* (RILEM) Sheffield, Paper 3.11.

Wolfsiefer, J. and Morgan, D.R. (1993) Silica fume in shotcrete. *Concrete International*, **15**(4), 34–39.

Wood, D.F. (1992) Specification and application of fibre reinforced shotcrete. *Procs. Int. Symp. on Rock Support in Mining and Underground Construction*, Ontario, 149–156.

6 Materials Selection, Specification and Quality Control

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6.1 Scope

Section I of the book has described the constituent materials and the physical properties of sprayed concrete produced by the dry and wet processes. Section II deals with the design and then the installation phases of a project. The designer has a key role in a number of activities, including:

(i) preferred choice of construction method;
(ii) selection of materials and mix design;
(iii) structural (reinforcement) design;
(iv) detailing and drawing production;
(v) preparation of the specification; and
(vi) quality control.

Whilst a considerable amount of this work is highly dependent on the type of application, there are fundamental issues relating to some of the processes which can be described in general terms. This chapter presents general information and observations on the choice of concrete and reinforcing materials, specification documentation, quality control and testing. Chapters 7 and 8 cover, in more specific detail, design for structural (new construction and repair) and tunnelling applications, which together form the vast majority of sprayed concrete applications. These chapters concentrate on activities (i) to (iv) above, with passing reference to specification and quality control.

6.2 Mix selection and design

Introduction

The first task is to determine whether spraying is a more appropriate method of construction than casting in formwork. In many instances concrete can be sprayed as opposed to cast, the choice being based on convenience, speed and cost of construction. Sprayed concrete is particularly suited to forming curved shapes, where layers of thin or variable thickness are required, or where the technique reduces or eliminates the need for formwork. It may also be appropriate where access is difficult or where normal casting techniques cannot be employed. A good bond to a substrate may also be an important design consideration.

The engineer should then consider whether a particular production process (dry or wet) is to be specified or whether the decision can be left to the contractor. This

choice can influence significantly the drawing up of the specification and associated quality control procedures. Wood *et al.* (1989) discuss a number of points to be considered when selecting the spraying process.

With the wet process, a minimum cement content, a maximum water/cement ratio, and an air content can be specified, together with strength, and these can all be checked easily for compliance. However, a more sophisticated mix design, possibly including an accelerator, may be necessary to achieve medium to high strengths. With the dry process, it is more difficult to specify limits on mix proportions because of the difficulties of checking compliance in situ (the in-situ mix proportions being considerably different to those of the dry mix). The engineer should specify a compressive strength, but could in addition, or as an alternative, specify a prescribed mix which it is felt will give the desired performance when placed.

Whatever the method of application it is vital to remember that well-compacted sprayed concrete performs similarly to conventionally cast concrete of similar proportions. This has been amply demonstrated by Hills (1982) for compressive strength (Figure 5.3), and many other physical properties will be similar. An appreciation of this removes some of the mystique sometimes attached to sprayed concrete and gives the inexperienced engineer more confidence in its use.

For certain applications the mix design may not be controlled by compressive strength but by other physical properties such as freeze/thaw resistance or water permeability. In the latter case a higher strength mix may be specified along with other appropriate properties that can be checked, preferably as part of routine quality assessment.

At this early stage the designer must also decide if the sprayed concrete is to be reinforced and, if so, whether to use bar reinforcement, fibres or mesh. In certain situations the designer might choose to specify fibre reinforcement principally on the basis of a potentially faster construction time. Alternatively, it may be left to the contractor to decide whether to take advantage of this and other possible benefits such as reduced volume of material and avoidance of steel fixing.

Dry process mixes

Most mixes contain ordinary Portland cement and a suitably graded sand with maximum particle size of 6–10 mm (see Section 2.4 regarding gradings). Dry mix proportions typically have sand/cement ratios in the range 3:1 to 4:1 by weight (producing in-situ ratios in the range 1.8:1 to 3.2:1, depending on the amount of rebound) with a water/cement ratio between 0.35 and 0.45. Figure 4.14 provides examples of contrasting mix and in-situ proportions. These rich low-water content mixes can achieve compressive strengths of 40 to 75 MPa.

Addition of supplementary cementing materials, such as pulverized fuel ash (fly ash), ground granulated blast-furnace slag and silica fume, is still relatively unusual in site-batched dry mixes. These materials are, however, more common in prebagged materials (see Chapter 3). Typical replacement levels are up to 20% for fly ash and 5–10% for silica fume, which are commensurate with contents used in conventionally cast concretes.

The most common admixture is an accelerator, but as always these materials should only be added where necessary and at the lowest possible dosage because of the detrimental effects on long-term strength and, with some types, concern over

Table 6.1 *Typical steel fibre reinforced mix designs (from Wood, 1992)*

Components	Dry Process		Wet Process	
	kg/m³	% dry materials	kg/m³	% wet materials
Cement	420	19.0	420	18.1
Silica fume additive	50	2.2	40	1.7
Blended aggregate	1 670	75.5	1 600	68.9
Steel fibres	60	2.7	60	2.6
Accelerator	13	0.6	13	0.6
Superplasticizer	-	-	6L	0.3
Water reducer	-	-	2L	0.1
Air entraining agent	-	-	if required	if required
Water	170*		180	7.7
TOTAL	2 383	100	2 321	100

* approximate value – controlled at nozzle

the operative's health. An accelerator may be required for: immediate structural support, overhead work, spraying onto wet rock and shore work.

Fibres, if included, are typically 18–35 mm long, with 25 mm often being preferred when balancing performance with ease of mixing and placing. Shorter fibres are easier to mix and shoot, but the strength properties of the hardened concrete, particularly toughness and post-crack resistance, are lower. The amount of steel fibres included has ranged from about 1.5 to 6% by weight of dry mix material, with around 3% by weight (1% by volume, 65 kg/m³) being most common (see Section 6.3 for further discussion on design of reinforcement).

All these components together produce a typical mix design for steel fibre reinforced sprayed concrete along the lines given in Table 6.1. Typical dry mixes containing fly ash and silica fume are given in Table 6.2. Amtsbüchler and Van der Weshuizin (1990) report improved cohesion and lower rebound on a tunnel project, the lower rebound being essential to keep the steel fibre losses to an acceptably low level economically. The cement replacement mix produced a 28-day compressive strength of 31.5 MPa, compared with 36.5 MPa with the plain mix (no accelerators). Table 6.3 provides a summary of mix design concepts (Morgan, 1990). Most specifications to date have given a prescribed mix, i.e. a method statement (usually copied from a previous specification!), but the designer should give serious consideration to placing some responsibility on the contractor by specifying those aspects of performance that are essential to the function of the sprayed concrete.

Wet process mixes

By contrast, wet process sprayed concrete can be designed for strength and workability in a similar way to conventionally pumped concrete. The mix design is

Table 6.2 *Examples of PFA (fly ash) mix design (from Amtsbüchler and Van der Weshuizen, 1990)*

	Standard Mix (kg/m³)	**Modified mixes (kg/m³)** plain	fibre reinforced
Cement	445	335	335
PFA	-	65	65
Silica fume	-	45	45
Steel fibre	-	-	100
Filler sand	440	440	440
Crusher sand	805	805	805
9.5 mm crushed stone	220	220	150

affected by the materials, pumping distance, hose diameter and required output rate. A maximum aggregate size of 20 mm is common, with up to 20 mm sometimes being specified for large volume applications. Water/cement ratios are typically 0.4 to 0.55. Mixes often contain additives, the most common being a water-reducer or superplasticizer, silica fume, and an accelerator (added at the nozzle). The latter allows higher slump mixes to be sprayed. Fibre sizes and contents are similar to those used in the dry process. Table 6.1 gives a typical fibre-reinforced wet mix and Table 6.3 typical admixture addition rates.

One approach is to produce a high workability mix (120–200 mm slump) that can be pumped easily, and then to add an accelerator at or near the nozzle so that the concrete adheres better when sprayed. This method is commonly used on tunnelling projects where high output rates, overhead spraying and minimum disruptions due to blockages are required. Sodium silicate, at 10–20% by weight of cement, and sodium aluminate have been the most common accelerators, but with the penalty of significant strength loss (of up to 50% or more) at all ages.

More recently, potassium aluminate based accelerators have been developed, which Wallace (1987) reports give no early strength loss and only a 10–20% reduction in 28-day strength. Other advantages claimed for this liquid admixture were greater layer thicknesses and lower rebound. There is considerable development in the field of accelerators at present, including retarder/set combination systems (see Section 16.5) and calcium aluminate (high alumina) based cements. The general trend now is to keep accelerators in the range 2–5% by weight of cement, wherever possible.

An alternative approach, which is favoured in the UK where there is a limited volume of wet process production, is to produce a medium workability concrete (50–75 mm slump) incorporating a water reducer which is sprayed without an accelerator. This method was used on the canoe slalom course at Holme Pierrepont in Nottinghamshire and also at Riyadh zoological gardens, these being contracts where overhead spraying and high early strength were not required and the output rate was moderate.

Table 6.3 *Summary of mix design concepts (Morgan, 1990)*

Material/Property	Comments
Cement content	18 to 21% by mass of dry component
Silica fume	8 to 13% by mass of cement
Aggregate gradation	ACI 506 (1990*a*), Table 2.1, Gradation No. 1 or (more commonly) No. 2.
Steel fibre type	High strength, deformed, drawn or slit-sheet fibre.
Aspect ratio	Length/equivalent diameter of 50–70
Steel fibre addition rate	50–80 kg/m^3 depending on the required toughness
Admixtures	1) Water reducers used in wet-mix shotcretes at about 0.5L/100 kg cement. 2) Superplasticizers required in wet-mix silica fume shotcrete at 1–1.5 L/100 kg cement. 3) Air entraining admixtures used in wet-mix shotcrete where freeze/thaw durability is important (10–12% air content at pump, 4–6% air content in situ).
Accelerator	Dosage depends on accelerator type and required setting time (2–5% by mass of cement is typical).
Water/cement ratio	0.3–0.4 for dry-mix shotcrete. 0.4–0.5 for wet-mix shotcrete.
Slump	40–100 mm for wet-mix shotcrete.

6.3 Reinforcement selection and design

Introduction

If substantial flexural load carrying capacity is required then continuous steel mesh or bars will be needed, located near the tensile face of the section. In this case fibre reinforcement of the full section will not normally be justified, but a thin surface layer may still be used to provide impact and wear resistance. If major flexural strengthening is not required then the choice of reinforcement is between fibres and a light mesh, both of which may give a modest improvement in flexural strength and some post-crack load carrying capacity. Although potentially greater, the moment of resistance of a mesh-reinforced section may be less than that of a steel fibre reinforced section because the mesh is often located near the centre of the sprayed concrete layer. In virtually all other respects the properties of a steel fibre reinforced matrix will be equal or possibly superior to those of a plain matrix containing steel mesh. This is due partly to its better energy absorbing characteristics and

partly because a mesh can impede spraying and consequently reduce the quality of the concrete matrix.

A discussion of the relative merits of fibre and mesh reinforcement which may help in choosing the most appropriate reinforcement type is given later in this section.

Mesh and bar reinforcement

Light meshes are common as reinforcement in sprayed concrete where major strengthening is not required; the mesh is intended to hold the sprayed concrete layer together in the event of cracking or debonding from the substrate. The mesh is often located near the centre of the layer where it makes little contribution to moment resistance. Meshes are typically 75 mm or 100 mm square with a wire diameter of 2.5 mm to 4.0 mm, giving a steel area of 90 to 130 mm^2/m. Lighter meshes are easier to handle and fix but should be rigid enough to prevent vibration during placement of the sprayed concrete.

In fully structural applications, conventional mild steel or high yield reinforcement will be required. Care must be taken however to provide adequate spacing to prevent inclusion of rebound behind or between bars. A fuller discussion of good practice relating to reinforcement is given in Section 10.7 and by ACI Committee 506 (1990*a*).

Steel fibres

The vast majority of applications of fibre-reinforced concrete to date have used steel fibres. This has been due to the uncertain durability of glass fibres and the relatively modest improvements brought about by using the older type of polypropylene fibres. In addition, neither of these two types of fibre was particularly suited to the dry spraying process.

There is a wide variety of steel fibres available. The straight round wire, straight deformed round wire and straight slit-sheet fibres are older, first generation steel fibres which are less likely to be specified in sprayed concrete today. The second generation steel fibres were designed to give improved performance, especially better bond and mixing characteristics; the main types being melt-extract, enlarged-end slit sheet and hooked-end wire fibres. The enlarged-end slit sheet fibre, popular in Scandinavia and Australia, is now available in many countries including the UK and USA. Although it is easy to spray, the toughness of the composite material has been found to be lower than that of equivalent hooked-end drawn wire fibre mixes.

When considering the mechanical performance of the composite, and in particular the toughness, the hooked-end wire fibre is generally superior to the melt-extract fibre (for the same fibre length and fibre content), because it is a strong, hard drawn wire with a very efficient end anchorage. A stainless steel melt-extract fibre is undoubtedly superior to any carbon-steel fibre for fibre durability. Although wire and slit-sheet fibres are available in stainless steel, their cost is prohibitive for civil engineering applications (whereas stainless steel is standard in refractory concretes). It is still a matter of debate, however, whether stainless steel fibres are necessary to ensure the composite's durability. Although carbon-steel fibres on the surface will rust, most evidence suggests that embedded fibres experience little corrosion, even

in a carbonated zone, possibly because it is difficult for anode and cathode regions to form on such short, discrete elements. However, it can be argued that carbon fibres in a cracked region may corrode over time given free access to oxygen and moisture.

Although a wide range of fibre lengths is available from manufacturers (typically 12–75 mm), the usual length for sprayed concrete work is between 18 mm and 30 mm, with 25 mm being the most common. Above this range steel fibres become increasingly difficult to spray and below it the reinforcing efficiency of the fibre is marginal. There is also a selection of fibre diameters available with drawn wire fibres (typically 0.25–0.80 mm) but for sprayed concrete it is necessary to restrict the aspect ratio (length/diameter) to around 65 or less if production problems are to be avoided. Thus a common choice is a 25 mm × 0.4 mm fibre. Melt-extract fibres can also be made in a variety of cross-sectional sizes, but in practice manufacturers offer as standard a single size, which should have an equivalent aspect ratio for sprayed work.

Other steel fibre types include crimped and machined fibres, which have been used in sprayed concrete in the USA, Europe and Japan. Steel fibres will probably continue for the present to be the first choice in most applications because of their wide usage and the amount of information available on properties and performance. In addition, where flexural strengthening is required from the fibre concrete, steel fibres are the obvious choice.

Polypropylene fibres

There is very little information available on appropriate types and geometry of polypropylene fibres for use in sprayed concrete. The older type of 'chopped string' fibre has been generally superseded by modern fibrillated types because of their somewhat higher modulus (up from about 2 GPa to 4 GPa), improved bond and better dispersion in the matrix.

Some fibre types are marketed principally for shrinkage crack control in cast concrete. They are available typically in lengths of 10–50 mm and have a denier of less than 125. Their modulus is approximately 3.5 GPa. These fibres are claimed to be effective in reducing shrinkage cracking at very low fibre contents of around 1 kg/m^3 (0.04% by weight), and have been used at this dosage on at least one UK sprayed concrete project.

High modulus fibrillated polypropylene fibres have been used recently in sprayed concrete at significantly higher fibre contents (0.25 to 0.75%). They are available in lengths of 6 mm to 48 mm with a denier of between 15 and 80 (width 100–300 microns and thickness 20–40 microns). Their modulus is quoted as ranging up to 18 GPa. Although applications for this fibre type are very limited, it may well have potential in repair applications (particularly in the wet process) where thin durable coatings are required to provide protection rather than strengthening.

Comparison of fibre and mesh reinforcement

The inclusion of fibres in concrete improves its post-crack ductility, toughness, impact resistance, fatigue resistance and flexural strength. The type and amount of improvement is dependent upon the fibre's tensile properties (strength and stiff-

ness), its bond strength (governed by shape and surface texture) and the quantity of fibres. The size and quantity of fibre reinforcement is usually limited by practical considerations concerned with the mixing process. Fibres vary considerably in cost but none can be considered cheap. Their use is therefore limited to forms of construction which will benefit substantially from the energy absorbing characteristics of fibre concrete. Certain applications of sprayed concrete fall into this category.

In many circumstances sprayed concrete is not required to carry large loads in flexure and is conveniently reinforced with light mesh. The purpose of the mesh is primarily to hold the concrete together in the event of cracking. The alternative of a sprayed fibre-concrete lining has the following possible advantages:

(i) greater post-crack resistance or toughness;
(ii) higher impact resistance;
(iii) saving in cost of fixing mesh reinforcement;
(iv) faster construction;
(v) reduced design thickness; and
(vi) reduced volume of material required to cover uneven surfaces.

These must be balanced against the possible disadvantages of fibre reinforcement:

(i) cost of fibres
(ii) high fibre losses (fibre rebound may be higher than material rebound in the dry process);
(iii) discomfort (particularly with steel fibres);
(iv) occasional difficulty in mixing and spraying; and
(v) durability of fibres.

The main issues are strength, durability and cost. With regard to strength, the primary property is flexural strength. The relative flexural strengths of the two reinforcements depend principally on fibre type and volume for one, and on the mesh size and position in the section for the other, both also being dependent on the depth of section.

A survey of published data reveals that fibre and mesh reinforced sections with thicknesses of 50–150 mm have comparatively similar flexural capacities, whether tested as one-way spanning beams or two-way spanning slabs (the latter usually in simulation of tunnel linings in conjunction with rock bolts). Some of the author's data on 28-day old 65 mm thick beams shows an A312 mesh (75 × 75 × 2.5 mm wire mesh) producing a slightly lower modulus of rupture (4.3 MPa) than the plain control (5.3 MPa) and both 2.2% by weight in situ of 25 × 0.4 mm straight wire fibre (6.8 MPa) and 3.1% of 25 mm melt-extract fibre (6.9 MPa). In this case the mesh at mid-depth of 65 mm could not increase the moment capacity and interfered with the matrix quality during spraying. The former can be predicted from simple calculations as shown in the following section. Some published data shows similar trends, whilst others give the mesh a slightly higher flexural strength.

The issue of comparative performance of mesh and fibre reinforcement has been extensively described by Kirsten and Labrum (1990) and Kirsten (1992) and summarized recently by Kirsten (1993). They examined mesh, hooked-wire and melt-extract fibres in 50, 100 and 150 mm thick two-way spanning panels tested under both distributed and point loading. Table 6.4 contains an extract of some of their data. They found comparable performance in both published literature and their own studies, although in the latter the mesh (75 × 75 × 3.1 mm diamond) rein-

Table 6.4 *Relative performance of mesh and fibre reinforced panels (Kirsten, 1993)*

Reinforcement type	Loading type	Standard thickness at peak (mm)	Peak load at standard thickness (kN)	Effective load (kN) at given deflections (mm)		
				50	100	150
Mesh (series I)	Point	150	108	67	32	30
		100	54	36	20	18
		50	13	9	6	4
	Distributed	150	212	158	126	115
		100	129	109	86	78
		50	58	53	42	37
30 mm hooked-wire fibre (1.4%) (series I)	Point	150	110	44	33	25
		100	66	32	24	19
		50	18	7	5	3
	Distributed	150	177	77	59	57
		100	118	55	42	41
		50	59	28	21	20
Mesh (series II)	Point	150	82	48	42	36
		100	46	32	28	23
		50	20	16	13	11
	Distributed	150	173	113	88	66
		100	114	89	75	68
		50	58	52	48	43
30 mm hooked-wire fibre (2.5%) (series II)	Point	150	132	53	43	40
		100	56	34	28	26
		50	22	15	12	11
	Distributed	150	-	-	-	-
		100	140	86	61	38
		50	76	50	32	17
25 mm melt-extract fibre (1.3%)	Point	150	84	38	28	21
		100	38	9	8	7
		50	19	4	4	4
	Distributed	150	142	44	32	20
		100	95	29	21	13
		50	47	15	11	6
35 mm melt-extract fibre (1.3%)	Point	150	326	228	220	213
		100	136	68	56	52
		50	57	27	23	18
50 mm melt-extract	Point	150	75	17	9	0
		100	44	14	7	0
		50	22	7	4	0
	Distributed	150	180	82	62	55
		100	90	36	33	30
		50	34	12	11	8

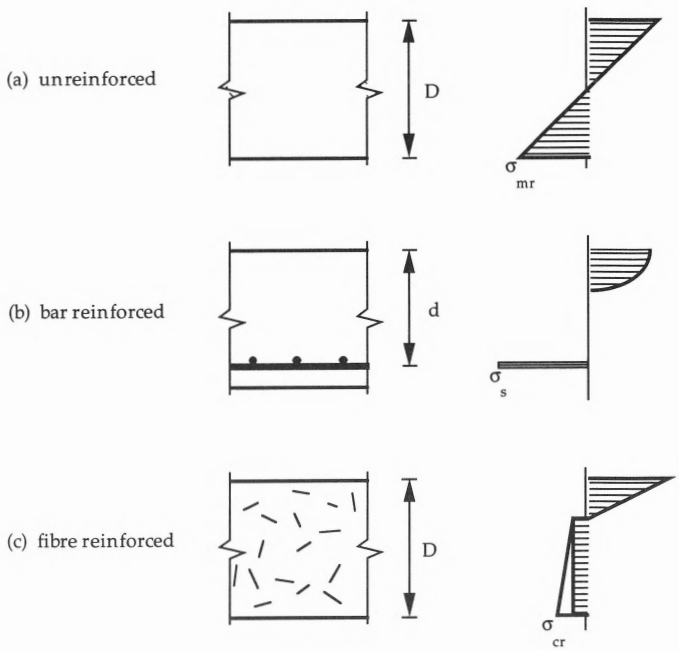

Figure 6.1 *Typical stress blocks for design*

forced panels were slightly better. However, they only achieved in-situ fibre content of 1.3–2.5% by weight and concluded that the fibre concrete performance would have equalled that of the mesh had they achieved their target of 3% in situ. It should be noted however that, with the dry process, a dry mix fibre content of over 5% by weight would usually be needed to obtain 3% in situ, which is above the current trend of 60–90 kg/m^3 (2.5–4% by weight).

Moment capacity calculation

There are a number of approaches that may be used for determining the moment capacity of a sprayed concrete section, some of which are outlined below. Kirsten (1992) has also presented similar analyses for mesh and fibre-reinforced sections, whilst Lub and Van Wanroij (1989) give theory for shear and moment capacity of bar-reinforced beams strengthened with a layer of mesh-reinforced sprayed concrete. The methods below are for the case of the sprayed section acting alone, though in some applications the engineer may wish to consider the concrete to be acting compositely with its substrate.

(i) Unreinforced

An elastic stress block (Figure 6.1*a*) can be assumed and a moment capacity calculated based on published flexural strength (modulus of rupture) data. The designer should be aware that measured moduli of rupture decrease with increasing specimen thickness. The ultimate moment of resistance M_u is given by:

$$M_u = \frac{\sigma_{mr}}{\gamma_m} b \frac{D^2}{6} \tag{6.1}$$

where σ_{mr} is the modulus of rupture of the matrix, b is the width of section, D is the overall depth of section, and γ_m is a material partial safety factor.

(ii) Mesh reinforcement

The ultimate moment of resistance may be calculated from conventional reinforced concrete theory using a stress block similar to that in Figure 6.1*b* or a simplified version. Assuming a maximum lever arm of 0.95d (as recommended by BS8110, BSI, 1985), then:

$$M_u = A_s \frac{\sigma_s}{\gamma_m} 0.95d \tag{6.2}$$

where d is the effective depth, A_s is the area of the steel and σ_s is the strength of the steel.

It should be noted that for a single layer of light mesh (around 100 mm^2/m) the ultimate moment capacity may often be that of the matrix alone before cracking (and hence given by equation 6.1).

(iii) Bar reinforced

A conventional reinforced concrete design approach will apply (Figure 6.1*b*). Using an approach following BS 8110, the ultimate moment capacity of a singly reinforced section will be the lesser of:

$$M_u = A_s \frac{\sigma_s}{\gamma_m} z \tag{6.3}$$

and

$$M_u = 0.234 \frac{\sigma_{mc}}{\gamma_m} bd^2 \tag{6.4}$$

where z is the lever arm and σ_{mc} is the compressive strength of the matrix.

(iv) Fibre reinforced

Whilst many theories have been proposed for the behaviour of fibre-reinforced, sprayed concrete, none have been widely accepted as a basis for design. Three possible methods are outlined below.

The most basic approach is to use published flexural strength data that has been obtained assuming an elastic stress block, to calculate a moment capacity. Equation 6.1 will apply, with the apparent modulus of rupture of the composite σ_{cr} replacing the modulus of rupture of the plain matrix σ_{mr}.

A second approach is to predict a modulus of rupture for a particular fibre concrete using an equation based on a regression analysis of fibre concrete data. The equation proposed by Swamy and Mangat (1974) and recommended by ACI

Committee 544 (1988*a*) gives:

$$\sigma_{cr} = 0.97\sigma_{mr}(1 - v_f) + 3.41v_f\left(\frac{\ell}{d}\right)_f \tag{6.5}$$

where v_f is the volume fraction of the fibres and $(\ell/d)_f$ is the fibre aspect ratio.

The third, and perhaps most correct, design method is to assume a more realistic stress block such as that shown in Figure 6.1*c*. Such an approach recognizes that the increase in flexural strength obtained with fibre reinforcement is associated with a shift in the neutral axis and is not due to a substantial increase in the composite's tensile strength. It is generally held that the concrete is still behaving elastically in compression, though various shapes have been suggested for the stress distribution in the tensile region.

Hannant (1978) has proposed a rectangular tensile stress block and a neutral axis depth of $D/4$. His approach however assumes that the composite is capable of carrying more load after the formation of the first flexural crack. In reality most sprayed fibre concrete has a fibre content below the critical fibre volume required for this to happen, though the composite will continue to carry load after cracking, albeit at a reduced level.

Mangat and Gurusamy (1987) consider the case where peak load coincides with the formation of the first flexural crack, and consequently the matrix in tension contributes to the ultimate moment capacity. They derive an expression for the moment capacity assuming a trapezoidal tensile stress block. However their approach, as well as Hannant's, requires a knowledge of the interfacial bond stress between fibre and matrix, and information on this property is not readily available for steel or polypropylene fibres. Mangat and Gurusamy overcame this difficulty by equating the moment capacity of their stress block to that of an elastic triangular stress block, and obtained an expression for the apparent modulus of rupture of the composite σ_{cr}, which is almost identical to equation 6.5. However, it would be misleading to assume from this type of expression that moment capacity is independent of fibre type; some steel fibre types are more efficient than others and will therefore sustain a higher fibre/matrix bond stress.

6.4 Specification

Introduction

In the past, specifications for sprayed concrete have often been weak, partly because of the designer's a lack of familiarity and understanding of the production process and the purpose of the material. Given a basic knowledge of the material and a clear idea of why it is being used, it should not be too difficult to draw up an adequate specification.

Designers now have available a number of national 'standard' specifications, which have developed over the last 15 years into quite refined, sensible documents. These are described below and form essential reading and reference for the conscientious engineer. It is neither appropriate nor practical to reproduce extracts in this book, it being sensible for designers/specifiers to obtain copies of the relevant

documents. Clients expect good practice to be followed and a designer would find it difficult to justify not considering these documents in the event of contractual problems.

A brief examination of the published literature reveals that there have been major developments worldwide in specifications and guideline documents in the last few years. This reflects both the increasing use of sprayed concrete and recognition of the needs of clients, designers and contractors for better and more detailed guidance which has been produced through widespread consultation in the industry.

Documentation for sprayed concrete

The first UK specification was produced in 1976 by the Association of Gunite Contractors. This was rewritten in 1986 as *Codes of Practice for Dry and Wet Process Sprayed Concrete* by the re-named Sprayed Concrete Association (SCA). The current document contains general information together with guidance on design and specification for both dry and wet processes. The SCA has most recently produced a *Guide to Certification of Sprayed Concrete Nozzlemen* (1994), as part of their scheme to improve construction standards. It is based on an equivalent American Concrete Institute report (ACI Committee 506, 1982).

In 1978 the Concrete Society (1978) published a report relating to the repair of fire-damaged structures with sprayed concrete, which included advice on specification. The Construction and Formwork Committee of the Concrete Society subsequently produced its *Specification for Sprayed Concrete* (1979), which was an end product or performance specification intended for application to new construction, including tunnels, and to repair and strengthening work. The following year a *Code of Practice for Sprayed Concrete* was published followed by *Guidance Notes on the Measurement of Sprayed Concrete*, the latter including the format for a schedule (Concrete Society Construction and Formwork Committee, 1980, 1981). These two documents were sensibly drafted to conform to CP110, the UK code of practice for the structural use of concrete. However CP110 was superseded by BS8110 in 1985 and the Concrete Society documentation has not been revised accordingly.

The British Standards Institution has not produced any national standards relating to sprayed concrete, but has supported the moves towards the development of a European Standard (N.B. it is BSI policy not to develop new standards just for the UK). CEN Technical Committee 104 has now resolved (Resolution BTS1 10/1994) to allocate a new work item on sprayed concrete, and hopefully a proper standard will evolve in due course.

The Highways Agency of the Department of Transport is currently drafting its own *Specification for the Repair of Concrete Highway Structures*, which includes a section on sprayed concrete. The draft covers materials, mix design, fibre reinforcements, workmanship, spraying procedure and approval tests.

The most substantive documentation has been produced in the United States, where ACI Committee 506 (1983) of the American Concrete Institute first published their *Recommended Practice for Shotcreting* in 1966. This was also adopted as an ACI Standard until its withdrawal in 1983, when it was replaced by the Committee's *Guide to Shotcrete*, most recently updated in 1990 (ACI Committee 506, 1990*a*). This publication gives recommendations on the applicability of sprayed concrete to different types of construction, material requirements, and application procedures.

Equipment requirements are given for both dry and wet processes, and the need for a well-qualified application crew is stressed.

The American Concrete Institute's *Standard Specification for Materials, Proportioning and Application of Shotcrete* (ACI Committee 506, 1990*b*) was first published in 1977, and subsequently became part of their manual of concrete practice in 1982. This specification has been used widely in the United States, although there has been debate recently concerning the $0.85f'_c$ strength reduction factor allowed on routine quality control cores. Gebler and Schutz (1990) argue convincingly that there is no logical reason for this reduction and that contractors ought to be able to achieve the same compressive strength as in preconstruction testing. ACI Committee 506 (1994) has recently proposed a revision of their specification, to be titled *Standard Specifications for Structural Concrete*. The main difference is the addition of a checklist containing over 30 notes to the architect/engineer to assist in document preparation using the standard specification. The checklist is not part of the specification itself, which can only be referred to as an ACI Standard if referred to in its entirety. This is an excellent document and highly recommended reading for all engineers involved in sprayed concrete work. The $0.85f'_c$ rule has, however, remained in the proposed revision.

ACI Committee 506 (1982) has also published a *Guide to Certification of Shotcrete Nozzlemen*. The suggested procedure includes a learning and training period, a written/oral examination and a workmanship demonstration. The issue of certification is discussed in Section 12.8.

The American Society for Testing and Materials has published: a *Standard Specification for Admixtures for Shotcrete*, C1141-89; a *Standard Practice for Preparing and Testing Specimens from Shotcrete Test Panels*, C1140-89; and a *Standard Test Method for Time of Setting of Shotcrete Mixtures by Penetration Resistance*, C1117-89 (ASTM, 1989*a*, 1989*b*, 1989*c*). These are referred to by the ACI Committee 506 Specification, along with 20 other ASTM standards relating to concrete.

In Europe there has been a German national standard since 1979: DIN 18 551 *Sprayed Concrete (Spritzbeton); Production and Quality Control*. This was revised and extended in 1992 with regard to repairing and renewing reinforced concrete structures (DIN, 1991). AFNOR released a new French Standard, NF P95-102 *Engineering Structures: Repair and strengthening of concrete and masonry construction – sprayed concrete – specifications for techniques and materials used* in 1992. This includes details of required materials (including aggregate gradings), cement contents (see Table 6.5), preliminary works, preparation of surfaces and reinforcement, mixing, spraying and quality control. The emphasis throughout is on repair applications. AFTES, the French Association for Underground Works, has also produced *Recommendations on Sprayed Concrete: Technology and Practice* (1992), an update of their first report in 1974 concerning tunnelling.

In 1993 the Norwegian Concrete Association published a specification entitled *Sprayed Concrete for Rock Support - Technical Specification and Guidelines*. This includes: (1) product specifications - requirements for materials, concrete performance (compressive strength and water/cement ratio, flexural strength, toughness and bond), preparation, production, quality control; (2) guidelines: on design (including the rock mass classification method), equipment, concrete, materials and test methods; and (3) specific guidance on toughness testing of steel-fibre reinforced

Table 6.5 *Recommended cement contents (AFNOR, 1992)*

Application	Cement content in situ (kg/m³)*	Cement content in mix (kg/m³)**	
		dry process	wet process
Repair of masonry	500	400	500
Surface repair	350	280	350
Repair of reinforced concrete structures	450	360	450

* for a minimum thickness of 2 cm
** allowing for a 20% reduction due to rebound with the dry process

concrete. The latter reflects the almost universal use of steel fibres in Norway, as does the whole emphasis on wet process sprayed concrete and tunnelling.

There has also been a move by EFNARC, the European Federation of National Associations of Specialist Contractors and Material Suppliers for the Construction Industry to produce a pan-European specification. The EFNARC Technical Committee for Sprayed Concrete has members from eleven countries. They have published a public draft for comment titled *Specification for Sprayed Concrete* (1993). The contents include: materials, concrete and durability requirements; mix composition; execution of spraying; requirements for final product (compressive strength, flexural strength and toughness, bond strength, fibre content, permeability and frost resistance); test methods; quality control; and an appendix on admixtures. Both the EFNARC specification and DIN 18 551 have recently been put forward to CEN as starter documents for the production of a European Normative (EN) standard. The issue is currently under consideration by CEN TC104.

In the Far East, the Japanese Society of Civil Engineers (JSCE) has produced a *Guideline for Construction of Steel Fibre Reinforced Shotcrete* (1984*a*). This gives advice on the quality of steel-fibre shotcrete, materials and mix proportions, equipment, placing, and quality control and inspection. Both dry and wet processes are covered, and particular emphasis is placed on the importance of regulating the water in the dry process to keep to the specified water/cement ratio. The material performance is specified in terms of strength (compressive and flexural) and toughness. The difference between the discharged mix and the adhered mix is emphasized, and the importance of allowing for the effect of rebound in the design of the discharged mix is underlined. Quality control tests required either during production or upon completion include fibre content determination, strength tests, toughness tests, and determination of the layer thickness of the sprayed fibre concrete.

Finally the International Tunnelling Association has produced both a *Status Report on Shotcrete in Tunnelling* (1991) and *Shotcrete for Rock Support: Guidelines and Recommendations - a Compilation* (1993). The first report reviews progress in fifteen ITA member countries, whilst the second summarizes their specification and guidance documents. The latter is a most useful and detailed review, which has

also been published in a journal in a slightly abridged form (ITA Working Group on Shotcrete Use, 1993). It includes substantial references to the ACI, AFTES, ASTM, DIN, EFNARC, JCI/JSCE, and Norwegian Concrete Association documents described above, and is therefore the most useful single document available.

Additional documentation for fibre reinforcement

There are no formal specifications or codes of practice available for sprayed fibre concrete, although reference to fibres occurs in some of the documentation relating to sprayed concrete. The engineer should therefore also make reference to standards relating to cast fibre concrete, in conjunction with standard specifications for conventional sprayed concrete, before drawing up a specification for sprayed fibre concrete. Modifying a specification for conventional sprayed concrete so that it can be used to specify sprayed fibre concrete should not be a difficult task, provided the specifier has a clear idea of the purpose for which the fibres are being used, and makes certain that adequate provisions are made to ensure that the finished product complies with what has been specified.

In the United States, ACI Committee 544 has updated its *Guide for Specifying, Proportions Mixing, Placing and Finishing Steel Fibre Reinforced Concrete* (1993). The report describes the current technology with regard to all these operations, the emphasis being on the differences between conventional concrete and steel-fibre concrete and how to deal with them. Guidance is provided on mixing techniques to achieve uniform mixes, placement techniques to ensure adequate compaction, and finishing techniques to assure satisfactory surface textures. Also of relevance are: the ACI Committee 544 report *Design Considerations for Steel Fiber Reinforced Concrete* (1988*a*), which has a section on shotcrete; ASTM C1116 *Standard Specification for Fiber-Reinforced Concrete and Shotcrete* (1991); and ASTM C1018 *Standard Test Method for Flexural Toughness and First-Crack Strength of Fiber-Reinforced Concrete* (1992).

The Concrete Committee of the Japanese Society of Civil Engineers has published its *Recommendations for the Design and Construction of Steel-Reinforced Concrete* (1984*b*). This publication covers similar ground to that covered by the ACI Committee 544 report. The JSCE (1984*c*) has also published seven *Standard Test Methods* relating to the testing of steel fibre reinforced concrete. A *Standard Specification for Steel Fibers for Fiber Reinforced Concrete*, A820-90, was produced by the American Society for Testing and Materials in 1990, though there is still no standard specification for fibres in the UK. The JSCE Concrete Committee has also published a *Specification of Steel Fibres for Concrete* (1984*d*). The specification covers fibres for cast and sprayed concrete applications, the only difference being that fibres longer than 40 mm are not permitted for sprayed applications. These two specifications cover drawn wire, slit sheet, melt extract and milled steel fibres and define materials for fibres, fibre shape and size, and minimum tensile strength.

Producing a specification

All engineers appreciate the importance of the specification document, both in terms of achieving quality construction and minimizing additional claims by the contractor. Historically, sprayed concrete works have been prone to problems for a number

of reasons, including poor standards of workmanship, inexperienced designers and lack of authoritative guidance for engineers.

Because it is not a standard form of construction it is natural that many engineers, when faced with a sprayed concrete application, are dealing with the material for the first time. When they then look for help, they may also find little experience elsewhere in their organisation. Compound this situation with lack of access to published information and you have a recipe for disaster. Experience of these problems has been one of the main driving forces behind this book, the hope being that by bringing together expertise and experience in many aspects of sprayed concrete we will have produced a useful and accessible source of reference.

As stated in the introduction, it is impractical to reproduce here extracts or samples of specification documents. However, over the last few years some excellent documentation has been produced, particularly in the United States and Europe. These have been described above and should form part of the engineer's library. You are urged to get them, read them and apply the relevant parts. Even where conflict exists, it will bring important issues to the attention of the designer, which in itself is likely to reduce the chances of problems or disputes occurring later. Some specific issues which you might consider include the following:

(i) Materials

Try not to place too much reliance on the advice of materials suppliers and avoid reference to proprietary products. Refer to published data, including those in Chapters 2 and 5, when selecting materials and identifying likely levels of performance.

(ii) Preparation

Preparation and bond to the substrate are of vital importance. Ensure appropriate cleaning and roughening techniques are specified to achieve a rough and sound bond. Avoid mechanical action where possible and specify high pressure water jetting or grit blasting. Ensure bond checks form part of the quality control requirements, including both sounding (tapping with a rod) and core pull-off techniques.

(iii) Construction method

Seek the views of contractors experienced in sprayed concrete. They will be able to give valuable guidance on the practical aspects of applying your draft specification and identify requirements that are unrealistic. They can also advise on the choice of process (dry or wet). The wet process is predominant in tunnelling and is now taking a substantial part of the new construction and repair markets. If it can provide the levels of flexibility and performance necessary it should be given serious consideration, either as an option or a requirement, because it offers potentially the more consistent and controlled (by water/cement ratio) product.

(iv) Preconstruction testing

This should form part of the specification. Preconstruction trials and tests are a valuable part of the design and construction process. If there are flaws in the specification, it is better to find them before construction. Trials will also identify inadequate contractors or operatives. Whenever possible make it a requirement that all nozzlemen are trained and have passed a recognized independent certification scheme.

Table 6.6 *Typical SFRS performance specifications (Wood, 1990)*

Property	Test method	Minimum requirements
Aggregate gradation	ACI 506 (1990*a*)	1, 2 or 3 as required
Accelerated setting time:	ASTM C-403	
Initial set		10 minutes
Final set		30 minutes
Compressive strength:	ASTM C-42	
8 hour (accelerated)		5 MPa
1 day		10 MPa
7 days		30 MPa
28 days		40 MPa
Flexural strength:	ASTM C-1018	
7 days		4 MPa
28 days		6 MPa
Toughness index	ASTM C-1018	
I_5		3.5 average
I_{10}		5.0 average
Boiled absorption	ASTM C-642	8% maximum
Volume of permeable voids	ASTM C-642	17% maximum

(v) Performance
Provide a clear set of requirements, identifying the test methods (standard whenever possible) and the required levels of performance. State the numbers of samples, minimum average value and minimum individual value for each test. Table 6.6 is an example of a fibre-reinforced sprayed concrete specification from the United States.

(vi) Bills of quantities
Think carefully about the method of measurement and bill presentation. National methods for general civil engineering may be inadequate, such as the Civil Engineering Standard Method of Measurement (CESMM) used in the UK (Leah, 1993). Unfortunately the method proposed by the Construction Committee of the Concrete Society (1981) has become outdated and virtually no other guidance exists. There is a need for new documentation, but in the meantime take care and seek advice if necessary (e.g. in choice of area (m^2) versus volume (m^3) measurement).

(vii) Tolerances
Problems with tolerances are common. Specifying a tight set of tolerances can result in the unnecessary rejection of sound work and disputes with the contractor

who considers the contract is unreasonable. In addition it may be necessary to cut back and possibly overwork the sprayed surface to achieve a fine tolerance, which can reduce the concrete's quality and its bond to the substrate, particularly on thin overlays (less than 50 mm). Designers should therefore be realistic in setting tolerance bands and advise the client of the likely appearance. Kolf and Gebler (1993) have recommended some reasonable tolerance limits (Table 10.2). Where aesthetics are important, it may be advisable to hold full-scale trials to determine an appropriate tolerance/finishing regime that is to the client's and contractor's satisfaction.

6.5 Quality control and testing

Introduction

Quality control of sprayed concrete is more difficult than that for conventional cast concrete because the mix proportions in situ may differ substantially from the batched proportions. Also, the concrete quality is more operative dependent. The latter is illustrated by one contract where the compressive strength was increased from 10 to 40 MPa merely by changing from novice to experienced operatives. One of the most important quality control measures is, therefore, to ensure that all spraying operatives are well trained and have passed a recognized training scheme, for example those of ACI Committee 506 (1994) and the SCA (1994), where available (see Section 12.8).

The most reliable determination of the quality of sprayed concrete in place is obtained by testing samples extracted from a typical gunned section. However, this is a costly procedure and it may sometimes be impracticable to obtain specimens for regular control tests in this manner. The next best solution, though even this has its shortcomings, is to extract cores from test panels gunned under field conditions. Test panels are also of use before the start of construction to check that the gunning crew can produce the required quality of sprayed concrete using the equipment, materials and mix proportions proposed for the works.

The inclusion of fibres in sprayed concrete has two important and quite separate implications for quality control testing. Firstly, measurements ought to be made of the in-situ fibre content and secondly, since the prime reason for using fibres will not be the enhancement of compressive strength, a routine quality control strength test (other than a core compressive test) is desirable.

Preconstruction testing

As already stated, preconstruction testing is a vital part of the design/construction process. A number of authorities describe good practice including ACI Committee 506 (1990*a*) who give details of the investigations that may be carried out prior to the start of the field work to verify that the specified quality of sprayed concrete can actually be expected in the structure. They recommend that test panels (minimum 750 mm square) are sprayed from each position required by the work (downhand, vertical or overhead) and for each mix design being considered. In addition to visual examination (for soundness and uniformity of material) and strength measurements, tests for bond, water absorption, shrinkage, resistance to freezing/thawing and other properties are also suggested.

Further guidance is given by AFTES (1992), EFNARC (1993), DIN 18551 (1991) and the Norwegian Concrete Association (1993), the latter dealing explicitly with the wet process. EFNARC suggest 600 mm by 150 mm thick test panels with 45° chamfered edges. They recommend checking: water demand, workability and pumpability/sprayability, rebound, air content, density (for the fresh concrete); and compressive and flexural strength, toughness, fibre content and bond (for the hardened concrete).

As an example, Morgan and McAskill (1984) describe a large sprayed steel fibre concrete tunnel project in British Columbia where the quality assurance programme included at the preconstruction stage:

- seminars to train inspectors in proper inspection and testing procedures;
- evaluation of the contractor's spraying crew, equipment and materials;
- evaluation of the proposed mix design; and
- establishment of a sprayed concrete testing laboratory at the site.

This project demonstrates the importance that should be placed on preconstruction testing. The engineer will need to convince the client that the associated expenditure is worthwhile to improve quality and reduce risk, problems and costs during construction, which will invariably be the case.

Panels for routine control testing

Most specifications for sprayed concrete projects call for the making of test panels during construction (typical between 500 and 750 mm square and 100–150 mm thick), from which test specimens are cut or sawn. Whilst test panels are more convenient than in-situ sampling, an obvious disadvantage is that the operator is aware that a test specimen is being produced and consequently the sample may not necessarily be a representative one. The edge effect of the panel and the backing material may also affect the concrete properties.

Guidance on the preparation and testing of test panels for sprayed concrete is given by ACI Committee 506 (1990*b*, 1994), AFNOR NF P95-102 (1992), ASTM C1140 (1989*b*), the Concrete Society (1980), EFNARC (1993), JSCE (1984*a*) and the Norwegian Concrete Association (1993). Section 6.4 and the references provide further details. Some of these include suggested acceptance criteria.

Fibre content determination

The engineer must choose between specifying a batched or in-situ fibre content and then ensure that the appropriate material is sampled regularly during construction. The specification of an in-situ fibre content is clearly preferable (particularly with the dry process) but the testing technique is slightly more complicated.

The author has successfully performed simple wash-out tests at many sprayed fibre-concrete trials to determine in-situ fibre contents (both steel and polypropylene). A fresh sample is weighed, then washed through a 150 μm sieve. The liquid passing is collected, allowed to settle (this process is accelerated by use of a flocculating agent) and the resulting sediment (mainly cement) dried in a microwave oven. The retained material is also dried and the fibres extracted. The mix proportions can then be calculated on a volume or weight ratio (see Section 4.5 for formulae). An

aggregate grading will allow adjustment for the small portion of silt passing through the sieve with the cement. EFNARC (1993) recommend a similar method along with the alternative of extracting steel fibres from crushed cores. The wash-out test is suitable for small or medium sized jobs, but for large contracts a quicker and more sophisticated technique, such as an electromagnetic method (Uomoto and Kobayashi, 1984) might be preferable. An additional advantage of the wash-out test is that the removed material can also be used to determine cement contents, water/cement and aggregate/cement ratios, and rebound figures. The method is similar to that of the Rapid Analysis Machine (RAM) but is performed by hand.

Core compression strength

Compressive strength is the principal measure of quality control of plain sprayed concrete and, whilst being relatively unaffected by the presence of fibres, still gives a reliable indication of matrix quality of sprayed fibre-concrete. Cores also allow visual inspection and grading of sprayed concrete quality. Most countries have appropriate national standards.

In order that representative test specimens are obtained, in-situ coring is clearly superior to coring a test panel and it is also the only effective method which can be used to investigate specific areas for bond, compaction and other properties. However, most organisations allow compressive testing of cores extracted from test panels for routine quality control (some also permit sawn cubes). If this is done it is prudent to take test cores periodically from the completed work to ensure that the control tests reflect the quality of material in the structure.

Beam flexural strength and toughness

A beam flexure test is clearly a potential candidate as a quality control test for sprayed fibre concrete since it yields information on limit of proportionality and ultimate flexural strengths, as well as toughness. These are all important properties of fibre concrete and are affected by in-situ fibre content (see Sections 5.4 and 5.5). Both ACI Committee 544 (1988*b*) and EFNARC (1993) make reference to the ASTM (1992) C1018 toughness index method of measuring toughness from a beam load/deflection curve, although EFNARC have proposed a Norwegian style specimen geometry (125 × 75 × 600 mm on 450 mm span) rather than the UK/US size of 100 × 100 × 400 mm on a 300 mm span; EFNARC have also proposed a slab test on a 600 × 600 × 100 mm specimen. The Japanese Concrete Institute/JSCE (1984*c*) method for measuring flexural toughness is similar to the ACI method, although the toughness is expressed as a total area (in Nm), not an index based on area ratios. An important aspect of both the JSCE and ASTM methods is that beams are loaded at a constant rate of beam deflection (not crosshead movement) and that the bending deflections are measured net of support settlements. Only with these measures will correct and reproducible load/deflection curves be produced and hence toughness values. These issues are discussed further in Section 5.5 and by Austin and Robins (1993), Vanderwalle (1993) and Wood (1992).

However, beam and slab samples can only be obtained from test panels and the test method is considerably more complicated than a core test. Consequently, the

most likely application of flexural testing is as part of a preconstruction testing programme to check compliance with specified minimum strengths and toughnesses, and to determine the necessary associated in-situ fibre contents.

Core splitting

Concrete cores are really the only feasible test specimens that can be extracted from the hardened in-situ sprayed concrete. Because the core compressive test yields no useful information on the effects of fibres, two indirect tensile tests on cores have been investigated as potential quality control tests for sprayed fibre concrete: a core cylinder splitting test (Robins and Austin, 1985*a*) and a core point-load test (Robins, 1984 and Robins and Austin, 1985*b*). The splitting test investigated was similar to the standard cylinder splitting test for plain concrete described in BS 1881, but was carried out on 100 mm diameter cores. In the point-load test a core is placed between two conical loading platens and the compressive load required to split the specimen is recorded. An index of strength is calculated from the failure load.

The relationship between beam flexural strength and point-load strength is discussed in 5.4 where it is shown that core point-load strengths are sensitive to changes in fibre content and vary approximately linearly with flexural strength over the practical range of sprayed concrete strengths. The point-load test therefore has some merit as a simple quality control test and is discussed in more detail elsewhere (Austin and Robins, 1993).

Bond strength

An important property of all sprayed concretes is the bond strength between the sprayed concrete and its substrate. Without an adequate bond, a sprayed concrete layer is ineffective no matter what the quality of the concrete itself. In the past this has rarely been measured because of the lack of a suitable test; reliance was placed on soundness tests (like tapping). Suitable quality control test methods are now available, including the 'Limpet' core pull-off test (Long and Murray, 1984), in which a partially-cored specimen is pulled from its substrate in situ. The test was developed for repair materials (and will comply with the TC 104 proposed Euro-standard for concrete repair materials), but there are few published results for sprayed concrete.

CIRIA has recently published three technical notes on standard tests for repair materials, including one on pull-off tests (McLeish, 1993). This useful document describes relevant codes and standards, as well as the range of equipment available, and makes recommendations on good practice. Austin *et al.* (1994) have also reported on tensile bond testing of concrete, in particular on the influence of material properties, surface conditions, testing method and material mismatch.

Bond testing should form part of any significant sprayed concrete quality control programme and is being increasingly specified by conscientious engineers.

Other strength tests

The preparation of test panels and coring tests are time consuming and quite costly procedures. Simple in-situ tests which can be carried out frequently and relatively

cheaply would clearly be an attractive alternative, if any such tests could be shown to yield reliable and useful information on the strength properties of sprayed concrete.

Some success has been claimed for the Windsor Probe system (Littlejohn, 1980), a test method in which the penetration into the concrete of a hardened alloy steel bolt, fired from a gun, is measured. On the Dinorwig pumped storage scheme the use of a pull-out short bolt test was found by Waller (1980) to give quite a good correlation with core strength for concrete up to 25 MPa, beyond which the standard error increased.

The Lok and Capo pull-out tests have been investigated by Little (1985) for measurement of in-situ compressive strength of sprayed steel-fibre concrete, although the methods were found to be unsuitable for routine quality control testing.

Testing for properties other than strength

A number of organisations refer to the use of hammer tests, gamma radiography, rebound hammer and covermeter devices, and measurement of ultrasonic pulse velocity, which can be applied to sprayed as well as conventional cast concrete, although a rough or undulating surface may cause some difficulties.

Hammers or short steel bars are often used on site to sound the concrete to locate hollow areas, poor compaction, cracking, lack of bond, and similar problems. This is a crude but cheap and effective technique. In addition to strength testing, cores of in-situ sprayed concrete can be inspected for voids, sanding and lack of bond to the substrate, and allow verification of the thickness of the sprayed concrete layer.

The permeation characteristics of sprayed concrete are often important as they have a direct bearing on the concrete's durability. A sprayed concrete layer usually contains steel, in the form of bar or mesh reinforcement, fibres or rockbolts, and is therefore prone to steel corrosion as a result of carbonation or chloride ingress. Cores may be used for water absorption or intrinsic permeability determinations, these being of particular relevance with water-retaining linings. Simple in-situ surface permeability tests include the ISAT water test (BS1881, 1970) and Figg water and air tests (Figg, 1973 and Cather *et al.*, 1984), which can be carried out on sprayed concrete and the Concrete Society (1987) give suggested quality values. EFNARC (1993) have proposed the use of the ISO 7031 method.

References

ACI Committee 506 (1982) *Guide to Certification of Shotcrete Nozzlemen*. ACI 506.3R-82, American Concrete Institute, Detroit.

ACI Committee 506 (1983) Recommended practice for shotcreting. *ACI Standard 506-66*, American Concrete Institute, Detroit.

ACI Committee 506 (1990*a*) *Guide to Shotcrete*. American Concrete Institute, Detroit.

ACI Committee 506 (1990*b*) *Specification for materials, proportioning and application of shotcrete*. ACI 506, 2–90, American Concrete Institute, Detroit.

ACI Committee 506 (1994) Proposed Revision of: Specification for Materials, Proportioning, and Application of Shotcrete (ACI 506.2). *ACI Materials Journal*, **91**(1), 108–114.

ACI Committee 544 (1988*a*) Design considerations for steel fibre reinforced concrete. *ACI Journal*, **85**(5), 563–580, and as ACI 544,4R-88, American Concrete Institute, Detroit.

ACI Committee 544 (1988*b*) Measurement of Properties of Fiber Reinforced Concrete, *ACI Materials Journal*, **85**(6), 583–593.

ACI Committee 544 (1993) Guide for Specifying, Proportioning, Mixing, Placing, and Finishing Steel Fiber Reinforced Concrete. Committee Report ACI 544.3R, *ACI Materials Journal*, **90**(1), 94–101.

AFNOR (1992) *Engineering structures - Repair and strengthening of concrete and masonry constructions - Shot concrete - Specifications for techniques and materials used.* AFNOR, Paris.

AFTES (1992) *Recommendations on Sprayed Shotcrete: Technology and Practice.* Report of AFTES Working Group No. 6, Paris.

American Society for Testing and Materials (1989*a*) *C1141-89, Standard Specification for Admixtures for Shotcrete.* ASTM, Philadelphia.

American Society for Testing and Materials (1989*b*) *C1140-89, Standard Practice for Preparing and Testing Specimens from Shotcrete Test Panels.* ASTM, Philadelphia.

American Society for Testing and Materials (1989*c*) *C1117-89, Standard Test Method for Time of Setting of Shotcrete Mixtures by Penetration Resistance.* ASTM, Philadelphia.

American Society for Testing and Materials (1990) ASTM A 820-90, *Standard Specification for Steel Fibers for Fiber Reinforced Concrete.* ASTM, Philadelphia.

American Society for Testing and Materials (1991) ASTM C 1116-91, *Standard Specification for Fiber-Reinforced Concrete and Shotcrete.* ASTM, Philadelphia.

American Society for Testing and Materials (1992) ASTM C 1018-92, *Standard Test Method for Flexural Toughness and First-Crack Strength of Fiber-Reinforced Concrete* , ASTM, Philadelphia.

Amtsbüchler and Van der Weshuizen (1990) Shotcrete tests at the Fish Ecca tunnel. Proc. Engineering Foundation Conference *Shotcrete for Underground Support V*, Uppsala, Sweden, 213–23.

Association of Gunite Contractors (1976) *Code of Practice for the Spraying of Concrete by the Dry Process Otherwise Known as Gunite or Shotcrete.* AGC, London.

Austin, S.A. and Robins, P.J. (1993) Test Methods for Strength and Toughness of Sprayed Fibre Concrete. *Procs. International Symposium on Sprayed Concrete*, Norwegian Concrete Association, Fagernes, Norway, 7–19.

Austin, S.A., Robins, P.J. and PAN, Y. (1994) Tensile bond testing of concrete repairs. Accepted for publication in *Materials and Structures.*

British Standards Institution (1970) *BS 1881:Part 5 Methods of testing hardened concrete for other than strength*, BSI, London.

British Standards Institution (1985) *BS 8110 Structural use of concrete, Part 1: Code of practice for design and construction.* BSI, Milton Keynes.

Cather, R., Figg, J.W., Marsden, A.F. and O'Brien, T.P. (1984) Improvements to the Figg method for determining the air permeability of concrete. *Magazine of Concrete Research*, **36**(129), 241–245.

Concrete Society (1987) *Permeability testing of site concrete.* Concrete Society Technical Report No. 31. Concrete Society, London.

Concrete Society Construction & Formwork Committee (1979) *Specification for Sprayed Concrete.* Concrete Society, London.

Concrete Society Construction & Formwork Committee (1980) *Code of Practice for Sprayed Concrete.* Concrete Society, London.

Concrete Society Construction & Formwork Committee (1981) *Guidance on the Measurement of Sprayed Concrete*, Concrete Society, London.

Concrete Society Working Party on Fire Damaged Structures (1978) Assessment of fire-damaged concrete structures and repair by gunite. *Technical Report No.15*, Concrete Society, London.

DIN 18551 (1991) *Sprayed Concrete; Production and Quality Control.* Deutsches Institut für Normung, Berlin.

EFNARC Technical Committee Sprayed Concrete (1993) *'Draft specification for sprayed*

concrete'. European Federation of National Associations of Specialist Repair Contractors and Material Suppliers for the Construction Industry, Aldershot, UK.

Figg, J.W. (1973) Methods of measuring the air water permeability of concrete. *Magazine of Concrete Research*, **25**(85), 213–219.

Gebler, S. and Schutz, R. (1990) Is 0.85 f '$_c$ valid for Shotcrete? *Concrete International*, **12**(9) 67–69.

Hannant, D.J. (1978) *Fibre Cements and Fibre Concretes*. J. Wiley and Sons, Chichester.

Highways Agency of the Department of Transport (1994) *Draft Specification for the repair of concrete highway structures.* DOT, London, June.

Hills, D.L. (1982) Site-produced sprayed concrete, *Concrete*, **16**(12), 44–50.

International Tunnelling Association (1991) *Shotcrete in Tunnelling, Status Report.* BeFo, Swedish Rock Engineering Research Foundation, Stockholm.

International Tunnelling Associatio (1993) *Shotcrete for Rock Support, Guidelines and Recommendations - A Compilation.* BeFo, Swedish Rock Engineering Research Foundation, Stockholm.

International Tunnelling Association Working Group on Shotcrete Use (1993) Shotcrete for Rock Support: a Summary Report on the State of the Art in 15 Countries. *Tunnelling and Underground Space Technology*, **8**(4), 441–470.

Japan Society of Civil Engineers (1984*a*) Guideline for construction of steel fibre reinforced shotcrete. *Concrete Library of JSCE*, **3**, 31–39.

Japan Society of Civil Engineers (1984*b*) Recommendations for the design and construction of steel fibre reinforced concrete. *Concrete Library of JSCE*, **3**, 4–29.

Japan Society of Civil Engineers (1984*c*) Method of tests for steel fibre reinforced concrete. *Concrete Library of JSCE*, **3**, 45–74, also published by the Japan Concrete Institute.

Japan Society of Civil Engineers (1984*d*) Specification of steel fibres for concrete. *Concrete Library of JSCE*, **3**, 41–44.

Kirsten, H.A.D. (1992) Comparative efficiency and ultimate strength of mesh- and fibre-reinforced shotcrete as determined from full-scale bending tests. *J. S. Afr. Inst. Min. Metall.*, **92**(11/12), 303–323.

Kirsten, H.A.D. (1993) Equivalence of mesh- and fibre-reinforced shotcrete at large deflections. *Can. Geotech. J.* **30**, 418–440.

Kirsten, H.A.D. and Labrum, P.R. (1990) The equivalence of fibre and mesh reinforcement in the shotcrete used in tunnel-support systems. *J. S. Afr. Inst. Min. Metall.*, **90**(7), 153–171.

Kolf, P.R. and Gebler, S.H. (1993) Shotcrete application tolerances. *Concrete Construction*, **38**, April, 287–289.

Leah, N. (1993) Measurement of Sprayed Concrete. *Sprayed Concrete Seminar*, Sprayed Concrete Association, Brunel, 8 September.

Little, T.E. (1985) An evaluation of steel fibre reinforced shotcrete for underground support. *Canadian Geotechnical Journal*, **22**(4), 501–507.

Littlejohn, G.S. (1980) Wet process shotcrete. *Proceedings of Symposium on Sprayed Concrete* (CI 80), Concrete Society, London, April, 18–35.

Long, A.E. and Murray, A.McC. (1984) The pull-off partially destructive test for concrete. *In Situ Nondestructive Testing of Concrete (SP-82)*, American Concrete Institute, Detroit, 327–350.

Lub, K.B. and Van Wanroij, M.C.G. (1989) Strengthening of reinforced concrete beams with shotcrete-ferrocement. *Journal of Ferrocement*, **19**(4), 363–371.

Mangat, P.S. and Gurusamy, K. (1987) Flexural strength of steel fibre reinforced cement composites. *Journal of Materials Science*, **22**, 3103–3110.

McLeish, A. (1993) *Standard tests for repair materials and coatings for concrete.* CIRIA Technical Note 139, Construction Industry Research and Information Association, London.

Morgan, D.R. (1990) Advances in shotcrete technology for support of underground openings in Canada. Proc. Engineering Foundation Conference *Shotcrete for Underground Support V*, Uppsala, Sweden, 358–82.

Morgan, D.R. and McAskill, N. (1984) Rocky Mountain tunnels lined with steel fibre rein-

forced shotcrete. *Concrete International*, **6**(12), 33–38.

Norwegian Concrete Association (1993) *Sprayed Concrete for Rock Support - Technical Specification and Guidelines*, Committee Sprayed Concrete, Publication No.7, NCA, Oslo.

Robins, P.J. (1984) Point-load test for tensile strength estimation of plain and fibrous concretes. *In Situ Nondestructive Testing of Concrete (SP-82)*, American Concrete Institute, Detroit, 309–325.

Robins, P.J. and Austin, S.A. (1985*a*) Melt extract fibre reinforced sprayed concrete. *Composite Structures 3: Proceedings of the 3rd International Conference on Composite Structures*, Elsevier Applied Science, London, 242–253.

Robins, P.J. and Austin, S.A. (1985*b*) Core point-load test for steel fibre reinforced concrete. *Magazine of Concrete Research*, **37**(133), 238–242.

Sprayed Concrete Association (1986) *Code of Practice for Wet Process and Dry Process Sprayed Concrete*, SCA, London.

Sprayed Concrete Association (1994) *Guide to Certification of Sprayed Concrete Nozzlemen*. SCA, Aldershot.

Swamy, R.N. and Mangat, P.S. (1974) Influence of fibre geometry on the properties of steel fibre reinforced concrete. *Cement and Concrete Research*, **4**, 452–465.

Uomoto, T. and Kobayashi, K. (1984) In situ test to determine fibre content of steel fibre reinforced concrete by an electro-magnetic method. *In Situ Nondestructive Testing of Concrete (SP-82)*, American Concrete Institute, Detroit, 673–688.

Vandewalle, M. (1993) Steel fiber reinforced shotcrete design requires a uniform toughness criterion. *Procs. International Symposium on Sprayed Concrete*, Norwegian Concrete Association, Fagernes, Norway, 455–464.

Wallace, M. (1987) Wet shotcreting just got better. *Concrete Construction*, **32**(11), 965–967.

Waller, E. (1980) Dinorwig tunnels and caverns. *Proceedings of Symposium on Sprayed Concrete* (CI 80), Concrete Society, London, April, 36–51.

Wood, D.F. (1992) Specification and application of fibre reinforced shotcrete, *Procs Int Symposium on Rock Support in Mining and Underground Construction,* Ontario, 149–156.

Wood, D.F., Nickel, G.B. and Borch, N.G. (1989) Developments in the use of shotcrete for tunnel support. *Proc. of International Congress on Progress and Innovation in Tunnelling*, Toronto, Canada, 1: 439–447.

7 Design for Structural Application

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7.1 Introduction

Concrete is possibly the most versatile material used in construction. By spraying the concrete, instead of pouring it between shutters, even greater flexibility in design and application can be obtained. In new works, sprayed concrete has established its place in construction's toolkit.

Sprayed concrete is also used successfully in repair. Comprehensive repairs to eradicate the cause of damage, as well as repairing the damage itself are becoming the norm. Such a strategy dictates the use of a durable repair material suitable for application to extensive areas; a use for which sprayed concrete is well suited and where other types of repair material have proved inadequate.

This chapter outlines the many benefits of sprayed concrete for the designer of new works and repairs. Guidelines for both structural and detailed design are given together with a consideration of specification. Under each subject area, the chapter deals first with new structures and then existing structures (i.e. repair). It is not intended that the sections on repair stand-alone since much of the content under new structures is also applicable.

7.2 Choice of material and method – new structures

Cast-in-place vs. sprayed

The traditional cast-in-place process for creating a reinforced concrete structure comprises:

- the creation of a formation/kicker
- the fixing of the steel reinforcement
- erection of shutters or formwork
- pouring the fluid workable concrete mix
- vibration to ensure good concrete compaction and steel encapsulation.

This is the process with which the construction industry has come to feel comfortable, so one may ask why do anything else? There are instances when spraying concrete into position can free the designers from the restrictions placed upon them by more conventional practice. The inclusion of bar or fibre reinforcement will ensure that the same structural product is achieved, whilst benefits can be gained in durability and aesthetics through the use of the sprayed concrete process.

The advantages that sprayed concrete has to offer over cast-in-place are:

The construction of free form designs
Because of the flowable nature of conventional concrete, the designer is constrained by the need for substantial shutters to all faces inclined at angles greater than about 30° from the horizontal. There are also the associated difficulties of compaction. Sprayed concrete comes into its own where unusual shapes are required, because often only a rear shutter is necessary. With full access to the front face, its form can take any profile that the designer chooses.

Reduction or elimination of shuttering
The costs of a conventional concrete pour can generally be divided into; formwork, steel-fixing, concrete materials and placing costs which vary with the shape and thickness of the pour, quantity and degree of steel-fixing, and access. Formwork accounts for between 25–55% of this cost (Cooke, 1990) thus substantial savings can be made if the extent of formwork can be reduced or even eliminated. Sprayed concrete does not require a front shutter and any rear shutter can be less substantial than for conventional concrete because the stiff nature of placed sprayed concrete means lower horizontal forces are produced.

High quality concrete
The very act of spraying concrete into place with some force produces dense, homogenous concrete. Of course it is possible to produce conventional concretes to very high specification with certain additives and a stringent curing regime. However, a well placed sprayed concrete will probably out-perform the average conventional concrete on a number of counts. Sprayed concrete is usually rich in cement, due in part to the rebound which consists mostly of aggregate. In addition, low water/cement ratios are easily achieved. These two properties can result in a dense concrete with a high strength and low permeability. Such a material is particularly suited to the construction of thin shells and similar structures.

A further benefit is the high abrasion resistance of sprayed concrete which can be enhanced by the use of special aggregates. For example, the fines can be made up of one part iron filings to two parts crushed rock, sand or graded blast-furnace slag. Certain proprietary aggregates produced as by-products of the cement manufacturing process give high abrasion resistance.

Efficient construction
Spraying concrete is an efficient method of placement because large volumes can be placed in a short time, particularly for large areas requiring relatively thin layers. In addition, labour is reduced since the placed concrete does not need compaction and often finishing is not required.

Unusual finishes can be achieved
The stippled as-sprayed finish can make a pleasant change from the flat featureless cast finish that shuttering leaves. There is aesthetic gain through the elimination of problems such as honeycombing, blow-holes, cold joints and tie holes. There is also scope for the addition of features after spraying, by careful use of the trowel (or

other means) on the exposed face whilst the concrete is still workable.

Difficult access problems are overcome
Because both wet and dry sprayed concrete is conveyed through a hose to the works site, the delivery/mixing equipment can be some distance away. With the right equipment and concrete mix, delivery hoses can be as long as 300 metres horizontally and 100 metres vertically.

Thermal stresses in thick sections can be reduced
Sprayed concrete is usually placed in layers with a thickness appropriate to the mix workability and face inclination. By the careful application of several layers, thermal stresses in thick sections can be minimized. Where accelerators are employed, allowance should be made for a possible associated enhancement of hydration heat.

Good bond between layers
The spraying process uses a high placement velocity which gives good bond, provided that the substrate has been prepared properly. Voids are also filled effectively by this method.

The disadvantages of sprayed concrete over cast-in-place are:

Variable concrete quality
Because the quality of the placed concrete is highly dependent on the skill of the operator, there is considerable scope for problems such as variations in concrete composition leading to non-uniform strength and durability characteristics, voids and poor bond between layers and poor encapsulation of reinforcing bars.

Labour intensive finishing
Unless an as-sprayed finish is required, the finishing of sprayed concrete is a time consuming and skilled activity.

High cost
It will be necessary, for each application, to compare the cost of sprayed concrete with conventional concrete. Factors to note when considering sprayed concrete are the higher costs of a cement rich concrete and chemical admixtures, the wastage of material from rebound and the need for specialist plant with back-up, and skilled labour. In addition, greater effort will prove necessary in quality control testing, to ensure a satisfactory finished product.

Typical uses for sprayed concrete

Sprayed concrete has been used successfully by engineers and architects to capitalize upon the benefits it offers over conventionally placed concrete. The uses can be divided into the following categories:

Free form designs
Applications where irregular curved shapes are required include swimming pools



Figure 7.1 *Sprayed concrete used to form structural lining for outdoor swimming pool* (Courtesy Tarmac Structural Repairs).

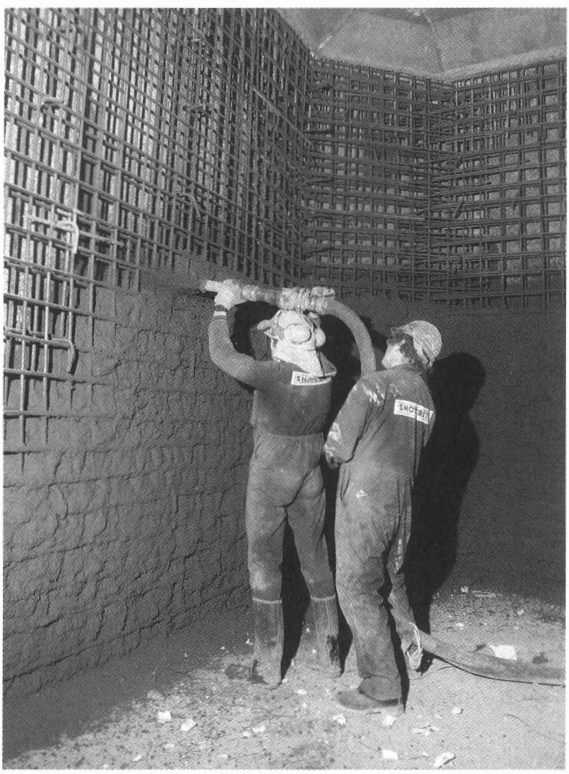

Figure 7.2 *Structural basement lining to piles* (Courtesy Sprayed Concrete Ltd.).

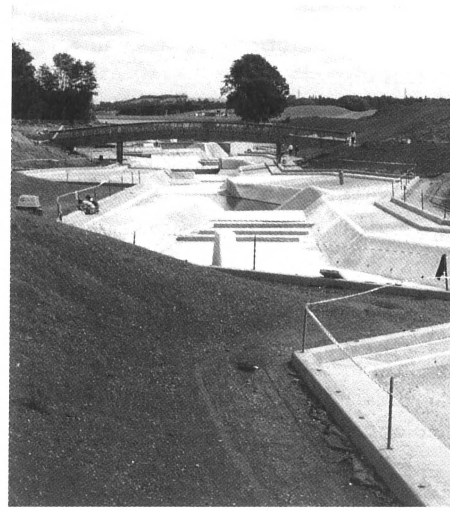

Figure 7.3 *Sprayed concrete used to line a canoe slalom course* (Courtesy Sprayed Concrete Ltd.).

(Figure 7.1), landscaping, marina mooring pontoons, canoe slalom courses, climbing walls, animal enclosures and theme parks.

Structural elements

Roofs can be made thinner and to more intricate shapes than is possible with conventionally compacted concrete. Shapes such as hyperbolic paraboloids, domes and barrel vaulting can be achieved. In addition, sprayed concrete can be used in applications such as squash-court walls where a final render coat provides the necessary close texture giving a very even surface.

Sprayed concrete is used increasingly in conjunction with diaphragm retaining walls and bored-pile walls. After the walls have been exposed on excavation and cleaned off, sprayed concrete is used for the facing (Figure 7.2). A minimum thickness of 150 mm will produce a smooth water-resistant, durable surface.

Protective coatings

Sprayed concrete is used as a fireproofing material, especially in chemical plants and oil refineries. Design is covered by BS 8110 (1985). The material can also provide effective corrosion protection for steelwork, for example steel pile walls, bunkers, silos and pipes and it can protect embankments, watercourses and dams from erosion.

Water-retaining structures

In the water industry sprayed concrete is used widely for the provision of both structural linings and protection. Reservoirs and other water-retaining structures such as sea walls, arch dams, aqueducts, swimming pools, storage tanks, lakes, water towers, sewers, canals, boats, drainage and irrigation channels and pleasure park water-retaining structures (Figure 7.3), can be lined successfully using sprayed con-

crete. The sides, which often slope, and the thin sections lend themselves to sprayed concrete, particularly in remote locations. For small reservoirs a circular wall is usually economical. In this instance, lightly reinforced sprayed concrete walls are cast against a shutter with wire wound around the outside which is stressed during winding. The wires are then covered by a second layer of sprayed concrete.

Security
Prison walls, bank vaults and blast proof structures can all make good use of sprayed concrete.

Choice of placement method

Chapter 4 describes the two methods for conveying sprayed concrete to the work site (the wet and dry processes). Careful consideration should be given prior to selection for any particular project.

Wet process
The wet process is most suitable where spraying as a continuous process is necessary because greater production is possible with greater economy overall. Mixing water is controlled at the delivery equipment and can be measured accurately ensuring that it is mixed thoroughly producing a more homogenous concrete of consistent quality. Steel fibres are also more easily incorporated into a wet mix. Compared to the dry process, less dusting and cement loss accompanies the gunning operation, making for better working conditions and suitability in situations in close proximity to the public. Additionally, rebound is less, resulting in less material waste.

Dry process
The dry process allows instant control over mixing water and the consistency of the mix at the nozzle, making it more suitable than the wet process for variable conditions. It is also better suited to situations where continuous placement is not possible. The dry material is also capable of being transported longer distances (the dry process is usually preferred where access is a problem) and is better suited for placing mixes containing lightweight aggregates.

7.3 Choice of material and method - existing structures

Inspection and investigation

Reinforced concrete structures are capable of achieving their design lives (which can be 120 years or more) provided that they are designed, constructed and maintained correctly. However, poor detailing, shoddy workmanship or lack of maintenance, combined with aggressive exposure conditions all too frequently lead to premature deterioration.

Concrete itself is a very durable material provided that due care is given to specification and production. Problems most often arise because there is a need to embed reinforcement. The material most commonly used for this purpose is steel bar which, unless protected properly, will corrode. Due to its high alkalinity (pH generally in the order of 12–13), concrete provides the perfect protection for steel. It

passivates the embedded steel, preventing it from corroding. However, should this passive layer be disturbed in any way then protection to the reinforcing steel is lost and the bars start to corrode. The three most common causes of reinforcement corrosion are; chloride attack, carbonation and poor quality concrete. There are a number of other reasons, however, why concrete may require repair, such as damage from impact or overload, fire damage, inadequate provision of cover, sulphate or other chemical attack, stray or induced current corrosion or frost damage.

It is necessary to be very clear why repairs are being carried out in order to select the most appropriate remedy. The decision to repair may be taken when:

- structural integrity is impaired;
- serviceability of the structure is affected; or
- damage becomes aesthetically unacceptable.

To ensure a repair to a structure is durable and effective, it is necessary to carry out an investigation to establish the cause and extent of the deterioration. A brief initial inspection to identify the likely causes and to assist with planning should precede any investigation. The investigation itself may include a combination of destructive and non-destructive tests and reference should be made to the relevant standards which give guidance on methods of testing concrete. It then remains to select the most appropriate method of repair for the particular circumstance.

Sprayed concrete in repair

There are five types of repair material, defined by placement method.

(i) Concrete – Concrete placed in a conventional manner behind shutters is an economic choice where large volumes are to be replaced. The finished product will be highly compatible with the substrate.



Figure 7.4 *Sprayed concrete is suited to the repair of large areas* (Courtesy Tarmac Structural Repairs).



Figure 7.5 *Repair of a cooling tower* (Courtesy Tarmac Structural Repairs).

(ii) Hand/trowel placed – A thixotropic repair material placed and compacted by hand or trowel. This is a labour intensive method suitable for small repairs and not requiring highly skilled labour. A variety of materials are available, from cementitious to resins.
(iii) Flowable – A fluid repair material is poured into a shutter through a funnel and pipe. Substantial shuttering is required but encapsulation of reinforcement is obtained. It is a fast placement method once shuttering is in place.
(iv) Flood grouting – A highly fluid grout poured through pre-placed single size aggregate. This is suitable only for horizontal top surfaces where very rapid placing is required with the minimum of batching and mixing equipment.
(v) Sprayed – Wet or dry mix concrete delivered to location by spray-line. Sprayed concrete in repair is best suited to relatively large, soffit or vertical repair areas (Figure 7.4). Otherwise, the advantages of sprayed concrete over other materials are largely as described in Section 7.2, with the following additions specific to repair work:

- sprayed concretes are cementitious and will therefore provide good material and structural compatibility with the concrete substrate and will provide a protective alkaline environment for the reinforcing steel.
- thick layers are more easily built up than with hand placed materials.
- good bond is obtained to appropriately prepared concrete substrates.
- the relatively low water/cement ratios achievable lead to low shrinkage.

The disadvantages already described in Section 7.2 also apply to sprayed concrete in repair. In addition, where there is a heavy concentration of reinforcement, sprayed concrete is not advisable because shadowing around reinforcing bars may jeopardize protection. If unavoidable, however, a grout sprayer should be used to get the mix around and behind the bars.

Typical applications for sprayed concrete in repair

Because of the very distinct advantages of sprayed concrete over other types of repair material there are specific applications where sprayed concrete is naturally the first choice.

Repair of structures where access is difficult
As explained previously, sprayed concrete is the ideal choice of material where large volumes of material need to be placed at height, such as in chimneys, high-rise buildings or cooling towers (Figure 7.5). It is also suitable where access is difficult such as tunnel inverts, inside service reservoirs, inside small diameter pipes/tunnels (sewers, water pipes, etc.). Entry is often gained through a manhole/hatch some distance from the repair site and repair concrete delivered through a hose is the only practical option. (*Safety Note: When working at height or in confined spaces, special consideration needs to be given to safety.)*

Strengthening of concrete structures
Sprayed concrete is suitable for use in strengthening because of its ease of placement to large, relatively thin areas and around reinforcement without shuttering. It is suitable for use on soffits and beams, particularly for the upgrading of bridges (assuming sufficient headroom) and structural linings.

The existing concrete surface should first be scabbled or water-jetted to provide a rough surface for good bond of the sprayed overlay. Reinforcement, usually mesh, is fixed to the concrete surface so that no movement is permitted under the force of the spray. Stainless steel mesh may be used in particularly aggressive environments or where full cover to the mesh cannot be provided. In this case, non-metallic fixings to the existing concrete should be employed to avoid any bi-metal-

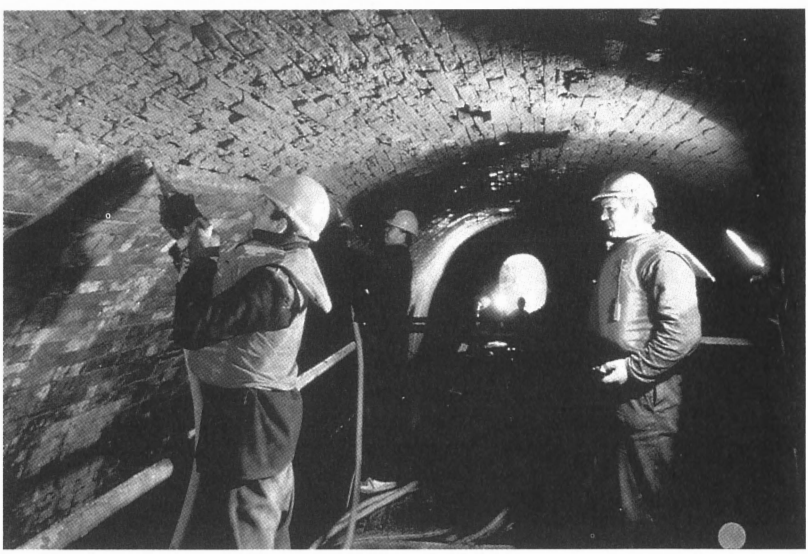

Figure 7.6 *Repair of a brick tunnel* (Courtesy Tarmac Structural Repairs).

lic corrosion between the mesh and the existing reinforcement. Sprayed concrete can also be used for covering external post-tensioning cables e.g. to strengthen/ stress a T-beam.

Repair of masonry structures
Repair to masonry structures is often required due to the disintegration or washing out of the mortar. Because of the many joints, re-pointing is very labour intensive and a layer of sprayed concrete provides a quick way of filling voids and joints and sealing the masonry. Sprayed concrete is often used for strengthening masonry arches in bridges, tunnels (Figure 7.6), reservoirs and sea walls.

Retaining walls
Retaining walls can be repaired and strengthened by applying a layer of reinforcing mesh to the front face of the wall and drilling ground anchors through to sound ground which are then connected to mesh. Weep pipes are then installed and the front face of the wall covered by sprayed concrete. The embankment can then be grouted to fill any voids.

Repair of fire damaged concrete
Large volumes of high early-strength sprayed concrete can be placed in a short space of time. This makes the method particularly appropriate to the repair of fire damaged structures where there may be a risk of collapse.

'Waterproofing'
Concrete is not a 'waterproof' material (Johnson, 1994*b*) but it can be designed to be highly impermeable to water. Sprayed concrete is a particularly dense product and can provide a water-resisting layer when applied to surfaces of cracked concrete, construction joints or masonry such as dams and basements.

Cathodic protection overlays
Because of the material's excellent adhesion properties and ease of application in thin layers, sprayed concrete is in regular use in overlays to cathodic protection anode meshes.

Choice of placement method

The two different methods of placing sprayed concrete have already been described in Section 7.2. The move over the last 5–10 years to correctly formulated repair mortars has meant that sprayed concrete in repair is usually the pre-bagged formulated proprietary product, either as wet or dry mix. This provides the benefits of

- polymer additives to improve bond to the substrate,
- shrinkage compensation,
- cement replacement carefully blended to provide a dense, impermeable concrete,
- uniform quality for small batches,
- ability to spray small batches with minimal waste,
- pre-determined performance characteristics, and
- no need to design the mix.

7.4 Structural design – New structures

General

There is nothing mystical about the structural design of sprayed concrete which, save for the method of placement, is essentially the same as conventional concrete. It is also reinforced in the same manner, using either steel bars/mesh or fibres. Reinforced sprayed concrete structures should therefore be analysed in accordance with elastic theory as for normal concrete (JSCE, 1984) and the same codes of practice/standards used for design e.g. in the UK, BS5400 for bridge design and BS8110 for structures. However, there are certain practical considerations that apply specifically to sprayed concrete which should be noted when designing.

Concrete material

Because of the placement method there are certain properties of sprayed concrete which may have an effect on the structural design. A dense concrete with high strength and low permeability is easily achievable, benefitting situations where slenderness of section is desirable, such as the construction of thin shells. Cover to reinforcement may be reduced, or where the material is acting as a water-resisting layer, a thinner layer may provide adequate watertightness. It is important, however, that such properties are not assumed without extensive permeability testing both on the design mix and on samples taken from the finished work.

The compressive strength of a material placed in layers, however, may not be isotropic i.e. possibly stronger in the direction of spraying.

Bar and steel mesh fabric reinforcement

Reinforcing bars are an inconvenience to be avoided where possible. This is because they form an obstacle lying between the nozzle and the back surface of the work that not only has to be sprayed around, but can prevent good compaction immediately behind the bars. As a general guide, and where the application is not structural, reinforcement is not required when the layer thickness is less than 25 mm. Greater than that and reinforcement should be incorporated to control shrinkage cracking, with adequate cover to the reinforcement (BS 8110, 1985).

The design of the reinforcement becomes a practical rather than academic problem in that bar diameter and spacing need careful consideration. Generally the work area should be designed to allow for good placement of concrete around the reinforcing steel and to minimize rebound from congested reinforcement.

Reinforcement type

Because sprayed concrete is suitable for use in large, relatively thin areas, the obvious choice of reinforcement is often steel mesh. The mesh is intended to hold the sprayed concrete layer together in the event of cracking or debonding from the substrate. Meshes should be light enough for ease of handling and fixing but should be sufficiently rigid to prevent vibration during placement of the sprayed concrete. However, combinations of small bars and mesh are used where mesh alone would not be adequate structurally, and where uniform spacing and cover are critical, as in

curved and irregular surfaces. Reinforcing bars should ideally be smooth, as deformations can hamper the flow of the concrete around the back of the bar. However, there may be greater advantage in using a smaller area of deformed bars.

Bar diameter and spacing
Typically meshes are 75 mm × 75 mm or 100 mm × 100 mm with a wire diameter around 3 mm or 4 mm, giving a steel area of about 95 to 130 mm^2/m. A mesh size less than 50 mm is not advisable due to increased rebound. As a general guide, (although section thickness, depth of cover and aggregate size will have a bearing) maximum bar diameter should be limited to 25 mm and clear spacing between parallel bars including laps, should be at least four times the bar diameter or 50 mm, whichever is the greater. The back cover to the rear reinforcement should be at least three times the bar diameter or 40 mm whichever is the greater.

Fibre reinforcement

Sprayed concrete that is reinforced conventionally can be further improved by the addition of fibres to the mix. However, the risks of shadowing behind bars and corrosion leading to concrete spalling in aggressive environments no longer arise if bar reinforcement can be eliminated altogether.

At the extremities of a concrete section, fibres can provide concrete with a tensile strength, where reinforcing bars cannot. Fibres eliminate the sometimes considerable steel fixing effort required to accommodate irregular shapes and provide concrete with a significant improvement in toughness. Other benefits of fibres include a higher resistance to abrasion, a reduction in crack widths and a possible reduction in the thickness of the section, with obvious savings in time and materials.

Fibres for concrete are manufactured from many different materials; steel, polypropylene, aramid, glass, polyacrylonitrile, acrylic and polyvinyl alcohol. Steel, polypropylene and glass are the most common fibres used in sprayed concrete. Of the three, steel fibres account for the largest usage, having applications in mine and tunnel linings, rock slope stabilization, thin dome construction, refractory linings, dam construction, repair of surfaces and fire protection coatings. Glass fibre reinforcement is less common, principally because of the concern over long term durability. The use of polypropylene in dry process spraying is more recent but applications include tunnel linings, shell domes and repair.

Steel fibres
The length and aspect ratio (fibre length/diameter) of steel fibres is important both for performance of the concrete and sprayability. Short fibres are easier to shoot but long fibres produce better mechanical properties within the hardened concrete. A mid-range of fibre length is generally used, 18–30 mm, with 20 to 25 mm being the most common. Fibre length should be less than 70% of the internal diameter of the spray hose unless a test has proven that longer fibres can be sprayed without blockage. Optimum aspect ratio for spraying is 50–65. Higher ratio fibres are more difficult to spray but yield better properties in the hardened concrete.

Fibre content is measured in kg/m^3 (of concrete). As a general rule, mechanical properties of the hardened concrete improve with increased dosage level, but ease of spraying decreases. Fibre contents vary from about 40 up to about 150 kg/m^3. If

durability is a consideration, then stainless steel fibres are available. (The specification of steel fibres is covered in depth by ASTM A820-90.)

There are also certain disadvantages associated with steel fibres. Firstly, the sprayed surface is very rough as the fibres tend to protrude to a certain extent. If the completed surface is in a location where people may brush past then it should be dressed to avoid scratching. Secondly, the fibres tend to rebound more than the material as a whole, values in the range 15–60% being reported. In-situ testing of fresh concrete is therefore vital to determine in-situ fibre content.

Polypropylene fibres

Polypropylene fibres have certain advantages over steel fibres. They are lighter to handle and are easier to pump because they have a lubricant effect within the mix. In place, they can help reduce plastic cracking during the first 12 hours after placement when the concrete is most vulnerable to external stresses. Furthermore, they will not corrode.

However, associated disadvantages are that they give the concrete a lower abrasion resistance than steel fibres and they have poor bond with the concrete matrix. From the point of view of performance, they do not significantly improve mechanical properties unless added in large quantities. Polypropylene fibres are available in lengths of around 5 mm to 50 mm with a cross section in the order of 120 × 20 microns. A conventional mix would contain about 0.1% by volume.

There are few data available on the rebound of polypropylene fibres, however, 35–40% has been measured on site when spraying a 35 mm thick mortar layer.

7.5 Structural design – Existing structures

Assessment of structure

One of the reasons for repair is to reinstate the structural integrity of the element lost through damage, whether the damage is due to chemical or mechanical agents. If load capacity is of importance then the structure should be assessed in the damaged condition.

The first step in this process is to take detailed measurements of the damage, including loss of concrete section, reinforcement section and anchorage to the reinforcing bars. Overall configuration of the damage with respect to supports, joints and other structural details is also important. The structural assessment will need to account for such factors in arriving at a reduction in capacity.

Guidelines on the assessment of bridges are given by Department of Transport Departmental Standard BD 24/84 (HMSO, 1993). Basically, structures are deemed capable of carrying the assessment load when the assessment resistance is greater than or equal to the assessment load effects, with the respective factors applied.

The assessment may need to be extended to the case where all the cutting-out for repair has been undertaken. This may be extensive. The current guidelines in the UK given by the Department of Transport, Specification for Highway Works (August 1988), allow a maximum total chloride content (expressed as % of total chloride ion by weight of cement) of 0.1%, 0.2% or 0.3% depending on structure and cement types. Even where chlorides are not as high, or carbonation is present, if the reinforcing steel has been exposed to any great extent then the concrete should

be cut back to at least 25 mm behind the bars to provide a good key for the repair material. Fire damage to concrete can lead to micro-cracking beyond the depth that is apparently damaged. This can only be established by taking cores and subsequent inspection in a laboratory. Any micro-cracked concrete must be removed as it will lead to a reduction of bond between the repair material and the substrate.

The assessment of loaded structures may lead to the conclusion that either the loading should be restricted or that propping should be installed.

Design of sprayed concrete repair

Having assessed the structure and concluded that repair is necessary and that sprayed concrete is the most appropriate repair material, it is necessary to design the repair to reinstate a load capacity appropriate to the level of current and likely future loading.

Reinforced concrete structures

Only limited research has been undertaken in the structural design of repairs and many questions remain concerning the load carrying capacity of a repaired section and the benefits of propping in transferring load into the repair material.

Research has proven that for a repair to carry a load equal to the parent concrete the modulus of elasticity of the two must be the same. Where there is a mismatch, more or less load will be attracted to the repair depending on whether the modulus of the repair material is greater or less than that of the concrete (Austin and Robins, 1993). Other factors which will affect the structural performance of a repair are total shrinkage/expansion, creep and bond strength.

Repair to beams is unlikely to affect ultimate strength significantly, will probably increase the flexural strength and make it more ductile, will reduce the bending moment at onset of yield of reinforcement and will increase deflections. Similarly for columns, a repair is unlikely to affect ultimate strength significantly and will result in slight column shortening. Repairs of most concern in columns would be those to one or two faces only, where differing mechanical properties may effectively introduce an eccentricity of loading into the column. It has also been shown that propping of a structure during repair does not affect ultimate capacity of the repaired section although deflections may be reduced (Cairns, 1992).

Where reinforcement is concentrated then full encapsulation of the reinforcement may not be achieved leading to local diminution in strength.

Steel structures

Reinforced sprayed concrete can be used to strengthen corroded steel beams. Firstly, full measurements should be made of web and both flanges and capacity calculated. The reinforcement must be designed not only to compensate for the loss of area through corrosion, but also to compensate for the weight of the encasement. If the beam is to be strengthened above its original value then the upper flange compression area will have to balance any extra tension steel laid on the bottom flange, in order to maintain the neutral axis. Web buckling must be assessed and bearing areas and shear flanges examined at the supports.

7.6 Detailed design - New structures

General

As for any new design, there are a number of factors which, if thought through at the design stage, will save time and money once the project reaches site. The success of any sprayed concrete work depends largely on the skill of the nozzleman. Adhering to the correct operating procedures will enable the nozzle handler to carry out the work speedily and efficiently to produce a first class job to the correct specification. Another general consideration is to allow for rebound and over-spray both in mix design and site procedures. Rebound is discussed in Section 7.8.

Durability

The limit of durability is reached when an item fails to perform, or unacceptable expenditure on maintenance is necessary to sustain its performance. In order to predict the durability of an item, it is necessary to identify the factors that are likely to have an effect, to measure the extent of their effect and the time for deterioration to reach the durability limit.

A durable product can be achieved by careful specification backed up by compliance testing. Careful consideration should be given to chloride, alkali, and air contents, water/cement ratio, cement content and cover to reinforcement. In addition, performance characteristics can be specified such as frost resistance, diffusion resistance to chloride ions, permeability and abrasion resistance. The impermeability of sprayed concrete in thin layers can be improved by the addition of polymer emulsions.

Surface preparation

Correct preparation of the surface which is to receive the sprayed concrete is important for a number of reasons. Too much dirt or contamination will prevent the sprayed concrete from adhering properly, so making spraying difficult, wasting material and giving a poor quality finish to visible surfaces. Dry surfaces should be pre-wetted to ensure full hydration of the sprayed concrete at the interface.

When applying material onto earth surfaces, retaining walls and other surfaces which may suffer from water seepage or infiltration, the surface should be sealed, using drainage channels if necessary, to ensure good adhesion and prevent washing out of fines. In addition, earth surfaces must not be frozen or spongy. To prevent excessive absorption of mixing water from the sprayed concrete the earth should either be pre-wetted, if suitable, or lined with properly fixed polythene sheet. If good adhesion to soft earth is desirable then the surface should be sprayed first with a layer of grout before applying the concrete, to prevent separation from the substrate.

Reinforcement fixing

Careful specification of reinforcement fixing requirements is prudent to ensure that the bars are eventually positioned where they are required structurally.

It is usual to spray an initial layer on to the substrate before placing the mesh.

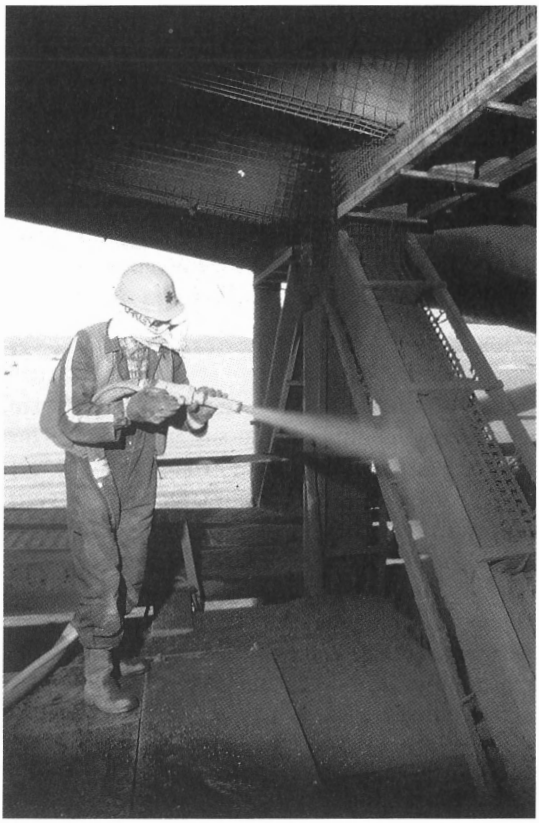

Figure 7.7 *Use of profile guides for line* (Courtesy Tarmac Structural Repairs).

This makes it easier to fix the mesh, reduces rebound and ensures better adhesion (Cooke, 1990). Where more than one layer of reinforcement is incorporated, bars in each face should be in line. It may then be preferable to spray over the rear layer of reinforcement prior to fixing subsequent layers.

Dimensioning

Accurate placement of sprayed concrete to line and level is achieved through the use of 'profile guides', rigidly fixed timbers or stretched wires (Figure 7.7). Fine details and sharp returns are not advisable in sprayed concrete but where required, particular attention should be drawn to them in the specification as they will require careful attention during placing.

A tolerance of ±10 mm over a 3 metre length is readily attainable on plane surfaces. Where smaller tolerances are required, and where the concrete has not been accelerated, sprayed concrete can be placed proud of the required alignment, carefully cut back with a timber straight edge and finished with a wooden trowel. Layers are typically 50–100 mm thick with, say, the first layer being 50 mm and the

subsequent ones 100 mm. The addition of fibres permits greater layer thicknesses and with silica fume added, layer thicknesses may be increased to 250–300 mm.

Joints

The nature of sprayed concrete application usually results in fewer construction joints than in placing of conventional concrete. Where possible it is desirable to avoid square ends, because they form a trap for rebound. However, where the joint will be subjected to compressive stresses, square joints perform most effectively, in which case trapped rebound at the joint must be removed. Prior to the application of material the entire joint should be thoroughly cleaned and wetted as is good concrete practice. The high bond characteristics of sprayed concrete mean that the installation of a water stop may be avoided. Where the specifier considers that a water stop is necessary, the contractor's advice should be sought prior to the commencement of work to ensure suitable fixing, the achievement of good bond and the avoidance of potential rebound traps.

Contraction joints may be provided by the pre-positioning of full thickness strips, usually wood or steel, which are left in place, or by saw cutting the sprayed concrete shortly after it has achieved its final set. Alternatively a channel formed in the wet concrete subsequently filled with a jointing compound may be adequate. For potable water structures, it should be noted that materials used in joints need to comply with the requirements of regulation 25 of the Water Supply (Water Quality) Regulations, 1989.

Finish

The cement-rich top layer of sprayed concrete can be prone to shrinkage cracking. If the surface is to be left undisturbed, it is standard practice to brush the surface with a soft plasterer's brush about one hour after placing; this will remove adhered rebound dust and prevent crazing. The surface achieved is known as an 'undisturbed nozzle finish'. Trowelling to obtain a flat surface true to line calls for a certain amount of expertise in determining 'false set', at which time the top layer can easily be cut and the excess will crumble away quite easily. The surface can be left rough, or finished off either by brushing, floating or a flash coat (which is also a useful curing aid). For fine finishes a top flash coat up to 6 mm thick is applied over the main work. The flash coat can be coloured and should contain a fine sand.

Safety

The designer/specifier has certain obligations with respect to safety of the site operation. Under the Health and Safety at Work Act, consultants are required to do "what is reasonably practicable" for safety. From October 1994, consultants and clients were given greater responsibility under EC directives in the form of the Construction (Design and Management) Regulations. These will require the nomination of persons to safety roles, both at the design and construction stages. It will also be necessary to formulate a safety plan, which must be initiated during the design stage of the scheme. Under the usual construction conditions of contract, the designer/specifier has a definite obligation to have considered all aspects of safety in the design e.g adequate site investigation, safe permanent works.

The HSE regulations are applicable to sprayed concrete as with any other construction work, but special precautions should be taken. It should be remembered that the technique involves working with compressed air and spraying concrete at high velocity on to a surface only a few feet away from the operator. Rebound presents additional hazard as it can reach speeds approaching 100 km/h and clearly the nozzle handler should wear protective clothing. Ventilation and lighting must be adequate.

7.7 Detailed design - Existing structures

Many of the items covered in section 7.6 are also relevant to the use of sprayed concrete in repair and this section develops these points with the emphasis on repair.

Durability

There are two aspects to consider when assessing the durability of a repair; the repair itself and the effect of the repair on the structural element.

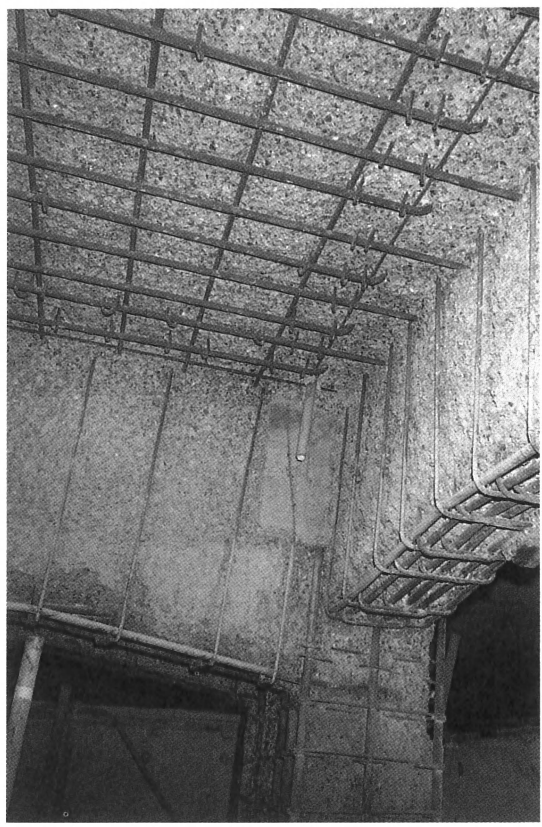

Figure 7.8 *Exposed reinforcement will provide an adequate key for a repair layer* (Courtesy Tarmac Structural Repairs).

There are a number of problems associated with assessing the durability of proprietary repair materials. Most of these materials have not been in existence for more than 10–20 years and long-term experience of in-situ testing is therefore not available. Older materials may not be representative of their modern counterparts because formulations change. Additionally, accelerated testing of materials may not necessarily represent their actual performance in use.

A judgement must be made based on the *claimed* composition of the material, on placeability trials and past performance of similar materials. Secondly, an effective repair should either prevent further foreseeable damage occurring (by removal of the cause of deterioration or by other means, e.g. cathodic protection). If this is not possible, then any damage which may occur in the future must be taken into account in the design.

Further protection to the reinforcement can be achieved by increasing the cover, however, any increase in section will of course add to the dead weight of the structure. Conversely, because sprayed concrete can achieve a greater diffusion resistance than many other repair materials then a thinner protective layer may be possible. The diffusion resistance should be proven by testing if this assumption is made.

Reinforcement fixing

It is important that the type and spacing of fixings should be specified to ensure that the reinforcement is adequately secured to prevent vibration or displacement under the forces exerted by spraying, and to prevent or retard future peeling of the sprayed concrete layer as a result of debonding in service. Debonding can have many causes including poor or non-uniform bond, deterioration of the substrate, overload or non-compatibility of the repair with the substrate. In addition, reinforcement accessories such as spacers and chairs must be minimized to prevent congestion.

Fixing to steel is achieved by mechanical clips, brackets or fixing lugs welded to the steel, or direct attachment. Fixings should ensure a suitable upstand to locate the reinforcing layer within the sprayed concrete thickness. Durability is a concern for the designer in avoiding bi-metallic corrosion.

A large number of plastic and metallic fastenings are available for fixing reinforcement to concrete, brick and masonry. It is even possible to glue directly to concrete. The choice depends on the application, type of reinforcement specified, position of the work, number and size of anchors and the cost. The manufacturers' recommendations for size and depth of hole, safe working loads in shear and pullout should be followed. The required spacing of the fixings will depend upon the rigidity of the mesh being used and the location and shape of the parent surface. In special circumstances where the mesh fixings may also be required to supplement the interface bond, mechanical or resin anchor bolts can be used.

It is advisable to employ a reinforcing layer to act as a key for a flat soffit application although an exposed reinforcement bottom mat usually suffices (Figure 7.8). For wall applications, layers up to 150 mm can be sprayed without the need for a reinforcement mesh, although some form of tie to the existing wall is recommended.

Interface bond

The way in which a concrete substrate is prepared prior to repair significantly affects the bond and thus the structural performance of the repair (Austin and Rob-



Figure 7.9 *A 1920's swimming pool roof repaired after chloride attack* (Courtesy Sprayed Concrete Ltd.).

ins, 1993). Generally, the surface should be rough, but not micro-cracked and should be saturated but not surface wet. This ensures proper hydration of the repair material at the interface. Application of sprayed concrete to galvanized steel or dense smooth materials should be avoided due to potential lack of adhesion. Where the sprayed layer is for strengthening or overlay and a composite action is required, a method of shear transfer between repair and substrate should be considered.

Finish

Wherever possible, the finished surface should be left 'as shot' in order to reduce any risk of disturbing the bond between the repair concrete and the substrate. However, a limited amount of trowelling or screeding is possible provided that it is done carefully. A more common treatment is to spray the main layers of concrete to approximately 5 mm below the required final profile, trimming off to a uniform profile and spraying a final 'flash coat' to the still-green concrete to give a good degree of uniformity of profile and texture. A smoother surface can be achieved by rubbing up the flash coat with a wooden float and closing the surface with a soft wetted brush. Figure 7.9 demonstrates the smooth finish possible with sprayed concrete, in this case following the repair of a swimming pool roof that had suffered reinforcement corrosion through chloride attack.

7.8 Specification of material - New structures

Guideline Documentation

There is a range of documentation available providing valuable guidelines to assist with specification writing. In the UK, the Sprayed Concrete Association (SCA) (the UK industry trade association), which has been in existence since 1976, has done much to promote the technique and has produced guidelines and specifications for both the wet and dry processes.

EFNARC Technical Committee on Sprayed Concrete has recently issued a draft specification for sprayed concrete. It is hoped that the document will form the basis for the draft European Standard. In the USA the American Concrete Instituite (ACI) maintain and publish detailed specifications on materials and procedures used for sprayed concrete.

The method of measurement for sprayed concrete is currently a problem. Standard documentation in use in the industry is; *Civil Engineering Standard Method of Measurement* (CESMM), *Standard Method of Measurement of Building Work* (SMM) and the *Department of Transport Method of Measurement*. None of these documents adequately cover sprayed concrete and there is no recognized method of measurement for sprayed concrete with common usage in the industry.

Mix design

(i) Specification method
The composition of sprayed concrete can be specified using the Designed Mix or Prescribed Mix approach.

Designed Mix
Designed mix is defined by BS 5328 (BSI, 1991) as "Mix for which the purchaser is responsible for specifying the required performance and the producer is responsible for selecting the mix proportions to produce the required performance". The mix is designed by the contractor to achieve the specified strength and/or other specified properties, such as minimum cement content, minimum fibre content (in situ), maximum water/cement ratio, flexural strength, toughness, early strength, maximum strength, permeability, water absorption and bond to substrate. A designed mix is preferred for sprayed concrete because it produces a better defined and more consistent end product than the prescribed mix approach.

There are obvious advantages in permitting the specialist contractor freedom to select constituent materials and flexibility in mix design. For example, the balance between coarse and fine aggregates can be selected to ensure the best pumping performance for wet mix.

Prescribed Mixes
BS 5328 defines prescribed mix as "Mix for which the purchaser specifies the proportions of the constituents and is responsible for ensuring that these proportions will produce a concrete with the performance required". Reliable previous experience with the available materials and expected workmanship is usually a prerequi-

site, either from a previous project or from trial mixes. The specification is based upon data such as cement type and content, water/cement ratio or consistency, fibre content (in-situ), type and quantity of aggregate, admixtures and additives. The water content cannot be prescribed with the dry process. The designer must be careful to clearly identify whether the proportions apply to the original mix (before spraying) or to the in-situ material. The mix specification approach will also be influenced by the quality control procedures that are envisaged to check compliance.

(ii) Materials

Cement
Portland cement should comply with the requirements of BS12 (1991). Other cements (e.g. sulphate resisting) may be used where appropriate. It is of particular importance to use cement of uniform chemical composition and fineness. Sufficient identification tests must be undertaken to ensure that this is the case.

Mineral additives
Latent hydraulic binder additives available for use in both wet and dry sprayed concrete are: pulverised fuel ash (PFA); ground granulated blast furnace slag (GGBS) and silica fume. The maximum replacement levels are generally 35%, 70% and 15% respectively.
The advantages of using mineral additives are:

- the hydration process is slowed resulting in reductions in the heat of hydration and shrinkage cracking and improvements in curing (PFA and GGBS);
- rebound is reduced with the addition of silica fume (values as low as 5%);
- thicker layers are easier to apply;
- mix workability is increased and fibres easier to work with;
- dust is lower in the dry process;
- there is improved bonding of cement matrix to fibres, aggregate and substrate (especially wet surfaces);
- compressive strength, density and thus durability are improved;
- segregation during mixing is reduced;
- freeze/thaw resistance and abrasion resistance can be improved;
- silica fume gives low permeability at higher water/cement ratios;
- silica fume reduces the required dosage of accelerator.

Drawbacks are an increase in the cost of the base concrete and a greater need for good curing.

Admixtures
There are special sprayed concrete admixtures which are added to the mix before or during the process of spraying to enhance certain properties of the concrete. They fall into the following broad categories:

- *accelerators.* Because of the free form, self-supporting applications for sprayed concrete it is often desirable to develop very early acceleration of the setting and/or very early hardening of the concrete beyond the limits of conventional accelerators. Accelerators can also reduce dust in the dry process.

The principal disadvantage of the use of accelerators is that at high dosages they can reduce the long-term strength of the concrete. Accelerators for spraying are normally added at up to 6% by mass of cement (8% if liquid).

- *retarders.* Retarding admixtures are used primarily in the wet-mix process to extend the workable life of the concrete, allowing it to be transported greater distances from a remote batching plant or to be stored for longer periods on site in the mixer or in pump lines. These effects can be mitigated by the addition of accelerator at the nozzle should this be necessary to achieve the required in-situ performance.

- *slump reducers.* Admixtures of this type improve the pumping properties, usually of marginal concrete, by thickening the grout phase of the concrete in order to increase its resistance to the forced bleeding of water from the cement paste. This prevents dewatering of the paste under pressure of pumping (which would result in the blockage of the pump line). Many of these admixtures also have a retarding effect which may necessitate the use of higher dosages of accelerator.

- *plasticizers/super-plasticizers.* These admixtures are used in the wet process in order to enhance the workability of the concrete where low water/cement ratios are required for high strength, high durability sprayed concrete. Many types retard the setting of the concrete and selection of particular materials should minimize this.

It is important that the effects of additives proposed, both beneficial and adverse, are established by compatibility tests and pre-trials, and subsequent regular checks over the course of the works. The aim should, however, be to minimize the quantity of admixtures incorporated in the concrete.

Aggregate

Aggregates should comply with BS882 (1992) and consist of graded sharp washed sand and coarse aggregate. The requirements for pumping must be taken into consideration with the wet-mix process.

The grading of aggregates is critical in sprayed concrete due to the lack of external vibration and the change in mix proportions created by rebound. Heavier particles rebound more than the lighter sand grains and cement, resulting in a more finely graded material in situ with a higher cement content. Gradings should therefore be kept coarse to ensure a balanced in situ material.

Water

Water should be clean and free from harmful matter. Testing should be in accordance with the requirements of BS3148 (1980) and where doubt exists, tests for compatibility with the cements and admixtures proposed for use should be carried out.

(iii) Typical mix proportions

Dry mix proportions typically have aggregate/cement ratios in the range 3:1 to 4:1 by weight, producing in-situ ratios in the range 1.8:1 to 3.2:1 depending on the amount of rebound, with water/cement ratios between 0.35 and 0.45. These rich

low-water cement mixes can achieve compressive strengths of 40 to 75 N/mm^2.

The design of wet mix is similar to the design of conventionally pumped concrete. The mix design is affected by pumping distance, hose diameter and required output rate. Aggregates of 10 mm are common, with 20 mm or larger sometimes used for large volume applications. Water/cement ratios can be controlled accurately and with water-reducing plasticizers, figures of 0.35 can be achieved, with 0.55 being a typical maximum. Mixes often contain additives, as described above, to assist pumping. It is customary for wet-mix designs to use cement contents in the range of 350 kg–450 kg per cubic metre. The resulting cube strength will usually be between 35 N/mm^2 and 55 N/mm^2 at 28 days.

A variety of pre-bagged materials now contain polymers, silica fume and superplasticizers. These materials are most suitable for small volume work because of their cost.

(iv) Rebound

Although there are sprayed concrete systems available which almost eliminate rebound, it is inevitable with conventional sprayed concrete. Rebound consists of material which has been sprayed through the nozzle, struck the surface and not adhered. Rebound comprises mainly the large aggregate, producing concrete with in-situ proportions that are significantly different to the original mix. It is most severe at the start of the process, particularly when spraying onto a hard surface. The amount of rebound is affected by the orientation of spraying; it may be 0–10% when spraying downwards; up to 25% for vertical; and up to 40% for overhead spraying. Rebound for the wet process is generally lower than for the dry. The other factors which affect rebound are the nature of the surface, congestion of reinforcement, nozzle distance from the substrate, mix design, the skill of the nozzlemen and the type of equipment being used.

Rebound results in a much richer concrete than the original mix producing higher compressive strengths. This enrichment, however, can be deleterious to durability by encouraging shrinkage cracking. In addition, the amount of sodium oxide equivalent may be increased to a level in excess of the recommended level thought to reduce the risk of alkali silica reaction (Cabrera and Woolley, 1993). Studies on the strengthening of a cooling tower (Woolley and Cabrera, 1991) by the addition of an external 50 mm reinforced layer showed that a contractor-designed mix of 3.5:1 resulted in a mix in place of 2:1. This enrichment gave high compressive strengths but the sodium oxide equivalent was above the recommended limit. In addition the permeability of the placed material was below the standard expected from a 'good concrete', despite the porosity being good. Field measured rebound was in the region of 21%. These findings led to the belief that the mix in place had a considerable volume of capillary pores arising from the uneven pressure of compaction and some micro-cracking arising from high heat of hydration due to enrichment. These effects can be minimized by high standards of workmanship, careful control of the in-situ curing procedures, and the addition of GGBS or PFA to the mix.

Other specification considerations

Performance requirements

The requirements of a performance specification should be tailored to suit the project.

There is no benefit to designer, client or contractor in specifying a list of performance requirements if they are not relevant.

Performance requirements may include:

- application thickness;
- characteristic compressive strength;
- modulus of elasticity;
- flexural strength;
- toughness properties (residual strength value, energy absorption capacity or residual strength factor). Units of these parameters differ;
- creep;
- diffusion resistance;
- abrasion resistance;
- impact resistance;
- shrinkage;
- thermal movement characteristics;
- colour;
- uniformity;
- permeability;
- chloride content;
- alkali content;
- requirements related to exposure conditions e.g. maximum water/cement ratio and cement content; and
- resistance to sulphates.

Workmanship and Site Trials

It is important that on any project of a reasonable size site trials are undertaken at an early date to confirm the method and equipment, to develop the mix, enable testing of placed concrete to take place and to test the proficiency of operatives. In the UK, it is customary to specify that the contractor be a member of the Sprayed Concrete Association (SCA) or provide satisfactory written proof of expertise in



Figure 7.10 *Spraying concrete on to a test panel.*

sprayed concrete. All nozzlemen must be certified by the Construction Industry Training Board (CITB) who took over the SCA certification scheme in 1993.

Works tests

Once work proper has started on site, a regime of works tests should be set up as quality control. Quality control is defined as "a combination of actions and decisions taken in compliance with specifications and checks to ensure that the specified requirements are satisfied". The extent of control can be minor, normal or extended (EFNARC, 1993) as selected by the designer and it will depend upon the type of project, the degree of difficulty and consequences of failure.

For strength testing, the use of test cube moulds is not relevant because spraying causes an agglomeration of the coarse material, particularly in the corners. The fine material, sand and cement, is carried out of the mould by escaping compressed air. For these reasons the testing of sprayed concrete is carried out on cores from specially prepared test panels (Figure 7.10) and also on samples taken from the work to confirm that placing is being undertaken properly and that the test panels are representative of the works.

The test panels are usually constructed of timber, 750 mm square, although panels 600 mm square are sometimes used in repair. EFNARC now recommends panels that are 600 mm square at bottom with 45° side slopes (EFNARC, 1993). The recommended depth *(ibid)* is 150 mm or greater (100 mm previously), placed in the attitude in which the concrete will be placed in the work, i.e. vertical, sloping, or overhead, using the same type of equipment and material and either reinforced or not. Panels are usually cured by leaving them adjacent to the works and the curing procedures applied to the works used. They are then cored and tested in accordance with BS1881, Part 120. Reinforcement can be placed in the panels to demonstrate nozzle techniques and reinforcement encapsulation and to check routine quality control. The panels can also be used for extraction of cores for testing (cores should not be taken within 125 mm of the edges of the panel), to judge the competence of the nozzlemen and set the standard of finish to be provided in the work.

Production and transport

Any special requirements for batching and mixing should be specified. These may include weigh batching, mixing method and time, and addition of additives. If it is important, the mode of transport should be specified, whether dry or wet mix, to avoid segregation and to ensure protection from the weather.

Equipment

Choice and use of the equipment should be the domain of the contractor. However, the specification should generally cover good sprayed concrete practice to allow the client some recourse in the event of a problem.

Delivery plant should be designed for sprayed concrete work and be capable of delivering a continuous, even flow of material to the nozzle. The metering of accelerators must be accurate and material delivery pipes and hoses should be inspected for required quality and laid out without kinks or bends. All equipment should be inspected, cleaned and serviced regularly. Control of water and effective mixing are also important considerations for the dry method.

For the wet method it is important that the base concrete is delivered by continuous conveyance and that an uninterrupted supply of compressed air is maintained at the nozzle to provide a pressure sufficient to ensure even distribution of material. The air line must be sound and attached to the delivery line at regular intervals.

Placing
General sprayed concrete practice should be implemented to include all aspects already discussed in Sections 7.4 to 7.7 and others including work in cold weather and curing.

Specification of fibres

Fibres are specified by type and amount in the concrete. This is usually left to the contractor's judgement and experience and should be selected on the basis of compliance with the specification and on the suitability and ease of use in the batching, mixing and concreting and compacting processes as demonstrated by site trials.

A specification for fibre reinforcement should cover storage conditions, fibre condition, compatibility of additives to fibres, tolerances in length and diameter and aspect ratio and fibre content. The specification performance requirements would need to include tests in addition to those listed previously and may include fibre bend test, tensile strength of fibres, steel fibre content, testing to determine concrete crack characteristics and distribution of fibres.

7.9 Specification of material - Existing structures

Guideline Documentation

For work of a specialist nature, pre-printed standard documentation is often not directly applicable. Concrete repair is no exception. However, the Concrete Society Technical Report No. 38 (1991), *Patch Repair of Reinforced Concrete subject to Reinforcement Corrosion,* is helpful. Another useful document is *Method of Measurement for Concrete Repair* (Concrete Repair Association, 1990), although the current edition contains a few pitfalls and should be used with caution until it is revised. The Sprayed Concrete Association is drafting an addendum to this document to include sprayed concrete.

It is recommended that contract documents for repair work be based on more widely recognized conditions of contract, specifications and methods of measurement, such as those published by the Institution of Civil Engineers, Joint Contract Tribunal, or the Department of Transport. By so doing, responsibilities under the contract and specification of peripheral activities are covered. The above two specialist repair documents can then be used to supplement standard documentation.

Specification Method

In addition to the designed and prescribed mix approaches, the specifier of a repair material may also have the option of specifying a particular proprietary product. The designed mix is the recommended approach since it better protects the employ-

er's interests and gives the contractor more flexibility to select a material with which he is comfortable.

Except where very large volumes of concrete can be placed without interruption, which is rare in repair work, pre-bagged material is usually used, either dry or wet mix. The advantages of using pre-bagged materials are:

- one component, ready-to-use repair material;
- economy due to less wastage in large areas;
- low rebound;
- stop-start placing can be accommodated easily.

Performance Requirements

A specification which merely lists all the tests that a specifier can think of is simply counter-productive and will inevitably involve his client in unnecessary expense. Most of the requirements of a repair will be satisfied by applying the *Repair Like with Like* rule, i.e. repairing a concrete structure with compatible materials (Wood, 1989).

Writing an achievable performance specification is also difficult since testing standards currently available are rarely relevant to concrete repair materials because they have generally been developed for conventional concretes (BS1881) or resins (BS6319). They are often used with some modification e.g. relating to curing regimes or sample size.

The selection of a product to comply with such a specification then also becomes difficult because technical information provided on data sheets is often more a function of convenient/available test methods than of the specifier's needs, and direct comparison between products may prove impossible where a different national standard has been used by each manufacturer.

The unification of performance standards throughout Europe relating to *Products and Systems for Protection and Repair of Concrete Structures* is currently being addressed by Committee CEN TC104 SC8. The areas covered are:

- repair mortars and concretes;
- structural bonding materials;
- crack injection materials;
- fixing and anchoring materials;
- reinforcement corrosion prevention systems.

For repair mortars and concretes, properties are being clearly divided into factors relating to identification, such as cement ignition loss, and those relating to performance, such as carbonation resistance and workability. This part of the standard will cover products or systems to be used for the repair of concrete in both structural and non-structural modes. Products and systems are defined as repair mortars and concretes in conjunction with bonding agents and reinforcement treatments where they are part of the system. Where suitable tests are not already available in the form of a current national standard, new ones are being developed, e.g. for shrinkage of hydraulic and polymer-modified mortars. Although the full standard is unlikely to be available much before the end of this decade, its emergence will make the performance specification of repair materials very much easier.

For most repair work, the specifier of a concrete repair material should consider the most appropriate performance requirements for a material without ignoring

Table 7.1 *Requirements of a concrete repair material*

Performance Group	Application	Longevity	Protection	Structural	Looks
Example Specification Parameters	Method of placing	Shrinkage	pH	Compressive strength	Colour
	Cost/Speed	Thermal movement characteristics	Diffusion resistance and permeability	Modulus of elasticity	Surface Finish
	Consistency	Pull-off resistance (Fig. 7.11)	Homogeneity	Flexural strength	
	Availability		Abrasion resistance	Creep	
	Dust and other placeability considerations		Impact resistance		

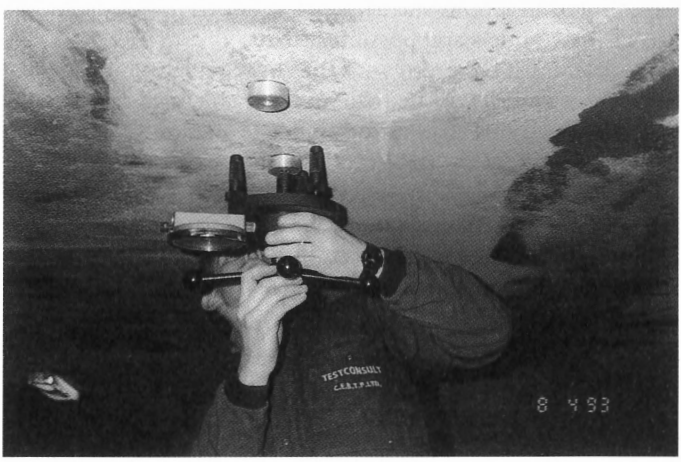

Figure 7.11 *Typical testing equipment for pull-off resistance test of a repair*

the broader aspects. The best material will fail just as quickly as the worst if the method of placement is inappropriate. The specification must take due consideration of concrete removal, cleaning/replacement of reinforcement, preparation of the substrate, material application, finishing, curing and quality control at an appropriate level, as work proceeds.

A well thought out specification should encompass each of six areas defined as the "SPALL" criteria. Under this system these the repair is usually required to achieve

the following:

*S*TRUCTURAL	Possesses the required structural properties
*P*ROTECTION	Provides protection for the reinforcement
*A*PPLICATION	Can be applied effectively within the given constraints
*L*ONGEVITY	Once applied it remains in place
*L*OOKS	Has an appropriate surface finish

The parameters which make up the specification for a repair product for any given situation will vary, the most common requirements are summarized in Table 7.1.

Curing

Finally, the specification of correct curing after completion of the repair is very important for the protection and longevity of the repair. Curing membranes should not be used on surfaces where there is to be concrete sprayed subsequently, unless they are first removed by grit-blasting. Curing times should be as for usual concrete practice or to manufacturers' recommendation if a proprietary material is used.

7.10 Quality assurance

BS 5750 defines quality assurance as 'All those planned and systematic actions necessary to provide adequate confidence that a product or service will satisfy given requirements for quality.' Quality assurance in design means control, documentation and traceability of all actions and decisions taken. It means planning the project beforehand to identify targets and possible pitfalls.

Initially, the brief must be agreed with the client to determine the exact requirements for the project and should be reviewed and amended as necessary to reflect subsequent changes. All information pertinent to planning, management, execution, auditing and storing of the project should be established and recorded at the start of the project and circulated to key staff.

Responsibilities for each design activity at every level should be established to ensure that the qualifications and authorization of named personnel are appropriate. Storage of all documentation: correspondence, reports, calculations, drawings and respective check copies, within the project should be arranged such that a master copy can be traced easily at any time. All documents pertinent to the project must be checked and approved by an authorized person prior to issue, to establish that output complies with the project brief and expected quality.

Where items or services are purchased from outside the organisation it is necessary to ensure that the purchased product conforms to the specified requirements. Sufficient details of required performance must be provided and the correct authorization and approval sought at the selection and purchasing stages. Performance of the product throughout use must be monitored against the specified performance and assessment made and recorded. All changes within the project should be managed carefully and reviewed as for all other project actions. Such changes should be documented and affected documents revised and re-issued.

Finally, it is important that all staff involved in the implementation of a quality system are provided with the necessary training to ensure the effective running of the system.



Figure 7.12 *Curved enclosures at Riyadh Zoo* (Courtesy Sprayed Concrete Ltd.)



Figure 7.13 *Retaining wall construction at Riyadh Zoo*

7.11 Examples

Riyadh Zoo

In the design of Riyadh Zoo, sprayed concrete was specified by the architect who wished to achieve a theme of sweeping curves and free-form design coupled with a faulted rock appearance. Sprayed concrete also offered a commercial advantage over conventionally placed concrete for structures where significant rock over-break would otherwise have been required for formwork of constantly changing radii.

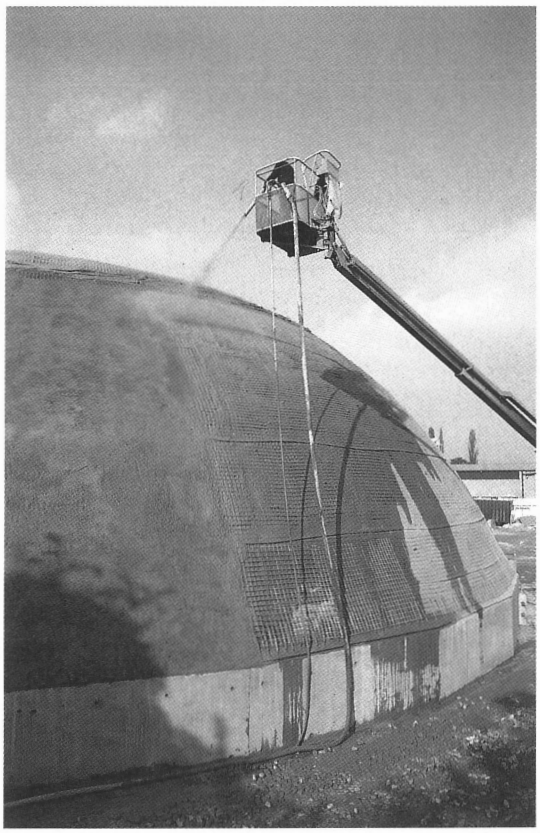

Figure 7.14 *Sprayed concrete being applied to the 'Spraydome'.* (Courtesy Llewellyn Stonecare Ltd.)

The sweeping curves were achieved (Figure 7.12) by means of a three stage construction. The first two stages were the application of a 14 mm down Portland cement concrete to each side of a fine mesh. Once this had been screeded to give the required alignment the surfaces were flashed with a 15 mm thick, 6 mm down light brown pigmented mix. The faulted rock theme structures required a 1 m cantilevered top edge and were constructed using either a fine wire mesh or 'K' lathe paper/wire composite positioned at the centre of the wall. The concrete was built-up on one side to a thickness of approximately 50 mm and when hardened, concrete was applied to the other side to the required thickness.

Figure 7.13 shows a 7 m high, 400 mm thick double reinforced retaining wall in the course of construction. The rock face was broken back and sealed with an accelerated sprayed concrete mix to stabilize the ground and prevent ingress of water from the perched water table. Where necessary, temporary relief pipes were positioned and water ingress piped away. The reinforcing cage was fixed on the ground and lifted into position by crane. The cage was wired to galvanized steel bars driven into the rock face to ensure rigidity and alignment. Joints were formed in the normal manner and thereafter concrete was sprayed from the open face,

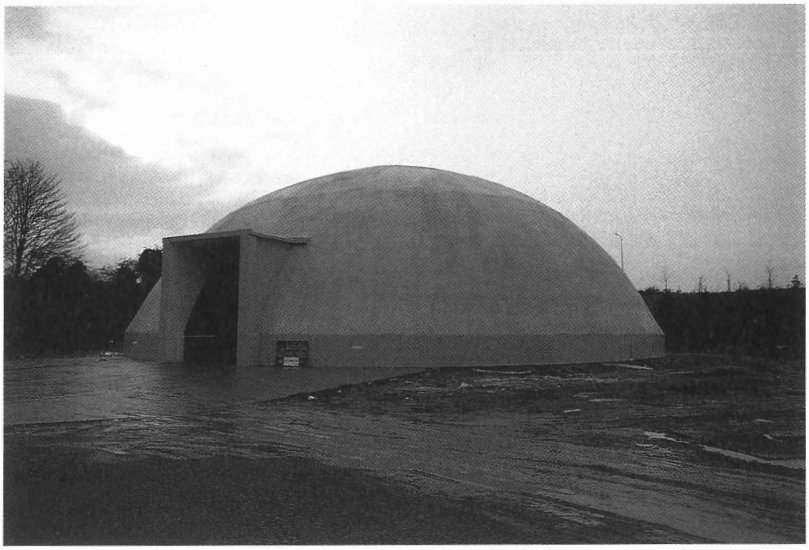

Figure 7.15 *The completed 'Spraydome'.* (Courtesy Llewellyn Stonecare Ltd.)

usually as a nightshift operation, followed by rigorous curing.

Owner:	Municipality of Riyadh
Engineer/Architect:	Safari Parks International
Sub-contractor for sprayed concrete repair:	Sprayed Concrete Limited

Free span, thin shell dome - 'Spraydome'

Spraydome is a system whereby, following the construction of a reinforced concrete perimeter base wall, a mesh-reinforced sprayed concrete dome is constructed using an inflatable internal form (Figures 7.14 & 7.15). After construction of the dome is complete, the base wall is post-tensioned to overcome local bending and resist hoop tensile forces imposed by the dome. After deflation of the former, the outside of the structure can be coated or weatherproofed as necessary.

The Spraydome can be designed in a range of sizes and is used for storage of de-icing salt, industrial storage, agricultural uses and, with insulation, for sports and leisure purposes. Typical dome dimensions may be 30 m diameter and 11 m height to crown with a 1.2 m high perimeter base wall, which houses all access points.

Silvertown Way Viaduct

The three-quarters of a mile Silvertown Way Viaduct was constructed in the 1930s to relieve severe traffic congestion at the entrance to the Royal Docks in London Docklands. The viaduct formed part of a larger scheme called the Royal Victoria and other Docks Approaches Improvement Scheme with a total value of £2.5m. The contract took 18 months to complete. The viaduct consists of a 12" deck slab carried on transverse beams (3' deep and 18" wide) and longitudinal beams (2'3" deep and 18" wide) supported on transverse rows of 6 columns at 17'6" centres. At

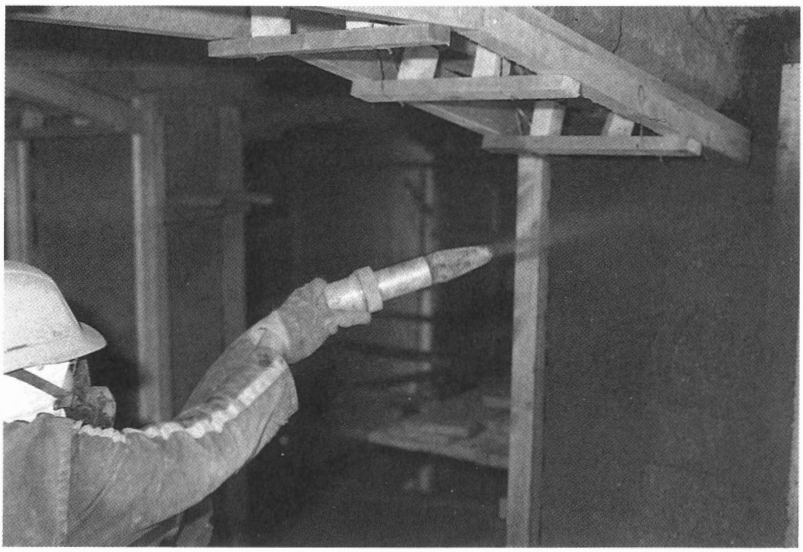

Figure 7.16 *Sprayed concrete repair of Silverton Way viaduct*

every third bay there is an expansion joint with a double row of columns. The column bases are supported on bored piles. Within the viaduct there are a total of ten bridges that cross roads and railway lines.

The viaduct was refurbished as part of the contract to build the Lower Lea Crossing, 1990–1992, and necessitated quite extensive investigation and repair. The principal reason for repair was fire damage but there was also extensive deterioration as a result of chloride-induced corrosion of reinforcement in transverse beams below contraction joints, and general carbonation. The fires occurred in commercial developments that occupied the bays below the viaduct. After a structural assessment to determine the need for propping of the viaduct during repair, it was determined that no overstress would occur with the current level of loading. Mott MacDonald specified sprayed concrete (Figure 7.16) to be used to repair the fire and other damage at the two most badly damaged sites. This avoided the need for extensive formwork and was a faster and more appropriate way to place such a large volume and area of repair concrete.

Owner:	London Borough of Newham
Consultant:	Mott MacDonald
Main Contractor:	Norwest Holst
Sub-contractor for sprayed concrete repair:	Tarmac Structural Repairs

Dartford Tunnel West

The Dartford River Crossing comprises two tunnels and a bridge which form part of the M25 London orbital motorway carrying traffic across the River Thames. Both the west tunnel which was completed in 1963 and the east tunnel completed in 1980 are about 1.5 km long and carry two lanes of northbound traffic. The bridge,



Figure 7.17 *Soffit repairs to Dartford Tunnel West*

completed in 1991, carries four lanes of southbound traffic.

The west tunnel has bolted cast iron linings and the road deck is formed of precast concrete tee-section units, continuity being provided by in-situ reinforced concrete strips. De-icing salt, carried into the tunnel by vehicular traffic, has caused some reinforcement corrosion damage to the road deck, which is not protected by waterproofing. The damage manifests itself in the form of road deck soffit spalling as a result of salt ingress through construction joints and other areas of weakness such as manhole openings. The repair work undertaken is therefore concentrated in two main areas; soffit repairs at construction joints and manhole repairs.

With regard to the former, damaged areas of soffit concrete are removed by high water pressure jetting to beyond the reinforcement. After reinstatement of the reinforcement section lost through corrosion, the concrete is replaced by sprayed concrete (Figure 7.17). The area of repair area at any one time is restricted to avoid expensive propping. A cathodic protection system is then installed over the repairs and adjacent concrete to prevent corrosion recurring.

When dealing with manhole repairs, a system of temporary propping and road plates is installed to permit traffic to run over the repair area after the manhole cover and frame and surrounding concrete has been removed. Once again, damaged areas of concrete are removed by high pressure water jetting and the reinforcement section lost through corrosion is reinstated. Either sprayed concrete or flowable concrete is used to reinstate the deck. Sprayed concrete was selected because of the difficult access for shuttering in the tunnel invert and for the good diffusion resistance to chloride ions provided by the proprietary material used.

Owner:	Dartford River Crossing Ltd
Consultant:	Mott MacDonald
Main Contractor:	Trafalgar House Construction
Sub-contractor for sprayed concrete repair:	*Contract 1:* Tarmac Structural Repairs *Contract 2:* Concrete Repairs Ltd.

7.12 Conclusions

In recent years, sprayed concrete has become an accepted method for concrete placement. With the range of additives and admixtures now available, a mix can be tailor-made for any application and comply with the tightest of performance specifications. The important roles to be played by skilled operatives and the correct choice of plant have been demonstrated by research and practical experience. It is vital that design and specification reflect the practical nature of this valuable construction technique.

In the repair of existing structures, specifiers now recognize that sprayed concrete offers a number of benefits over hand placed and flowable materials for certain applications. With the correct equipment and skilled operatives, repairs can be carried out quickly, efficiently and result in a high quality, durable repair.

References

ACI Committee 506R-90 (1994) Guide to shotcrete. *ACI Manual of Concrete Practice, Part5*. American Concrete Institute, Detroit, 41.

ACI Committee 506.1R-84. (1994) State-of-the-art report on fibre reinforced shotcrete. *ACI Manual of Concrete Practice, Part5*. American Shotcrete Institute, Detroit.

American Society for Testing and Materials (1989) ASTM C1140-89. *Practice for Preparing and Testing Specimens from Shotcrete Test Panels*. ASTM, Philadelphia.

American Society for Testing and Materials (1989) ASTM C1141-89. *Specification for Admixtures for Shotcrete*. ASTM, Philadelphia.

American Society for Testing and Materials (1990) ASTM A 820-90. *Standard Specification for Steel Fibers for Fiber Reinforced Concrete*. ASTM, Philadelphia.

American Society for Testing and Materials (1991) ASTM C 1116-91. *Specification for Fiber Reinforced Concrete and Shotcrete*. ASTM, Philadelphia.

Austin, S.A. and Robins, P.J. (1993) Development of patch repair test to study behaviour of shallow concrete patch repairs. *Magazine of Concrete Research*, **45**, No. 164, Sept., 221–229.

British Standards Institution (1980) *BS 3148 Methods of test for water for making concrete*. BSI, London

British Standards Institution (1985) *BS 8110 Structural Use of Concrete*.

British Standards Institution (1988) *BS 6920 Suitability of non-metallic products for use in contact with water intended for human consumption*.

British Standards Institution (1990) *BS 812 Testing aggregates*.

British Standards Institution (1990) *BS 5400 Steel, concrete and composite bridges*.

British Standards Institution (1991) *BS 12 Specification for Portland Cement*.

British Standards Institution (1991) *BS 5328 Concrete*.

British Standards Institution (1992) *BS 1881 Testing concrete*.

British Standards Institution (1992) *BS 882 Specification for aggregates from natural sources for concrete*. BSI, Milton Keynes.

British Standards Institution (1993) *BS 6319 Testing of resin and polymer/cement compositions for use in construction*.

Cabrera, J.G. and Woolley, G.R. (1993) *Potential for developments in sprayed concrete*. Sprayed Concrete European Seminar, Brunel University, Uxbridge, UK

Cairns, J. (1992) *Relief of load during structural repairs to reinforced concrete beams*. Heriot-Watt University. Unpublished Research Report, 21pp.

Cooke, T.H. (1990) *Concrete Pumping and Spraying, a Practical Guide*. Thomas Telford Ltd. 266pp.

DoT (1984) *The assessment of highway bridges and structures*. Departmental Standard BD 21/84.

EFNARC Technical Commitee Sprayed Concrete (1993) *Draft specification for sprayed concrete*. European Federation of National Associations of Specialist Repair Contractors and Material Suppliers for the Construction Industry, Aldershot, UK.

Henager, C.H. (1978) SFS, *A state of the art report*. Eng. Foundation Conference, Shotcrete, Austria, ASCE.

Holmgren, J. (1985) Advanced tunnel support using steel fibre reinforced concrete. In *Steel Fibre Concrete – US Sweden Joint Seminar*, eds. S.P.Shah & A.Skarendahl, (NSF-STU), Stockholm. 361–376.

HMSO. (1991) Water Industry Act, (consolidating the Water Act 1989), 238pp.

Japan Society of Civil Engineers. (1984) Recommendation for the design and construction of steel fibre reinforced concrete. *Concrete Library of JSCE*, **3**, 4–9.

Johnson, R.A., Leek, D.S., King, E.S. and Dunne, H.B. (1994*a*) *Underground Service Reservoirs: Waterproofing and repair manual.* CIRIA Research Project 449.

Johnson, R.A., Leek, D.S., King, E.S., and Cope, M.P. (1994*b*) *A guide to water resisting basement construction*. CIRIA Research Project 419

King, E.S. (1992) *Concrete as an alternative concrete repair material*. Sprayed Concrete European Seminar, Brunel University, The University of East London.

King, E.S. Ecob, C.R. (1993) *Review and Specification of concrete repair materials*. Structural Faults and Repair Conference, Edinburgh.

Mangat, P.S. and Gurusamy, K. (1986) Is steel fibre concrete durable?. *Conference, Our World of Concrete and Structures, Singapore,* vol. 5, 26–27, 157–169, Singapore.

Morgan, D.R. (1985) *Steel fibre shotcrete for rehabilitation of concrete structures.* Transportation Research Record 1003.

Morgan, D.R. and Mowat, D.N. (1984) A comparative evaluation of plain, mesh and steel fibre reinforced concrete. *ACI Publication, SP-81,* 307–324.

Naaman, A.E., Shah, S.P., and Throne, J.L. (1985) Some developments in polypropylene fibres for concrete. *ACI Int. Symposium, SP-81, Fibre Reinforced Concrete,* 375–96.

Opsahl, O.A. (1985) *A study of a wet-process shot-creting method*. Volume 1. Report BML 85.101, Division of Building Materials, the Norwegian Institute of Technology, NTH, The University of Trondheim, Norway.

Overlie, F.E. and Rippentrapp, G. (1987) Steel fibre microsilica shotcrete with remote controlled equipment. *Rapid Excavation and Tunnelling Conference, New Orleans, Louisiana.*

Ramakrishman, V. (1981) A comparative evaluation of fibre shotcretes. *Concrete International,* **3**,1.

Refai, F.E. and Morsey, E.H. (1986) Some properties of fibre reinforced concrete with superplasticizers, *FRC 86. Developments in fibre reinforced cement and concrete. RILEM Symposium, Vol. 1.*

Rose, D. (1985) Steel fibre reinforced shotcrete for tunnel linings. The State of the Art. *Rapid Excavation and Tunnelling Conference,* **1**,*392–412.*

Ryan, T.F. (1973) *Gunite–a handbook for engineers*. Cement and Concrete Association. 64pp.

Sandell, B. (1978) Sprayed concrete with wire fibre reinforcement. *Tunnels and Tunnelling,* **10** (3), 29–30.

Schupack, M. (1985) Durability of SFRC exposed to severe environments. In *Steel Fibre Concrete – US Sweden Joint Seminar*, eds. S.P.Shah & A.Skarendahl, (NSF-STU), Stockholm.

Shah, S.P. (1987) Fibre reinforced concrete, properties and applications. *ACI SP-105.*

Wood, J.G.M., King, E.S. and Leek, D.S. (1989) Defining the properties of concrete repair materials for effective structural applications, *Structural Faults & Repair-89,* Engineering Technics Press, London, **2**, 231–5.

Woolley, G.R. and Cabrera, J.G. (1991) Composition and Properties of Gunite used for Strengthening Cooling Towers. *European Seminar and Workshop on Sprayed Concrete*, Loughborough University of Technology.

8 Design of Tunnel Support

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8.1 Introduction

Central Europe has long traditions in tunnel construction. A number of large tunnel projects were constructed in the nineteenth century (including the St. Gotthard, Arlberg and Simplon railway tunnels) during which adverse tunnelling features, many of them unexpected, were encountered, causing enormous construction challenges and problems. The squeezing effect often encountered in weak ground has been a constant problem in Alpine tunnelling. The need for improved tunnel excavation and support techniques has, therefore, existed for decades. Several pioneers have made important field observations which have contributed to the development of tunnelling in weak ground.

The New Austrian Method (NATM) made use of earlier experience gained from tunnelling over several decades, but took advantage of the new support technology that was made available in the late '50s and '60s. To divide this new method from earlier tunnelling practice – where heavy rock supporting works were installed – it was called the New Austrian Tunnelling Method. Officially, the NATM was introduced by Rabcewicz at the 13th Geocolloquium in Salzburg 1962. This new trend in Austrian tunnelling soon gained national attention. International recognition was achieved through a paper in *Water Power* (Rabcewicz, 1964). Since then numerous tunnel projects in Central Europe and also in many other countries have been excavated and supported using NATM principles.

Parallel to the launching of NATM in Austria and Central Europe, great advances were made in excavation by the drill and blast method in Scandinavia. Development from pneumatic to hydraulic drilling machines, and from hand-held borers to hydraulically operated, mobile jumbos made large contributions to the rate of tunnel excavation. At the same time the development of rock support methods such as rock bolts, cast-in-place concreting techniques, and especially the spraying of shotcrete have pushed forward the technique of tunnelling in jointed rocks.

From numerous tunnel and underground excavations, mainly for hydropower exploitation, the Norwegians have made important advances in the development of tunnelling techniques. Annually, about 100 km of tunnels have been excavated since the beginning of the '60s. The need for design methods based on a numerical classification of the rock mass through which the tunnel would pass was realized in the development of the Q-system (Barton *et al.*, 1974), which incorporated a large amount of tunnelling experience. Since its presentation in 1974 the Q-system has been applied increasingly in tunnelling projects worldwide.

The main contribution to tunnel excavation efficiency and cost cutting in the last 15 years has been the development of sprayed concrete (shotcrete). The Norwegians have been in the forefront in improving this method for rock support, especially through their development of the wet spraying method and later in refining fibre-reinforced shotcrete. As is discussed in Section 8.3, the application of this method in place of the dry method and mesh reinforced shotcrete, has effectively increased the rate of tunnel excavation, improved the tunnel working environment, and kept tunnelling costs stable, even producing a reducing trend. The technique, which incorporates the Q-system, is now termed the Norwegian Method of Tunnelling (NMT).

8.2 The New Austrian Tunnelling Method (NATM)

Introduction

It is important to note that the new Austrian tunnelling method (NATM) has been developed for tunnelling in *weak or squeezing ground*. Such ground requires the use of structural supports, either to re-establish equilibrium or to limit displacements around the tunnel. The rock or soil material itself may be soft or hard.

The method was developed by L. von Rabcewicz, L. Müller. and F. Pacher between 1957 and 1964. It is essentially an empirical approach, evolved from practical tunnelling experience. Rabcewicz (1965) stated the goals of the NATM as:

> *"To provide safe and economic support in tunnels excavated in materials incapable of supporting themselves, e.g. crushed rock, debris, and even soil. Support is achieved by mobilizing whatever humble strength the rock or earth possesses."*
>
> *"To use surface stabilization by a thin auxiliary shotcrete lining, suitably reinforced by rockbolting and closed as soon as possible by an invert.".*

Later, other important features were introduced and incorporated into the NATM, such as contractual arrangements, excavation procedures and more advanced design methods. It is basically a 'build as you go' approach based on monitoring, backed by theoretical considerations.

The NATM has sometimes been assumed to be synonymous with the use of shotcrete during tunnel construction, probably because this rock supporting method is often applied in connection with the NATM. This is wrong; in practice the NATM involves the whole sequence of weak rock tunnelling from investigation during design, engineering and contracting to construction and monitoring. Consequently, an overview of the NATM will include most features involved in the execution of a tunnelling project and tends to be a comprehensive work on tunnelling. In this chapter, therefore, its main elements are described briefly. Important features of the NATM such as the accumulation and active use of construction experience are not included.

The main design principles in the NATM

A basic principle in the NATM is to take advantage of the load-bearing capacity of weak rocks. This is achieved by utilizing the property rock masses have to dilate or bulk as they yield. During this process the high ground stresses close to the tunnel dissipate and the surrounding rock mass is transformed from a loading body into a

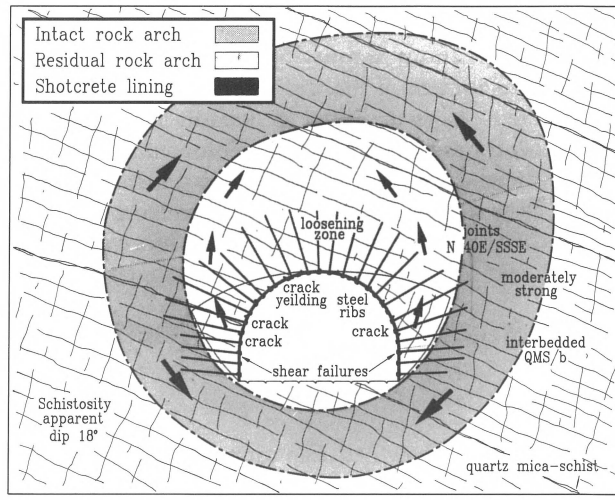


Figure 8.1 *The various zones around a tunnel in weak ground (after Hagenhofer, 1990)*

load-carrying element (Figure 8.1). Only a reduced support is therefore needed to confine the unstable ground close to the tunnel.

This principle is achieved practically by allowing the rock masses around the underground opening to deform in a controlled way. The rock support has therefore mainly a confining function to stabilize the rock masses that deform. As a

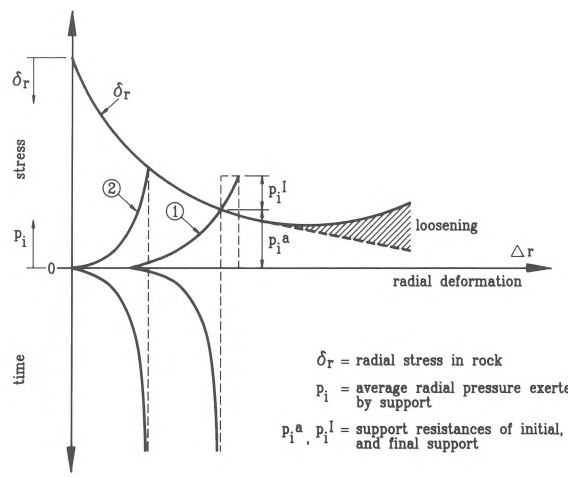


Figure 8.2 *An example of a ground support interaction diagram or Fenner-Pacher curve (after Brown, 1981). The numbers 1 and 2 show two different support systems installed at different times. The importance of stiffness and timing of the support is described in the text.*

consequence, the support must have suitable load-deformation characteristics and be installed at the right time. This approach requires a knowledge of the interrelationships between ground deformation and load as well as between support deformation and load.

For this purpose the Fenner-Pacher curve is often applied in the design of rock support. This ground response curve (Figure 8.2) shows the rock/support interaction and the deformations with time. It provides a tool to optimize rock support, to help determine a favourable time for installation and an appropriate stiffness. There are, however, several limitations connected with response curves caused by simplifications and problems in generating relevant input data on rock mass characteristics.

Rabcewicz (1965) stresses the importance of a *deformable* rock support which should be neither too stiff, nor too flexible. A stiff rock support will be carrying a larger load because the rock mass around the opening has not had the possibility to deform enough to bring the stress peak further into the surrounding rocks (see Figure 8.2). Conversely, if the support is too flexible, the deformation may become too large and unsafe conditions may arise. Generally, this requires a support system consisting of systematic rock bolting and shotcrete. Whatever support system is used, it is essential that it is placed and remains in intimate contact with the surrounding ground and deforms with it.

The ground response curve in Figure 8.2 indicates also that the *timing* of rock support installation is a further important factor for a favourable mobilization of the inherent strength of the rock mass. If the rock support is installed too early, a heavier support is required to carry the resulting rock mobilized. An installation made too late may cause deformations of the rock masses surrounding the tunnel resulting in loosening and failures. It is however difficult to predict the time factor and its variations during tunnelling, even for experienced rock mechanics and tunnelling engineers. The use of monitoring and stress measurements in the tunnel during construction (see later) is therefore an important characteristic of the NATM.

In Austrian tunnelling practice, the ground is described behaviourally and allocated a ground class, based on field observations. The qualitative ground description used is associated, rather inconsistently, with excavation techniques together with principles and timing of standard support requirements. Although there are guidelines in the qualitative NATM classification, the ground class is mainly determined from individual observations by the engineering geologist. Brosch (1986) does not know of any Austrian experience with the common international classification systems (i.e. the RMR and Q systems). This rather unsystematic use of geodata is a drawback which limits communication between people involved in tunnelling and the further development of the NATM.

Rock support and excavation principles

As a part of the NATM 'the dual-lining support' (initial and final support) for tunnels was introduced. This is the concept of letting the rock masses surrounding the tunnel and the initial support deform before the final or permanent support is applied. The two stages of rock support have been described by Rabcewicz and Golser (1973) as:

(i) The initial support–often carried out as an outer lining designed to stabilize the

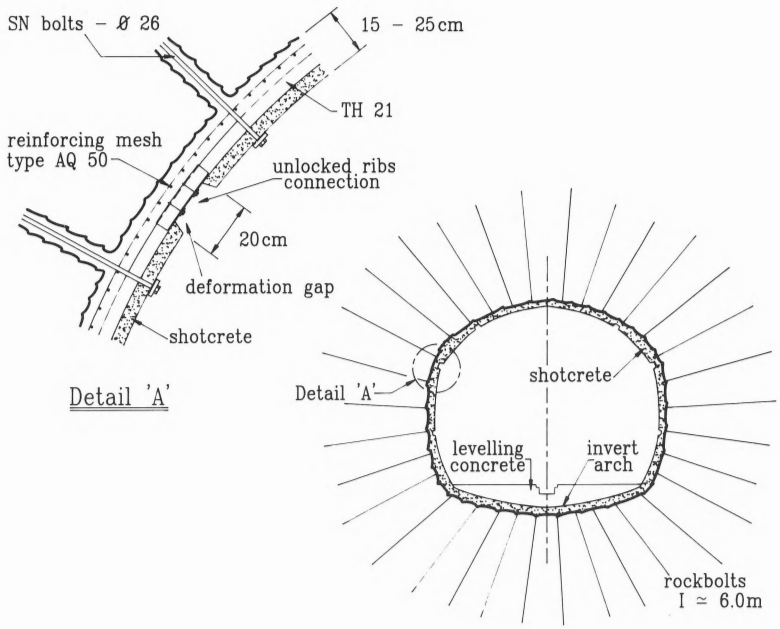


Figure 8.3 *Where large deformations take place in the tunnel walls it is important to have a highly flexible lining to interact with the deformations. The figure shows an example from the Tauern tunnel where the initial lining of shotcrete and rock bolts was designed with longitudinal joints to meet this requirement (adapted from Amberg and Cristini, 1986).*

rocks during excavation. It consists mainly of shotcrete, systematically bolted and reinforced by additional steel ribs if required. In addition, a closing of the invert is carried out in very weak ground; and

(ii) *The final support*–often carried out as a concrete lining. It is generally not installed until the deformations of the initial support have reached an acceptable, decreasing trend.

The initial support can partly or completely represent the total support required. The final lining may be necessary for structural reasons:

(i) when the initial lining is stressed beyond its elastic limit, or

(ii) when squeezing or swelling from time-dependent loads will exceed the bearing capacity of the initial lining.

A second lining may also be required for waterproofing. The dimensioning of the final support is made from assessments based on results from monitoring of stresses in the initial support element and/or of deformations of the tunnel surface and the ground surrounding the tunnel. In strongly squeezing ground the support should be designed to absorb large movements, as shown in Figure 8.3.

The practical execution of NATM involves the close coordination of the tunnel excavation technique and rock supporting works, and these two operations must be planned and designed according to the ground conditions. In very weak ground it

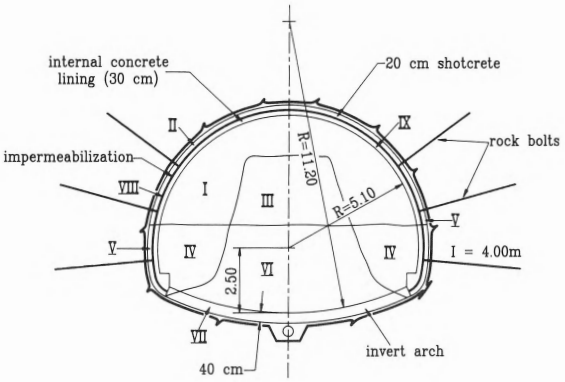


Figure 8.4 *A sequential tunnel excavation from a highway tunnel close to Florence, excavated in clayey schists (adapted from Amberg and Cristini, 1986)*

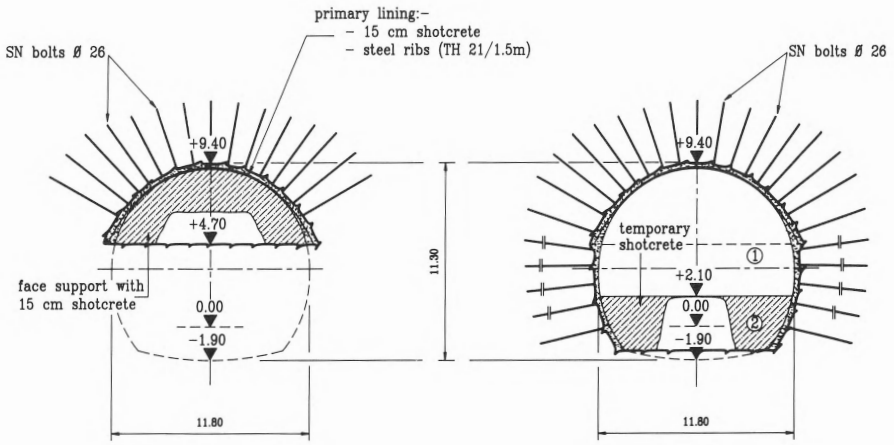


Figure 8.5 *Excavation and initial (primary) support from the Tauern road tunnel in a part consisting of strongly foliated chloritic phyllite alternating with quartz-rich phyllite (from Amberg and Cristini, 1986)*

might be necessary for reasons of stability to excavate smaller parts of the tunnel cross section, for example an upper heading and benching or alternatively the arch, the core and the invert arch of the tunnel section may be appropriate solutions (see Figures 8.4 and 8.5).

The excavation and support sequences (Figure 8.4) are as follows:
(i) Excavation of arch (I) leaving a central core in order to shore the walls and the arch. Immediately after excavation, execution of a first layer of reinforced shotcrete, placement of light ribs and a further increase of the shotcrete thickness until final value (II);
(ii) Excavation of central core (III) and side trenches by stage (IV), prestrengthening with a mesh reinforced shotcrete lining and steel ribs (V);
(iii) Excavation of the trench (VI), execution of the invert arch (VII); and
(iv) Waterproofong membrane (VIII) and final concrete lining (IX).

Monitoring of deformation and stresses

In order to investigate the behaviour of the ground during and after excavation, correct application of NATM is based on systematic in-situ measurements primarily of deformations and stresses (see Figure 8.6). From the progress of the deformations, it is possible to recognize early enough if an unacceptable trend appears and to act accordingly. Thus, monitoring of tunnelling in weak ground is not research, but an essential means of knowing whether the tunnel construction is proceeding satisfactorily.

The instruments are installed in sections along the tunnel when the initial support is placed. In addition to hazard control, the information from the measurements is related to the characteristics of the ground and the size of the opening. When interpreted, it is possible to adapt the type and dimensions as well as the timing of rock support to the actual ground conditions encountered during the excavation. In this context, it is obviously very important to have an effective calculation model which permits a quick interpretation of the data, and the best possible representation of reality.

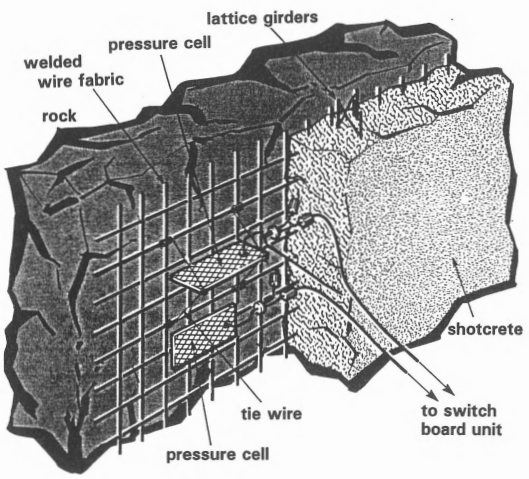


Figure 8.6 *Example of instrumentation of stresses in the shotcrete (adapted from Martin, 1984)*

Experience with the NATM

The NATM has been applied successfully in a large number of tunnels in many parts of the world, some of which were constructed in poor and difficult ground conditions. Compared to traditional tunnelling considerable cost savings have often been gained in addition to shorter construction times. NATM has, however, also experienced unpleasant downfalls (Wallis, 1987, 1988).

The versatility and adaptability of the method have been demonstrated from its basic principles and from the flexibility of using shotcrete and rock bolts both for initial and final support. A significant advantage of using shotcrete is the facility to adjust its thickness to the actual rock mass condition, i.e. by the application of further shotcrete layers.

Where NATM is used in conjunction with drill and blast or mechanical excavation, the flexibility of these methods can be fully utilized. Various sizes of tunnels and excavation sequences, for example for pilot headings and benching, can be made. The main benefit of NATM is for tunnels constructed in weak ground, i.e. materials that have a lower strength than the rock stresses they are exposed to. Tunnels excavated in stable and slightly loosening rock will generally benefit little from application of the NATM.

8.3 Norwegian Method of Tunnelling

Introduction

Although NATM has been used with good results in numerous soft ground tunnels, it may fall short of requirements and be too expensive when tunnelling in harder, jointed rock that require drilling and blasting. The reasons for choosing an alternative to NATM in such cases is that overbreak is more easily and effectively treated with fibre-reinforced shotcrete, *S(fr)*, than with mesh reinforced shotcrete, *S(mr)*. There is great wastage of shotcrete when voids (overbreak) have to be filled to cover the less flexible mesh reinforcement. In addition, jointed ground that causes overbreak can be effectively characterized so the required thickness of *S(fr)* and bolt spacing can be estimated accurately.

Following the development of wet process fibre-reinforced shotcrete in Norway at the end of the '70s, *S(mr)* was gradually replaced by *S(fr)*, and the less flexible mesh reinforced variety has virtually been eliminated over the last 15 years. The combination of systematic bolting, *B*, and wet process, robotically applied fibre-reinforced shotcrete provide the essential physical components of the Norwegian Method of Tunnelling (NMT) in jointed rock. The third component that puts NMT design on a more secure footing than rule-of-thumb estimating is the use of the *Q*-system of rock mass characterization (Barton *et al.*, 1974). This, in contrast to the descriptive rock mass classes used in NATM, provides a numerical rating of the rock mass and allows appropriate selection of *S(fr)* thickness (in cm) and bolt spacing (in metres) for tunnels or caverns ranging from about 2 to 100 metres in span. The selection of rock support for NMT is based on a very large data base (1 300 cases) which is synthesized in a recently updated *Q*-system support chart (Grimstad and Barton, 1993). Table 8.1 summarizes other essential features of NMT.

Table 8.1 *Essential features of NMT (after Barton et al., 1992)*

1) **Areas of usual application:**
   Jointed rock giving overbreak; harder end of uniaxial strength scale (σ_c = 3 to 300 MPa)
   Clay bearing zones, stress slabbing
   Q = 0.001 to 40 or more

2) **Usual methods of excavation:**
   Drill and blast, hard rock TBM, machine excavation in clay zones

3) **Temporary rock reinforcement and permanent tunnel support may be any of following:**
   CCA, *S(fr)+RRS+B*, *B+S(fr)*, *B+S*, *B*, *S(fr)*, *S*, *sb*, (NONE)
   (see key below and Figure 8.7)
   - temporary reinforcement forms part of permanent support
   - mesh reinforced shotcrete not used
   - dry process shotcrete not used
   - steel sets or lattice girders not used; *RRS+S(fr)+B* are used in clay zones and in weak, squeezing rock masses. In worst cases *CCA* is used.
   - contractor chooses temporary support
   - owner/consultant chooses permanent support
   - final concrete linings are less frequently used, *i.e.*, *B+S(fr)* is usually the final support

4) **Rock mass characterisation for:**
   - predicting rock mass quality
   - predicting support needs
   - updating of both during tunnelling (monitoring in critical cases only)

5) **The NMT gives low costs and**
   - rapid advance rates in drill and blast tunnels
   - improved safety
   - improved environment

CCA = cast concrete arches, S(fr) = steel fibre reinforced shotcrete, RRS = reinforced ribs, B = systematic bolting, S = shotcrete, sb = spot bolts, NONE = no support needed.

Q-System of rock mass characterization

(i) Rationale

The vast majority of the thousands of kilometres of tunnels constructed worldwide every year do not have the benefit of performance monitoring as often used in NATM. Design decisions are nevertheless required both before and during construction. No matter how many sophisticated rock mechanics test programmes and finite element analyses are performed, design engineers will come back to the basic question: "Is this bolt spacing, shotcrete thickness, or unsupported span width reasonable in the given rock mass?"

At present one has to rely on engineering judgement, or on classification methods, where the design is based on precedent, and where a good classification method

will allow one to extrapolate past designs to different rock masses and to different sizes and types of excavation. Underground excavations can be supported with some confidence, primarily because many others have been supported before them and have performed satisfactorily.

(ii) Method for Estimating Rock Mass Quality (Q)
The six parameters chosen to describe the rock mass quality (Q) are combined in the following way:

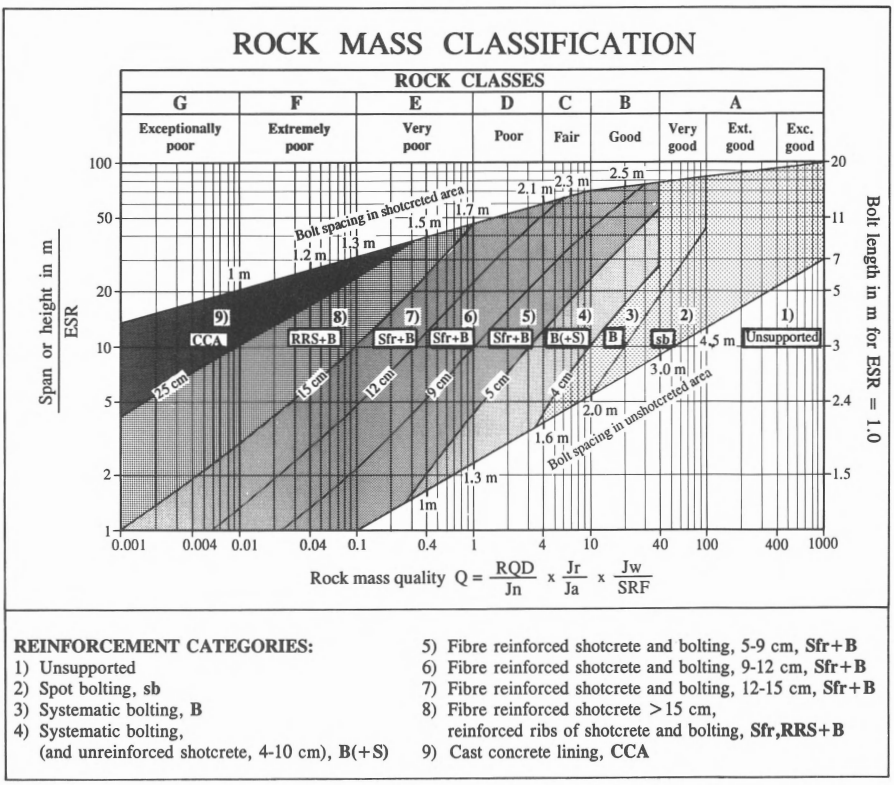
$$Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} \tag{8.1}$$

where:
RQD = rock quality designation (Deere *et al.*, 1967),
J_n = joint set number,
J_r = joint roughness number (of least favourable discontinuity or joint set),
J_a = joint alteration number (of least favourable discontinuity or joint set),
J_w = joint water reduction factor, and
SRF = stress reduction factor.
The three pairs of ratios (RQD/J_n, J_r/J_a, J_w/SRF) represent block size, inter-block shear strength, and active stress, respectively. These are fundamental geotechnical parameters. It is important to observe that the values of J_r and J_a relate to the joint set or discontinuity most likely to allow failure to initiate. The important influence of orientation relative to the tunnel axis is implicit.

Detailed descriptions of the six parameters and their numerical ratings are given in Table 8.2. The range of possible Q-values (0.001 to 1000) encompasses the whole spectrum of rock mass qualities from heavy, squeezing ground up to sound, unjointed rock. The original case records examined by Barton *et al.*, (1974), include 13 igneous rock types, 26 metamorphic rock types, and 11 sedimentary rock types. More than 80 of the case records involved clay-bearing rock. However, most commonly the joints were unfilled and the joint walls were unaltered or only slightly altered.

The original case records from Scandinavian and international tunnel and cavern projects (numbering approximately 200), have since been supplemented by 1,050 Norwegian case records from main road tunnels. The new support selection chart shown in Figure 8.7 was presented by Grimstad and Barton (1993) and is a modification of the chart developed by Grimstad *et al.* (1986), when the original 1974 support recommendations were first updated to include fibre-reinforced shotcrete. It should be noted that the tunnel or cavern span or height given on the vertical axis in Figure 8.7 is divided by the term ESR. The numerical value of ESR appropriate to given types of excavation and their safety needs is shown in Table 8.3.

(iii) Tunnel Mapping Techniques
During the 20 years in which the Q-system has been utilized for tunnel support design, a variety of methods have been used for recording and presenting the rock mass characterization data. Two common methods are presented here of which the first (Figure 8.8) is a tunnel log on which principal joints and discontinuities are recorded, together with the relevant Q-system parameters. Recommended support



REINFORCEMENT CATEGORIES:

1) Unsupported
2) Spot bolting, **sb**
3) Systematic bolting, **B**
4) Systematic bolting, (and unreinforced shotcrete, 4-10 cm), **B(+S)**
5) Fibre reinforced shotcrete and bolting, 5-9 cm, **Sfr+B**
6) Fibre reinforced shotcrete and bolting, 9-12 cm, **Sfr+B**
7) Fibre reinforced shotcrete and bolting, 12-15 cm, **Sfr+B**
8) Fibre reinforced shotcrete >15 cm, reinforced ribs of shotcrete and bolting, **Sfr,RRS+B**
9) Cast concrete lining, **CCA**

Figure 8.7 *Rock mass classification – permanent support recommendation based on Q and NMT (note extensive use of S(fr) as permanent support). (Grimstad and Barton, 1993).*

is selected, as shown in the right hand side of the log. The 1980 recommendation for support in the zone between chainage 810 and 817 consisting of *B* 1.5 m c/c and *S*(*mr*) of 15 cm thickness is close to the 1993 recommendation that would be obtained from application of Figure 8.7.

Type of tunnel: headrace to hydroelectric power plant
span = 10 m span/*ESR* = 10/1.6 = 6.25 m
height = 16.7 m *Q* (of zone) = 0.1–0.3 (very poor)
Recommended support: *B* 1.3–1.4 c/c, *S*(*fr*) 10–13 cm thickness

Based on the original 1974 *Q*-system, such zones would traditionally have been supported locally with cast concrete linings of about 30 cm thickness together with systematic bolting of about 1 m c/c. The flexibility of shotcrete, and especially that of robotically applied *S*(*fr*) is revolutionizing tunnel support methods, and increasingly replacing cast concrete.

Table 8.2 *The ratings of the six parameters for calculating rock mass quality, Q*

	1. Rock Quality Designation	*RQD*
A	Very poor	0–25
B	Poor	25–50
C	Fair	50–75
D	Good	75–90
E	Excellent	90–100

Note: i) Where *RQD* is reported or measured $\leq$ 10 (including 0), a nominal value of 10 is used to evaluate *Q*.
ii) *RQD* intervals of 5, i.e., 100, 95, 90, etc., are sufficiently accurate.

	2. Joint Set Number	J_n
A	Massive, no or few joints	0.5–1.0
B	One joint set	2
C	One joint set plus random joints	3
D	Two joint sets	4
E	Two joint sets plus random joints	6
F	Three joint sets	9
G	Three joint sets plus random joints	12
H	Four or more joint sets, random, heavily jointed, "sugar cube", etc.	15
J	Crushed rock, earthlike	20

Note: i) For intersections, use $(3.0 \times J_n)$
ii) For portals, use $(2.0 \times J_n)$

	3. Joint Roughness Number	J_r
a)	*Rock-wall contact, and b) rock-wall contact before 10 cm shear*	
A	Discontinuous joints	4
B	Rough or irregular, undulating	3
C	Smooth, undulating	2
D	Slickensided, undulating	1.5
E	Rough or irregular, planar	1.5
F	Smooth, planar	1.0
G	Slickensided, planar	0.5

Note: i) Descriptions refer to small scale features and intermediate scale features, in that order.

c)	*No rock-wall contact when sheared*	
H	Zone containing clay minerals thick enough to prevent rock-wall contact	1.0
J	Sandy, gravelly or crushed zone thick enough to prevent rock-wall contact	1.0

Note: i) Add 1.0 if the mean spacing of the relevant joint set is greater than 3 m.
ii) J_r = 0.5 can be used for planar slickensided joints having lineations, provided the lineations are oriented for minimum strength.

Table 8.2 continued

	4. Joint Alteration Number	ϕ_r approx.	J_a
	a) Rock-wall contact (no mineral fillings, only coatings)		
A	Tightly healed, hard, non-softening, impermeable filling, i.e., quartz or epidote		0.75
B	Unaltered joint walls, surface staining only	25–35°	1.0
C	Slightly altered joint walls. Non-softening mineral coatings, sandy particles, clay-free disintegrated rock, etc.	25–30°	2.0
D	Silty- or sandy-clay coatings, small clay fraction (non-softening)	20–25°	3.0
E	Softening or low friction clay mineral coatings, i.e., kaolinite or mica. Also chlorite, talc, gypsum, graphite, etc., and small quantities of swelling clays.	8–16°	4.0
	b) Rock-wall contact before 10 cm shear (thin mineral fillings)		
F	Sandy particles, clay-free disintegrated rock, etc.	25–30°	4.0
G	Strongly over-consolidated non-softening clay mineral fillings (continuous, but < 5 mm thickness)	16–24°	6.0
H	Medium or low over-consolidation, softening, clay mineral fillings (continuous, but < 5 mm thickness)	12–16°	8.0
J	Swelling-clay fillings, *i.e.*, montmorillonite (continuous, but < 5 mm thickness). Value of J_a depends on percent of swelling clay-size particles, and access to water, etc.	6–12°	8–12
	c) No rock-wall contact when sheared (thick mineral fillings)		
KLM	Zones or bands of disintegrated or crushed rock and clay (see G, H, J for description of clay condition)	6–24°	6, 8, or 8–12
N	Zones or bands of silty- or sandy-clay, small clay fraction (non-softening)	–	5.0
OPR	Thick, continuous zones or bands of clay (see G, H, J for description of clay condition)	6–24°	10, 13, or 13–20

	5. Joint Water Reduction Factor	water press. (kg/cm^2)	J_w
A	Dry excavations or minor inflow, *i.e.*, < 5 l/min locally	< 1	1.0
B	Medium inflow or pressure, occasional outwash of joint fillings	1–2.5	0.66
C	Large inflow or high pressure in competent rock with unfilled joints	2.5–10	0.5
D	Large inflow or high pressure, considerable outwash of joint fillings	2.5–10	0.33
E	Exceptionally high inflow or water pressure at blasting, decaying with time	> 10	0.2–0.1
F	Exceptionally high inflow or water pressure continuing without noticeable decay	> 10	0.1–0.05

Note: i) Factors C to F are crude estimates. Increase J_w if drainage measures are installed.
ii) Special problems caused by ice formation are not considered.

Table 8.2 continued

	6. Stress Reduction Factor			*SRF*
a) Weakness zones intersecting excavation, which may cause loosening of rock mass when tunnel is excavated				
A	Multiple occurrences of weakness zones containing *clay* or chemically disintegrated rock, very loose surrounding rock (any depth)			10
B	Single weakness zones containing *clay* or chemically disintegrated rock (depth of excavation $\leq$ 50 m)			5
C	Single weakness zones containing *clay* or chemically disintegrated rock (depth of excavation $>$ 50 m)			2.5
D	Multiple shear zones in competent rock (*clay-free*), loose surrounding rock (any depth)			7.5
E	Single shear zones in competent rock (*clay-free*) (depth of excavation, $\leq$ 50 m)			5.0
F	Single shear zones in competent rock (*clay-free*) (depth of excavation, $>$ 50 m)			2.5
G	Loose, open joints, heavily jointed or "sugar cube", etc. (any depth)			5.0
Note: i) Reduce these values of SRF by 25–50% if the relevant shear zones only influence but do not intersect the excavation.				
b) Competent rock, rock stress problems		σ_c/σ_1	σ_θ/σ_c	*SRF*
H	Low stress, near surface, open joints	>200	<0.01	2.5
J	Medium stress, favourable stress condition	200–10	0.01–0.3	1
K	High stress, very tight structure. Usually favourable to stability, may be unfavourable for wall stability.	10–5	0.3–0.4	0.5–2
L	Moderate slabbing after >1 hour in *massive* rock	5–3	0.5–0.65	5–50
M	Slabbing and rock burst after a few minutes in *massive* rock	3–2	0.65–1	50–200
N	Heavy rock burst (strain-burst) and immediate dynamic deformations in *massive* rock	<2	>1	200–400
Note: ii) For strongly anisotropic virgin stress field (if measured): when $5 \leq \sigma_1/\sigma_3 \leq 10$, reduce σ_c to $0.75\sigma_c$. When $\sigma_1/\sigma_3 > 10$, reduce σ_c to $0.5\sigma_c$, where σ_c = unconfined compression strength, σ_1 and σ_3 are the major and minor principal stresses, and σ_θ = maximum tangential stress (estimated from elastic theory).				
iii) Few case records available where depth of crown below surface is less than span width. Suggest *SRF* increase from 2.5 to 5 for such cases (see H).				
c) Squeezing rock: plastic flow of incompetent rock under the influence of high rock pressure			σ_θ/σ_c	*SRF*
O	Mild squeezing rock pressure		1–5	5–10
P	Heavy squeezing rock pressure		>5	10–20
Note: iv) Cases of squeezing rock may occur for depth $H > 350\ Q^{1/3}$ (Singh *et al.*, 1992). Rock mass compression strength can be estimated from $q \approx 0.7\gamma\ Q^{1/3}$ (MPa) where γ = rock density in kN/m^3 (Singh, 1993).				
d) Swelling rock: chemical swelling activity depending on presence of water				
R	Mild swelling rock pressure			5–10
S	Heavy swelling rock pressure			10–15

Note: J_r and J_a classification is applied to the joint set or discontinuity that is least favourable for stability both from the point of view of orientation and shear resistance, τ (where $\tau \approx \sigma_n \tan^{-1}(J_r/J_a)$). Choose the most likely feature to initiate.

$$Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF}$$

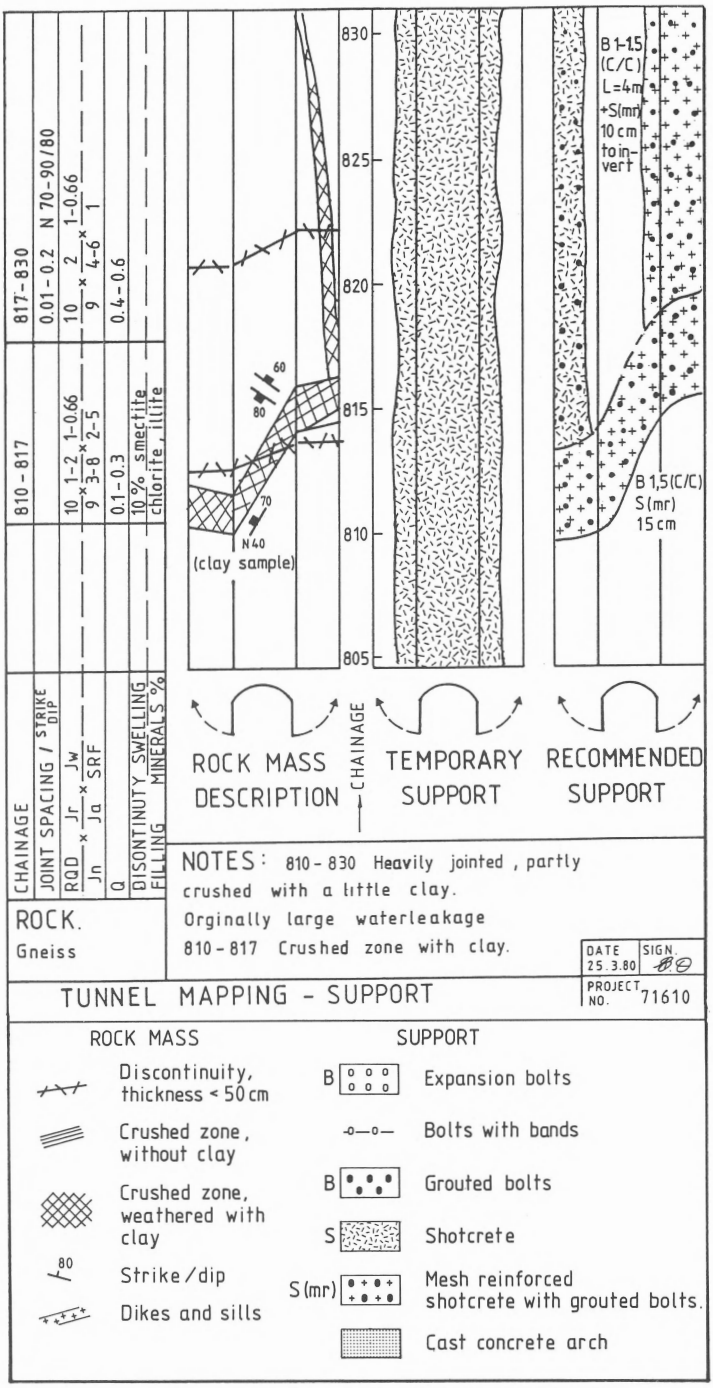


Figure 8.8 *A method of mapping tunnels for Q-system design of the rock reinforcement needs. Headrace tunnel, span 10 m, height 16.7 m (Barton et al., 1980).*

Table 8.3 *Excavation Support Ratio (ESR) for a variety of underground excavations*

	Type of Excavation	*ESR*
A	Temporary mine openings, *etc.*	*ca.* 3-5?
B	Permanent mine openings, water tunnels for hydropower (excluding high pressure penstocks), pilot tunnels, drifts and headings for large openings	1.6
C	Storage caverns, water treatment plants, minor road and railway tunnels, surge chambers, access tunnels, *etc.*	1.3
D	Power stations, major road and railway tunnels, civil defense chambers, portals, intersections	1.0
E	Underground nuclear power stations, railway stations, sports and public facilities, factories	*ca.* 0.8?

An inescapable feature of the rock masses through which tunnels are driven, as compared to the shotcrete and concrete used for their support, is their huge variability. For this reason it may be difficult to specify just one value of Q for a given stretch of tunnel, for a length of drill core, or for a surface rock exposure. With this in mind, the statistical method of recording the Q-parameters has been developed, as shown in Figure 8.9. This figure is also a convenient reminder of the parameter ratings shown in Table 8.2. The recorded statistics for RQD, J_n, J_r, J_a, etc., for the logged location in the rock mass provide a more reliable basis for support selection than a single Q-value. A weighted average, and typical minima and maxima are usually estimated as a basis for the tunnel support decision. The example shown in Figure 8.9, taken from the mapping of the 10 m span top heading of the 62 m span Olympic Ice Hockey cavern at Gjøvik, shows variability and main quality trends equally well. Further examples of the use of this mapping method at Gjøvik are given by Bhasin *et al.* (1993).

Design of shotcrete and rock bolt support for marked weakness zones of limited thickness, with different side rock qualities, should be performed on an individual basis. A method developed by Løset is described by Grimstad and Barton (1993).

Tunnel Support Details

Application of sprayed concrete and rock bolts as tunnel reinforcement allows great flexibility in the amount of support since the sprayed concrete thickness, the spacing between rock bolts and the spacing and thickness of sprayed concrete ribs for poor ground can be varied readily to suit the rock conditions. Only in the most adverse conditions and exceptionally poor rock masses are cast concrete arches necessary (see Figure 8.7, Class 9).

(i) Spacing between rock bolts

It will be noted that the spacing between rock bolts is 20 to 40% greater when steel fibre reinforced sprayed concrete is utilized than when only rock bolts are used. The bridging effect of the sprayed concrete, particularly when fibre-reinforced, is obvious.

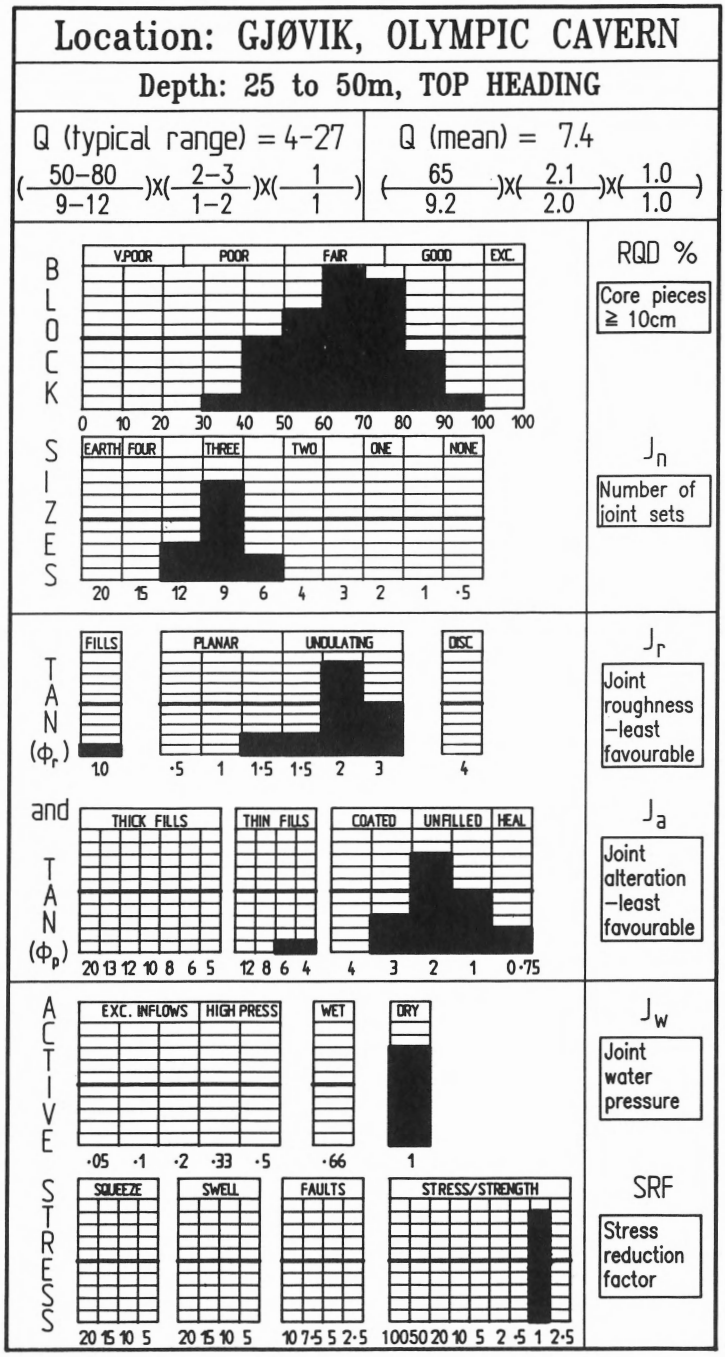


Figure 8.9 *Statistical recording of Q-system rock mass parameters (Barton, 1991)*

(ii) Length of rock bolts
The length of rock bolts used in normally-jointed rock mass, where systematic bolting is required, is given on the right side of the diagram in Figure 8.7. The length given is based on the equation:

$$L = 1.4 + 0.184 \times B \tag{8.2}$$

where L = bolt length, B = the span of the tunnel and ESR = 1.
(This is a modification of $L = 2.0 + 0.15\ B/ESR$ in the original Q-system.)

In cases with steep joints running parallel to the tunnel, or when deep wedges are likely to be released, the length of the bolts often has to be longer than given by this equation, and would be chosen specially to suit the particular case to ensure sufficiently deep anchorage.

(iii) Thickness of sprayed concrete
The reinforcement Class 4 (Figure 8.7) consists of rock bolts and *unreinforced* sprayed concrete when the block size is limited ($RQD/J_n < 10$). The typical thickness of S will be 4 to 6 cm in smaller tunnels. However, in large excavations for power houses with significant wall height, it is customary to use up to 10 cm thickness, even when the rock quality Q is as high as 30. The reinforcement Classes 5, 6 and 7 consist of $S(fr)$ varying in thickness from 5 to 15 cm, combined with systematic rock bolts. The bolt spacings given on the upper diagonal will apply in these cases. In these classes of rock mass involving significant deformation, the advantage of selecting the appropriate toughness index for the $S(fr)$ to suit the problem needs emphasis. The same applies to the next class of support. Thin layers of $S(fr)$ are more flexible than thick layers, which act more like cast concrete. Hence the rock should be allowed to deform before spraying the final layers of $S(fr)$.

(iv) Reinforced ribs of sprayed concrete (RRS)
The reinforced ribs of sprayed concrete shown as Class 8 reinforcement in Figure 8.7 will be necessary when the usual thickness of $S(fr)$ is insufficient for bearing the load, or if the shape of the blasted opening is very irregular and a more circular shape has to be built up in order to support the rock. RRS is an extremely flexible method in which the thickness, width and spacing of the steel bar reinforced ribs can be varied according to needs.

The use of spiling (inclined bolting) ahead of the tunnel face, and monitoring of closure will generally be an advantage in these extremely poor quality rock masses which typically have Q-values in the range 0.001 to 0.1. The contrast in ground control when using RRS instead of regular shaped steel sets and blocking is fairly clear, and the total amount of concrete (and time used) is potentially greatly reduced. The traditional use of steel sets and blocking is also known to cause an increase in the effective SRF value of the rock mass due to unnecessary loosening. Final loads on the support may be increased as a result. This type of rock mass deterioration can be minimized by use of RRS.

(v) Cast concrete arches (CCA)
In exceptionally poor rock (swelling or squeezing conditions) and in larger excavations, it will be necessary to use multiple drifting, spiling, pre-injection and drain-

age measures, and supplement the temporary RRS (or its equivalent) with full profile cast concrete arches using steel shuttering. Depending on the amount of overbreak that has occurred prior to placement of the temporary $B+S(fr)$ or RRS, the CCA thickness is likely to vary from an average 30 cm to 1 m or more locally. A stiff invert, preferable with a convex form, will be essential in this type of squeezing or swelling ground. Analysis of the stability, and monitoring of deformations in the area temporarily supported by $B+S(fr)$ or RRS (before placement of the cast lining) is essential.

Support pressure estimation

The poorest rock mass qualities almost always cause appreciable deformation of the tunnel periphery. In these cases, it is important to provide temporary support which is flexible, but strong enough to increase stand-up time and prevent collapse, while allowing the rock mass to gain a new stress distribution. The final support can be installed based on observations. In Norway, the temporary support is almost always a part of the final support.

Selection of *type* of support, and general *thickness* of support was given in the Q-NMT design chart (Figure 8.7). Some guidance concerning maximum likely rock pressures acting on the support is provided by the following empirical equation which fitted the available case records in 1974:

$$P_{arch} = \left(\frac{20}{J_r}\right) Q^{-\frac{1}{3}} \tag{8.3}$$

where P_{arch} is the support pressure in tons/m^2.

As an example, when $Q = 1$, and J_r (joint roughness number) is equal to 1.5, the typically designed support capacity will be 13 tons/m^2. A recommendation for a given bolt spacing in Figure 8.7 can therefore be converted to select the appropriate working load for the bolts. The choice of bolt diameters is frequently 20, 25 or 32 mm, with corresponding *yield* loads of approximately 13, 20 and 32 tons respectively, when steel quality of 500 N/mm^2 is used.

In the case of thick RRS or CCA linings, where structural support is provided by the consistently positive (i.e., non-negative) radius of the concrete or shotcrete arch, then the theory of thin-walled cylinders can be applied to help check the required thickness of concrete, assuming only compressive loading. An appropriate working stress for the concrete is needed. A more accurate solution can be obtained with numerical modelling.

8.4 Conclusion

The NATM support design philosophy (Rabcewicz, 1964/65) has been used on numerous occasions for weak ground tunnelling, in general with great success. NATM, which is most appropriate for weak ground, is based on a descriptive behaviouristic ground classification (often involving about 6 classes), appropriate selection of temporary support based on these ground classes, monitoring of deformation, and application of additional support where required from the measured deformations. The soundness of an active design approach, sometimes called design-

as-you-go (or more correctly, design-as-you-monitor), has been demonstrated by major cost savings compared to conventional, inflexible design approaches. However, it would be unfair to the NATM concept, and incorrect, to refer to all tunnels that have shotcrete and rock bolting as being "driven by NATM", as appears to be occurring in some quarters.

A newer concept, the NMT (Norwegian Method of Tunnelling), which is most appropriate for drill-and-blast tunnels in jointed rock which tends to overbreak, is frequently based on a quantitative (numerical) rock mass classification such as the *Q*-system (Barton *et al.*, 1974), appropriate use of temporary reinforcement such as rock bolting and fibre reinforced shotcrete, and supplementary reinforcement and support according to the engineering geologist's *Q*-based permanent support design. The tunnel span and the purpose of the excavation also figure in this selection of final support.

Despite the success of NATM in many weak ground tunnels, it clearly cannot be the best or cheapest method for tunnels in extensively jointed, harder rock masses that are drilled and blasted (as opposed to machine excavated). Extensive overbreak frequently causes mesh-reinforced shotcrete and lattice girders to be impractical, time consuming, possibly unsafe and to invite corrosion. Such methods may also cause unnecessarily large use of concrete. For this reason, Norwegian tunnellers were only too ready to stop using mesh reinforcement and steel ribs within a few years of developing the wet process, steel-fibre reinforced shotcrete method. Commercial application of wet process fibre-reinforced shotcrete in Norway by 1978 (Opsahl, 1982) gradually caused mesh-reinforced shotcrete to fall out of use by about 1984. Use of this revolutionary initial reinforcement and final support method since 1978 has increased to a level of 60,000 to 70,000 m^3 per year in Norway, close to the highest use in the world at present, despite Norway's small population. Robotic application 10 to 20 metres above, to the side of, or in front of the operator, production rates of 10 to 25 m^3/hour, low dust levels (rebound 5 to 10%), secured rock bolting conditions in unstable ground, and no problems with uneven profiles and overbreak, have caused a revolution in driving rates and tunnelling costs.

Cast concrete lined sections for permanent support of fault zones and clay-bearing rock are disappearing from use due to their cost and time constraints when compared to fibre-reinforced shotcrete. Rib (rebar) reinforced shotcrete with shotcrete and bolting are now used as permanent support in such zones at approximately half the cost of cast concrete. Similar advantages can be expected when such types of rock support are used as permanent support in tunnels or caverns in soft jointed rocks and in over-consolidated fissured clays, such as London clay.

In the past, attempts to combine the *Q*-system with NATM have been reported. Certainly, a more quantitative description of the six or seven NATM rock classes, using the *Q*-system, or using the RMR method of Bieniawski (1989), is inherently attractive. An interesting combination of NMT and NATM principles has recently been proposed for a major tunnel in partly soft and partly hard rock. Up-front prediction of support needs using the *Q*-system, temporary support close to the face, monitoring of resulting performance, and adjustment of support class (if necessary) for the application of final support well behind the advancing face appears to be an ideal combination of three well tried techniques, namely *Q*, NMT and NATM.

References

Amberg W. and Cristini F. (1986) The new Austrian tunnelling method in railway tunnel construction. *Rasegna dei lavori pubblici*, **5**, 241–252.

Barton, N., Lien, R. and Lunde, J. (1974) Engineering classification of rockmasses for the design of tunnel support. *Rock Mechanics*, **6**, (4), pp. 189–236.

Barton, N., Løset,F., Lien, R., and Lunde, J. (1980) Application of the Q-system in design decisions concerning dimensions and appropriate support for underground installations. *Int. Conf. on Sub-surface Space*, Rockstore, Stockholm, Sub-surface Space, Vol. 2, 553–561.

Barton, N. (1991) Geotechnical Design. *World Tunnelling*, November, 410–416.

Barton, N., Grimstad, E., Aas,G., Opsahl, O.A., Bakken,A., Pedersen, L. and Johansen, E.D. (1992) Norwegian Method of Tunnelling. WT Focus on Norway, *World Tunnelling*. June/August.

Bhasin, R., Barton, N. and Løset, F. (1993) Engineering geological investigations and the application of rock mass classification approach in the construction of Norway's underground Olympic stadium. *Engineering Geology*, Elsevier Science Publishers, Amsterdam, **35**, 93–101.

Brown E.T. (1981) Putting the NATM into perspective. *Tunnels & Tunnelling*, **13** (11), 13–17.

Brosch F.J. (1986) Geology and the classification of rock masses – examples from Austrian tunnels. *Bull. IAEG*, **33**, 31–37.

Deere, D.U., Hendron, A.J., Patton, F.D., and Cording, E.J. (1967) Design of Surface and Near-Surface Construction in Rock, in *Failure and Breakage of Rock*. (Ed. C. Fairhurst), Society of Mining Engineers of AIME. New York, 237–302.

Grimstad, E., Barton, N., Lien, R., Lunde, J., and Løset, F. (1986) Classification of Rock Masses with Respect to Tunnel Stability - New Experiences with the Q-system. In Norwegian in *Fjellsprengningsteknikk*, Bergmekanikk, Geoteknikk, Tapir Press, 3.1–3.18.

Grimstad, E. and Barton, N. (1993) Updating of the Q-System for NMT. *Proceedings of the International Symposium on Sprayed Concrete - Modern Use of Wet Mix Sprayed Concrete for Underground Support*, Fagernes, Norwegian Concrete Association, Oslo, 44–66.

Hagenhofer F. (1990) NATM for tunnels with high overburden. *Tunnels & Tunnelling*, **22** (5), 2.

Martin D. (1984) How the Austrians cracked the hard American nut with NATM. *Tunnels & Tunnelling*, **16** (12), 23–26.

Rabcewicz L.v. (1964/65) The new Austrian tunnelling method. *Water Power*, Part 1: November 1964, 511–515, Part 2: January 1965, 19–24.

Rabcewicz L.v. and Golser J. (1973) Principles dimensioning the support system for the new Austrian tunnelling method. *Water Power*, March, 88–93.

Singh, B. (1993) *Workshop on Norwegian Method of Tunnelling*. CSMRS, New Dehli.

Wallis S. (1987) Counting the cost of NATM downfalls. *Tunnels and Tunnelling*, **19** (10), 5.

Wallis S. (1988) Avoiding an NATM downfall. *Tunnels and Tunnelling*, **20** (6), 4.

9 Equipment for the Production of Sprayed Concrete

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P.Sommavilla, Aliva Ltd., Switzerland

This chapter describes the various methods and available apparatus for the production of sprayed concrete, as well as the individual features of special fields of application.

9.1 Spraying methods

Various production processes have been developed for the sprayed concreting technique. The distinguishing features are the manner of feeding the starting materials (dry mix or wet mix) and the method of transporting the sprayed concrete. Figure 9.1 gives an overview of the different methods. Other processes not included here have been developed and tested, though none have achieved widespread usage (see section on further developments).

Dry and wet spraying are the methods which have always dominated. There are essential differences between these two methods which influence the choice of the method for different applications.

Dry spraying method

In the dry spraying method, a dry mixture of cement, aggregate and occasionally powder accelerator additives is transported from the spraying machine to the spraying nozzle by compressed air, where the water is added via nozzles and the mixture is applied at velocities of 20 to 30 m/s and thereby compacted. Modern systems also use liquid accelerator additives which are added upstream of the spraying nozzle.

The water is generally controlled manually by the nozzle operator who thus has a significant influence on the w/c ratio and on the quality of the sprayed concrete. Disadvantages of this method are the development of high dust levels due to the compressed air and the relatively high percentage rebound caused by the high material velocity.

The decisive advantage of this method is its great flexibility. For example, small quantities of sprayed concrete can be processed easily and any necessary breaks in spraying can be bridged without the need to clean the equipment. Furthermore, the dry spraying method ensures trouble-free transport even over long distances (up to 350 m), thus eliminating the need for frequent movement of the equipment. Figure 9.2 shows a schematic representation of the dry spraying method, using the example of tunnel construction.

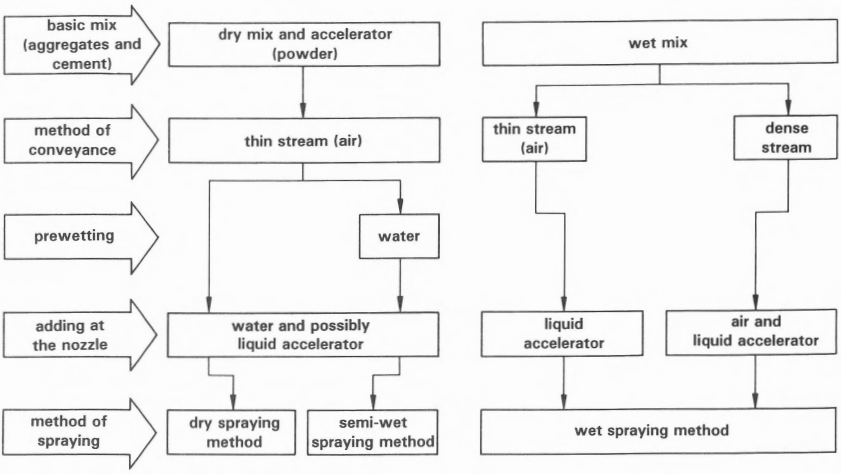

Figure 9.1 *Summary of concrete spraying methods.*

Wet spraying method

In the wet spraying method ready-mixed concrete (a mixture of cement, aggregates and make-up water possibly together with plasticizers) is transported to the spraying nozzle by pumps or compressed air. This produces a homogeneous concrete and causes less dust as the make-up water can be added during the production of the mix, maintaining a given w/c ratio.

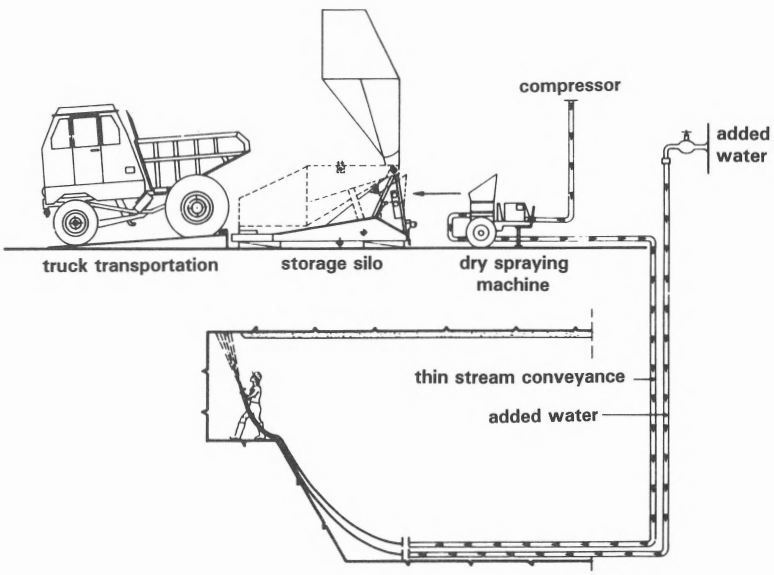

Figure 9.2 *Process technology of the dry spraying method.*

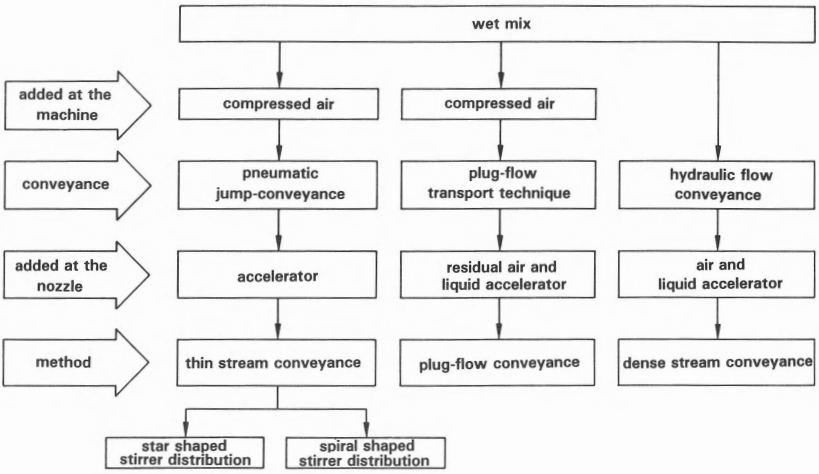

Figure 9.3 *Overview of the transport techniques for the wet spraying method.*

Disadvantages of this method are the shorter transport distances, the difficult handling of the filled spraying hose and nozzle and in particular its lack of flexibility. It is not suitable, for example, for processing smaller quantities of sprayed concrete with numerous breaks in placement, as prolonged stoppages in spraying necessitate the removal of the hardening concrete and a thorough cleaning of the complete spraying unit.

However, when spraying large quantities, this method is to be highly recommended because of the high delivery rates which can be achieved. A fundamental distinction is made between the two methods of transport for the wet spraying method (Figure 9.1):

- thin stream conveying method
- thick stream conveying method

Figure 9.3 shows an overview of the transport techniques for the wet spraying method. In the thin stream method, the compressed air necessary for transport and placement is admitted to the ready mixed concrete in the wet spraying machine. The concrete is transported pneumatically, in a similar manner to that used in the dry spraying method. The plug-flow transport technique which is very similar to the thin stream method differs from the conventional thin stream in that only the compressed air necessary for transport is admitted to the concrete in the machine. The air for placement is supplied at the nozzle; this air atomizes the concrete plug forced through the transport line and accelerates the concrete for placement. Use of the thin stream technique has decreased in recent years.

During thick stream transport (Figure 9.3), the material admitted to the transport line by the machine is transported hydraulically to the nozzle in a compact material stream. Conventional concrete pumps are generally used as spraying machines so that a forced conveying state is created in the transport line. At the nozzle, the compact concrete stream is atomized by the addition of compressed air and accelerated to the velocity necessary for placement and compaction at the surface. Powder or liquid accelerator additives can also be added at the nozzle. The wet

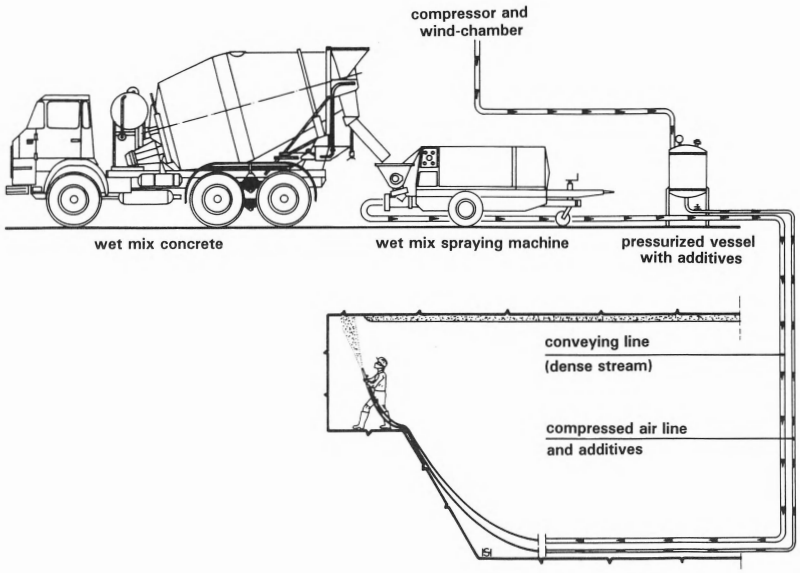

Figure 9.4 *Process technology of the wet spraying method.*

spraying method is illustrated schematically in Figure 9.4.

Comparison of the methods

The two methods are compared and contrasted in Table 9.1. The principle aspects to be considered are:

- operational;
- concrete technology;
- occupational health; and
- economic.

The comparison shows that there can be no fundamental preference for one of the two methods, as both methods offer undisputed advantages for specific applications. For example, the dry spraying method is to be preferred for small cross-sections at the face of the heading and also in mining due to its greater flexibility and the better transport of the mix. This is despite the problems of occupational health, the economic disadvantages (particularly with respect to the operating costs) and the slightly lower concrete quality. However, if cost-effectiveness and high placement rates are demanded, for example in tunnel construction where large volumes of concrete are to be placed, then the thick stream wet spraying method is to be preferred, particularly where spraying manipulators can be used.

Further developments

In the past, efforts have been made to develop new areas in sprayed concrete production to eliminate process-specific disadvantages and ideally to combine the advantages of the different methods.

Table 9.1 *Comparison of dry and wet spraying methods*

	Dry Spraying Method	Wet Spraying Method	
		Thin stream	Thick stream
A. Operational aspects			
Placement rate[1,2]	up to approx. 14m³/h		up to approx. 20m³/h
Machine power requirement[3]	low electrical energy only for injection into the air current, not for the actual transport		high hydraulic drive to generate the transport power
Compressed air requirement[3]	large for the pneumatic transport		low due to the hydraulic transport
Wear[4]	Slightly elevated due to dry material to be transported and high air volume (velocity)	Slightly lower due to lubrication of the wet mix (friction disc)	Low due to lubrication of the wet mix and low air volume
Transport distance[5]	up to 340 m	up to 80 m	up to 100 m
Transport problems[2]	Risk of blockages increases with increasing transport distance		Risk of blockages depends on concrete consistency, particularly with negligent maintenance and cleaning
Additive metering[2,6]	Powder and liquid additives, metering problems particularly with powder additives	Addition of liquid accelerator with additives, high requirement, particularly with large layer thickness	Metering problems in some cases during change over of double-piston pumps
Mix working time[2]	long with low intrinsic moisture content	short due to the risk of premature hardening of the ready mixed concrete	
Flexibility[2,6]	very high due to low space requirement/ operating weight, short set-up times, short cleaning times and long transport distances	moderate, due to low space requirement/ operating weight, short set-up times, but long cleaning times and short transport distances	very limited due to high space requirement/ operating weight, long set-up times, long cleaning times, limited transport distances
Interference with other operational activities[6]	low due to high flexibility		higher due to limited flexibility
Rebound	relatively high due to the high material velocity (large air volume)		relatively low due to low material velocity (small air volume)

Table 9.1 *cont'd*

	Dry Spraying Method	Wet Spraying Method Thin stream	Thick stream
B. Concrete technology aspects			
w/c ratio[2]	not defined, generally fluctuating due to control by the nozzle operator, low w/c ratios possible	clearly defined constant, generally high w/c ratios necessary (if FP is eliminated)	
Homogeneity of the concrete quality[2,6,7]	moderate, fluctuating w/c ratios and possible segregation during pneumatic transport	clearly defined constant w/c ratio. However, constant addition of accelerator additive essential	
Cement content[5]	300–400 kg/m^3	270–350 kg/m^3	330–450 kg/m^3
Additives	primarily accelerator additives, normal metering	primarily accelerator additives, highly increased metering	accelerator additives with generally highly increased metering, plasticizers frequently required, FP and AA problematical
Early strength	necessary early strength can be achieved with low AA metering	necessary early strength can only be achieved with high AA metering	
Final strength	generally higher due to low w/c ratios and lower AA metering, but larger variation	generally lower due to higher w/c ratios and higher AA metering, smaller variation	
C. Occupational health aspects			
Dust development at the spraying machine[8]	heavy development of dry dusts	less dust development	
Dust development at the nozzle[8]	heavy development of dry dusts	relatively heavy development of damp dusts due to high air requirement	less heavy development of damp dusts, visible coarse dust minimized greatly
Weight of the nozzle	reasonable for manual placement		reasonable for manual placement with low placement rates
Noise and vibration	widely differing from machine to machine, in some cases ear protectors recommended, irrespective of method		

Table 9.1 *cont'd*

	Dry Spraying Method	Wet Spraying Method	
		Thin stream	Thick stream
D. Economic aspects			
Equipment costs	relatively low due to the lower technical complexity		higher due to expensive concrete pumps
Energy costs	considerably higher due to the energy costs for the generation of the transport air		low due to hydraulic transport
Material costs[3]	higher due to the high rebound rate		much lower due to low rebound, but higher cement requirement
Personnel costs/m³ sprayed concrete[9]	decreasing personnel costs with increasing placement volumes		due to high placement rate up to 20m³/h, considerable cost reduction possible
Economic application criteria	use for low placement rates, frequent movement and with limited available space	use for very small w/c ratios (silica fume and plastic-modified concrete)	use for large placement rates and when manipulator can be employed

[1] Maidl, 1984; [2] Schreyer, 1986; [3] Wind and Kern, 1987; [4] SIA 118; [5] Brux *et al.*, 1981; [6] Egger, 1985; [7] Ruffert, 1984; [8] Handke, 1987; [9] Lauffer, 1987

The main new developments in this context are:

- the vortex chamber method;
- the SEC Shotcrete (*S*and *E*nveloped with *C*ement) or two-way method; and
- the roller formwork method.

Vortex chamber method

The vortex chamber method is a modification of the dry spraying method. The method employs a pressure chamber installed in the line in which the water (with controlled metering) is mixed with the cement by an agitator arm. Where necessary, accelerator additives are admixed at the nozzle. The vortex chamber method creates little dust (Brux *et al.* 1981) and the influence of the nozzle operator on the w/c ratio is eliminated. The method has been tested on construction sites, but has not yet become particularly widespread.

SEC shotcrete

A further development, promoted particularly in Japan, is the SEC Shotcrete method. This method closely resembles the two-way method developed in Germany by Bilfinger and Berger in conjunction with Intradym which has never competed with the two traditional concrete air placement methods.

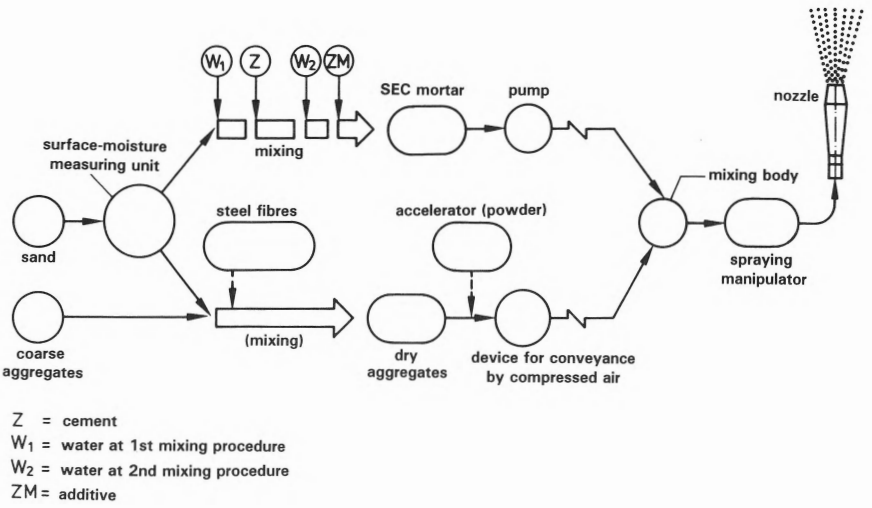

Figure 9.5 *The SEC shotcrete production process.*

In the SEC Shotcrete method, the mortar and coarse aggregates are prepared and transported separately. The mortar is prepared as SEC mortar in a special process and pumped to a mixer located upstream of the spray nozzle. The special feature of the preparation process is the split mixing process in which sand with an exactly controlled surface moisture content is first mixed with cement and then the remaining make-up water and a special additive are admixed in the second stage of the

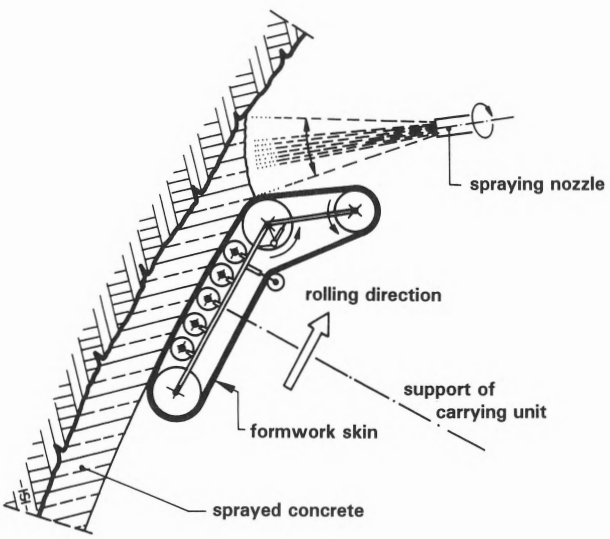

Figure 9.6 *Holzmann roller formwork.*

mixing process. This confers on the mortar a particularly good pumpability. The mortar is transported by compressed air in the thin stream method to the mixer. In the mixer, the mortar transported by a screw pump and the coarse aggregate are brought together and transported via the spray nozzle to the surface to be coated (see Figure 9.5). Despite the undeniable advantages of the two-way method, it has not established itself due to the high investment costs, the high degree of mechanization and the complexity of the system (size of the equipment and susceptibility to malfunctions).

Roller formwork method

A further development of the spraying method is the Holzmann roller formwork method developed in 1985 by the Philipp Holzmann AG (Figure 9.6). This method was developed to solve the problems of rebound and dust associated with the air placement method (Braun, 1991). The system is based on a roller formwork element which functions on the principle of a crawler chain. A flexible endless formwork "skin" ensures a brief supporting and levelling of the sprayed concrete coating. The sprayed concrete jet is aimed at the gap between the rock face and the roller formwork in such a way that the bonding and adhesion to the rock face and the compacting effect are assured. The period which the concrete spends between the rock face and the roller formwork depends on the adhesion to the rock and is generally only a few minutes. The roller formwork permits immediate construction of the sprayed concrete shell in its full thickness and is guided either by a frame or, with larger tunnel cross-sections, by the booms of mobile equipment. A similar technique is used in the Swift Lining Method promoted by Tekken Construction and Saga Kogyo.

A further system (Figure 9.7), also developed in Japan especially for tunnel construction, is the Sliding Press Lining (SPL) method. Here again a type of mobile formwork with a roller-guided endless belt running across its surface is guided, under computer control, along the excavation surfaces by a manipulator arm. The

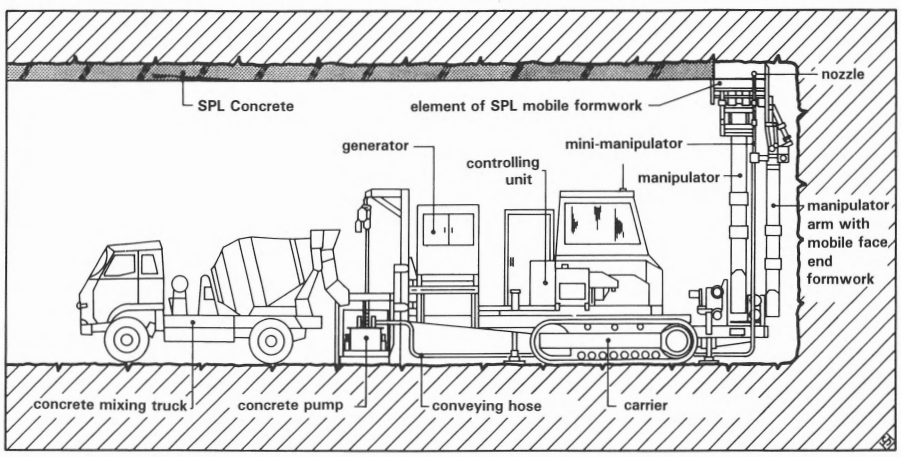

Figure 9.7 *Sliding Press Lining machine, SPLM (Gifu Kogyo Co. Ltd., Japan).*

concrete is injected between the rock face and the formwork element and compressed by the pressure exerted by the manipulator arm. The end of the face is formed by a mobile face end formwork.

This system permits the continuous production of tunnel shells from sprayed concrete without any rebound and without developing dust. The process combines the benefits of the conventional dry and wet spraying methods (Egger, 1985; Distelmeir, 1985), but requires larger cross-sections and is relatively inflexible.

9.2 Mixture preparation and placement

The sprayed concrete production process can be split into two stages, firstly the preparatory stage in which the starting material is produced (generally using mixers) and then the placement process, which includes all the aspects of the continuous production process from injection of the material into the transport lines up to the nozzle operation.

Preparation

The equipment and apparatus for the preparation of the mixture for production of sprayed concrete is essentially dictated by the amount of the spraying to be performed and frequently by limitations on the space available.

If the site has sufficient space for the storage of aggregate and cement and for installing a mixer, the mixture is generally prepared for both the dry spraying and wet spraying method in a stationary mixer. In this case, particular attention must be paid to the setting up of the aggregate store; of particular importance with the dry spraying method is the moisture content of the aggregate. Excessive moisture contents have a detrimental effect on the transport behaviour of the material and result in an increasing number of blockages, and thus a noticeable decrease in performance.

In confined spaces a ready mixed material is usually used. For the wet spraying process, this comes in the form of ready-mixed concrete fed to the sprayed concrete pump by mobile mixers. For dry spraying an oven-dried mixture is used, supplied by the concrete manufacturer in sacks, big bags or containers.

When processing large quantities of dry mixture supplied in bags, the mix is generally buffer-stored in silos or hydraulic hoppers with a capacity of several cubic metres. These are raised gradually to load the spraying machine (see Figure 9.2). The frequent filling processes required can result in an enormous development of dust which can be avoided in some cases by the use of container material. In this case, the complete mixture is supplied by the concrete works in closed silos, ready mixed to the customer's requirements. The silos are then delivered to the site where they are set up and the material can be drawn directly from the silos.

The use of predamping systems also allows dust levels to be reduced in the preparation area. A further advantage of predamping is that it reduces the difficulty of achieving an adequate mixing of the otherwise kiln-dry material with the make-up water at the nozzle.

In confined spaces and rapidly changing working sites (typical in tunnel construction) the use of mobile preparation units has proved to be effective. Figure 9.8 shows this type of compact mobile preparation unit. This unit, developed by VER-



Figure 9.8 *The mobile preparation unit, Robomix 7000AS (Vertex International AB).*

TEX International AB (Sweden), comprises all the equipment necessary for the preparation of the concrete: storage silos for cement and aggregate, metering facilities for water and additives, an integral placement manipulator and a steel-fibre feed unit. The unit can be used for both wet and dry spraying.

Placement technique

The placement technique involves the variabilities of nozzle operation, including manual and mechanical nozzle operation up to automatic procedures with all its advantages and disadvantages (see Section 9.5). In this respect also, a distinction is made between dry (Section 9.3) and wet spraying (Section 9.4), as different equipment is used due to the differences in methods of feeding the starting material and transport.

9.3 Dry spraying equipment

Dry spraying machines

A distinction can be made between the following four types of dry spraying machines, each of which is represented commercially:

- pressure chamber machines;
- screw-type machines;
- rotor-type machines; and
- automatic guniting machines.

The pressure chamber machines are regarded as the oldest air placement machine system. Their development goes back to the earliest days of sprayed concreting technology, around 1910. Even though no significant design improvements have been made since around 1950, pressure chamber machines are still used (albeit in decreasing numbers) due to their thoroughly developed and sturdy technology.

The pressure chamber machines comprise two chambers one above the other: a storage chamber and, beneath, a working chamber from which the material is drawn off and fed into the spraying line using a pocket wheel (Figure 9.9). Since the working chamber has to be pressurized in order to transport the material into the transport hose, the two chambers are separated from one another by a cup valve. When

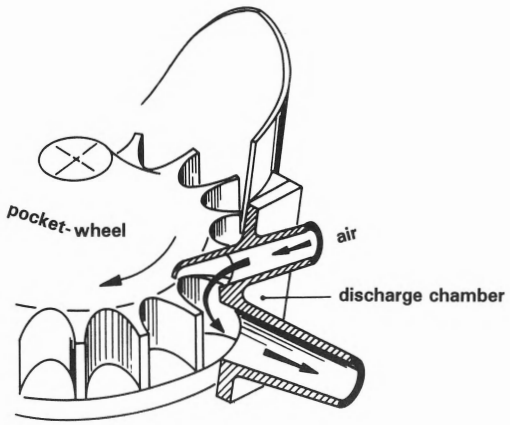

Figure 9.9 *Pocket wheel of a two chamber machine.*

the lower chamber is empty, the charging port above the upper chamber is first closed; this chamber can then be pressurized. The valve between the two chambers is then opened and the lower chamber is filled by the material sliding in from above. When the shut-off valve is closed, the upper chamber can be opened and filled again. This system permits a more or less continuous process to be maintained. The delivery rate can be varied with the size of the chambers (i.e. machine type). With the same machine type, the delivery rate can be varied by changing the blow-out nozzle and the diameter of the connected transport hose (Brux *et al.*, 1981).

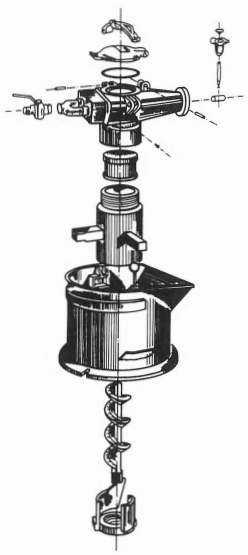

Figure 9.10 *Explosion draft of a screw machine.*

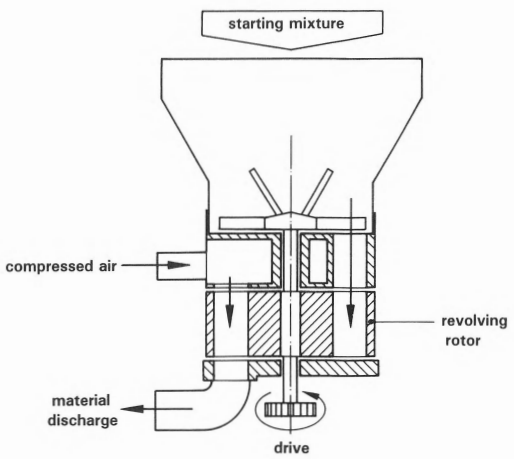

Figure 9.11 *Functional principle of a rotor-type machine.*

The screw-type machines were developed with the intention of achieving continuous transport of the dry spraying material. This development was substantially advanced by Senn, later to be the founder of Aliva AG, who in 1940 designed a machine with an Archimedean screw which lifted the dry mix continuously into the transport line where it was picked up and transported by the air current (Figure 9.10). However, the principle of this process has hardly been used for the dry spraying method since the mid-1960's as the wear caused to the transport screw by the dry material could not be controlled (Scherer 1987).

Rotor-type machines, whose development goes back roughly to 1950, are those used most extensively for dry spraying. The principle of this type is illustrated in Figure 9.11. These machines consist of a flat steel cylinder with different openings arranged parallel to the axis. A storage hopper is mounted on this cylinder which resembles the horizontal barrel of a revolver. The material fed into this hopper fills the openings of the cylinder and falls into the blow-out nozzle below when the rotor turns. The compressed air admitted here then blows the material into the hose. A thick rubber disc is installed underneath the rotor to seal the pressurized blow-out nozzle from the holes in the rotor which are open from above. Due to the wear caused by the cylinder rotating on this disc, it has to be replaced at regular intervals. Figure 9.12 shows an example of the rotor-type machines.

Design improvements aim to reduce the wear of the rubber seal under the rotor (in some cases by using automatic lubrication systems) and to increase the ease of maintenance. Of note here is a system patented by Aliva in which the rotor chambers are designed as expandable hoses. These hoses expand when subjected to compressed air ("breathing") and thus create a self-cleaning effect with no settling of the material transported on the rotor vessels (Scherer, 1987).



Figure 9.12 *Spraying machine with rotor feed, Aliva 262 (Aliva AG).*

A new type of machine is the SBS automatic spraying unit, a further development of the classical two-chamber machine. The unit has only one working and pressure chamber from which the material is drawn off by a pocket wheel in the same way as in the two-chamber machines. However, the continuous filling of the chamber is effected by a rotating cone with pockets located horizontally under a charging hopper and not by a second pressure chamber arranged above the working chamber. The material falling from the charging hopper into the pockets of the cone is transported into the working chamber by the rotation of the cone. This new development thus combines the two proven systems of the two-chamber machine and the rotor-type machine. The unit has a lower air requirement than two-chamber machines of the same size, transports continuously and is subject to less wear than rotor-type machines. The automatic charging also permits the use of remote control facilities, i.e. attachments with which the nozzle operator can directly control the delivery rate, delivery pressure, etc. as required.

Spray nozzles for the dry spraying method

The nozzle fulfils an important role as the mixing of the dry material with the make-up water and possibly liquid accelerator additives takes place in the nozzle area. There are various nozzle designs, but to date no scientifically based comparative studies have been undertaken on them. The first investigation and theoretical studies are currently being carried out at the Ruhr University, Bochum.

The conventional nozzle (Figure 9.13) consists of a conical plastic tube preceded by a water ring through which the make-up water is admitted to the material flow. The water supply is normally regulated by the nozzle operator via a control valve. An additional system for the admixing of accelerator additive is not necessary as in the dry spraying method the additive is mixed as a powder with the dry mix or is admitted in liquid form with the make-up water.

Any attempt to improve this simple nozzle technique has to accommodate these requirements:

- achieve an optimum metering and distribution of the make-up water and, where necessary, accelerator additive to achieve a homogeneous and high quality sprayed concrete.
- bind the fine dust in the dry mix before it leaves the nozzle to improve the working conditions of the nozzle operator.

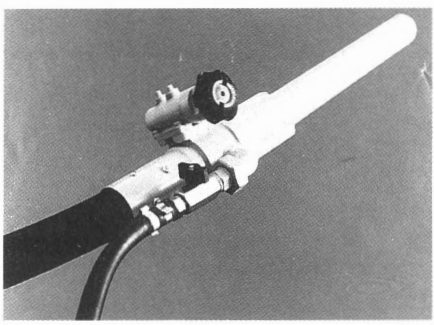

Figure 9.13 *Spray nozzle, Aliva 221 (Aliva AG).*

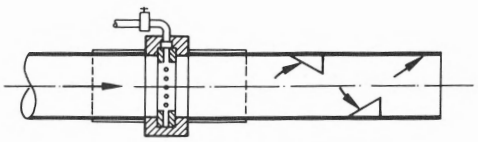

Figure 9.14 *Spray nozzle with flow hinderers.*

Metering of the make-up water during the dry spraying process has to date been left to the experience and subjective judgement of the nozzle operator who thus has a significant influence on the quality, dust development and rebound. The introduction of metering and control units for regulating the water and compressed air supply would certainly be an expedient measure. However, the continuous metering of the material flow necessary for altering the water volume relative to the fluctuating material flow remains a problem. Furthermore, such devices must be very sturdy and easily operated.

Several methods are used to achieve a complete mixing of dry mix and make-up water to produce a homogeneous concrete with binding of the fine dust. For example, obstacles in the nozzle create greater turbulence and thus better mixing (Figure 9.14), as does a change in cross-section, such as expansion and reduction. Although this results in better mixing, the obstacles also increase the risk of blockages in the nozzle area and the greater turbulence results in more extreme dust development after the material leaves the nozzle (Blümel and Lutsch, 1981).

In premoisturizing nozzles water is added through water rings at a fixed distance from the nozzle body to create a longer mixing section. To reduce dust, the optimum distance between the water addition and the end of the nozzle is approximately 2 metres (Handke, 1987). An enormous increase in the water pressure (approximately 100 bar) creates a better mix but the critical factor here is the velocity at which the water is injected into the material stream. With this type of nozzle, the mixer is located at the nozzle. The arrangement of several distribution rings in this system creates a water curtain through which the dry mix is blown. There are not yet any systems which achieve the high velocity using diaphragms or variable water openings with normal pressure conditions.

The use of special discharge nozzles for the make-up water has also been investigated, but without notable success. In some cases, such special nozzles have even increased the dust development (Wind and Kern, 1987) and resulted in a significant increase in wear. A nozzle which applies a spiralling impulse to the spray jet, similar to that in the barrel of a gun, has been used in the USA.

Also worth mentioning is a special nozzle for steel-fibre sprayed concrete where the steel fibres are admixed directly at the nozzle. In this system, the steel fibres are transported pneumatically through a hose to the nozzle and mixed into the dry material flow at the nozzle (Brux *et al.*, 1981).

9.4 Wet spraying equipment

Due to the different transport techniques employed, a distinction should be made between the thin stream and thick stream methods.

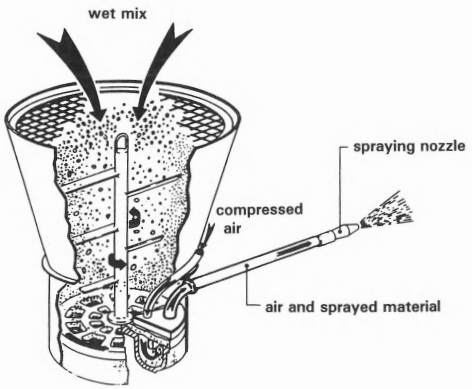

Figure 9.15 *Functional principle of the system patented by Reed Manufacturing Co.Inc.*

Thin stream machines

Although wet spraying using the thin stream process has become less common in recent years, the equipment used for this and for the plug-flow technique (which is very similar to the thin stream process) are discussed here. The following all use the same functional principles of the thin stream method:

- wet spraying machines with pocket wheel and cell wheel;
- rotor-type machines;
- pressure chamber machines with screw conveyor;
- pneumatic pumps with plug-flow transport.

Wet spraying machines with pocket wheel and cell wheel do not differ significantly in function from the corresponding dry spraying machines. They are often the same machines used for dry spraying, for example the Reed Lova machine (Figure 9.15) described below.

The charging hopper of this machine forms the working chamber and contains agitator arms for remixing the wet mix which drops into the cells of a cell wheel. The cells are divided into an outer and an inner ring by a rib extending to half the cell depth. As the cell wheel turns, one cell at a time is positioned under an air nozzle. The air jet presses the wet mix under the rib and out of the inner ring via the outer cell half into the transport line to the spray tube. Due to its open design, the spraying machine operates continuously. The cell wheel operation with sealing segments of the same size (one sixth of the rotor surface area) exhibits low wear (Brux *et al.*, 1981), though in order to prevent smearing and blocking of the machine parts, only concrete mixes with low w/c ratios are used (Blümel and Lutsch, 1981).

The rotor-type machines used for wet spraying in the thin stream technique are generally machines which can also be employed for dry spraying. One example is the Aliva 285 (Figure 9.16). The operating principle of the rotor-type machine is explained in Section 9.3.

The pressure chamber machine with screw conveyor is another thin stream process machine. A horizontal screw located under a tank filled with material transports the concrete in a dense material stream to the feed opening where compressed



Figure 9.16 *Rotor-type machine, Aliva 285 (Aliva AG).*

air is admitted. The air breaks up the dense concrete stream and transforms it into a thin stream. At the same time, the compressed air transports the concrete constituents to the spray nozzle. The material tank above the screw is pressurized and must therefore be sealed after filling and before the start of conveying. This is normally achieved using a bell-type valve. The resulting discontinuous transport can be avoided if two tanks linked by connecting pipework are used. Whilst the material is being drawn from the one tank, the other can be filled.

Pneumatic pumps with plug-flow transport is a pump system which is used primarily for the processing of floor screed and mortar and only very seldom for the production of sprayed concrete. Due to their design, these pumps operate discontinuously which leads to problems in processing the material at the nozzle. However, the principle has proved effective for mixing and transporting stiff-plastic to earth-moist materials. The wet mix in the pressure tank is transported to the blow-out opening by mixer arms, loosened and accelerated with compressed air from an injection nozzle and transported by compressed air to the spray nozzle where it is sprayed by a further addition of compressed air.

Thick stream machines

These are not special spraying machines. The following types of commercial concrete pumps, possibly with minor modifications, are used for the thick stream technique:

- piston pumps;
- pumps with screw conveyors;
- rotor-type hose pumps.

Piston pumps are conventional concrete pumps and account for most of the machines used for thick stream transport. The material is pushed into the transport line by one or two alternating pistons and transported smoothly to the placement point. A distinction must be made here between single-piston pumps, double-piston pumps, reciprocating piston pumps and differential piston pumps. The technical developments of the single-piston pump principle have been aimed at increasing the delivery (double-piston pump) and at achieving a more continuous delivery.

The technology of the double-piston pump has gained ground to such an extent in recent years that this pump design is almost exclusively used for the thick stream technique. In contrast to the conventional concrete pumps of this design, the duration of the changeover phase between the pipes is much shorter so that a nearly continuous delivery is achieved.

Concrete pumps with a screw conveyor are characterized by continuous and pulsation-free transport which favours an accurate metering of additives. As these machines require no valves (which frequently cause problems), the screw pumps can be regarded as operationally reliable. The wet mix is transported by a conveyor screw (rotor), which is mounted in a screw barrel (stator) made of an elastic material, through the transport line to the placement point. Screw pumps can develop delivery pressures of up to 20 bar so that long transport distances are possible.

Spray nozzles for the wet spraying method

There are important differences between nozzles for thin stream and thick stream systems. The simplest nozzles for the thin stream process are spray tubes, simple extensions to the transport line, though these can only be used when nothing else is to be added (accelerator, compressed air) at the nozzle. If accelerator additives are necessary, spray nozzles are used which are very similar in design to the conventional dry spraying nozzles. An accelerator is injected into the concrete stream by

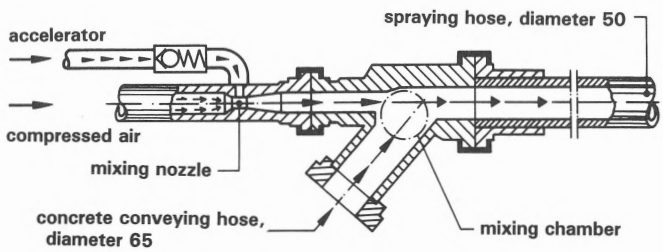

Figure 9.17 *Top-Shot turbo injector nozzle (Schwing GmbH).*

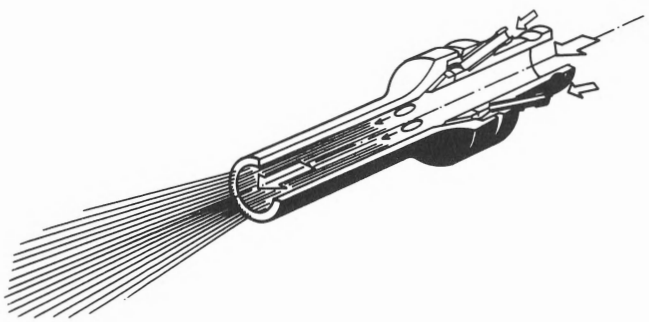

Figure 9.18 *Betojet nozzle (Putzmeister GmbH).*

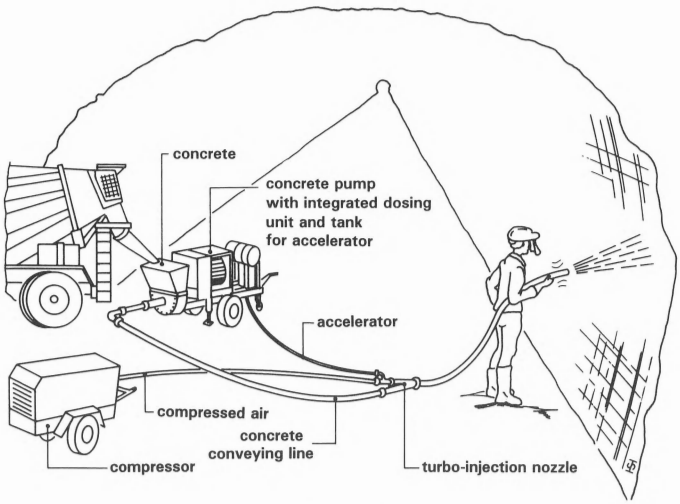

Figure 9.19 *The Top-Shot system (Schwing GmbH).*

compressed air via distribution rings in much the same way that water is added in the dry spraying technique.

When wet spraying with the thick stream technique the ready mixed concrete is transported in a compact stream to the nozzle (Figure 9.17). At the nozzle, the material first has to be accelerated to the placement velocity necessary for compaction; this is achieved by the addition of compressed air. A transition from thick stream to thin stream thus takes place in the nozzle. Accelerator additives can also be injected into the concrete with the compressed air. Differences in design of the wet spraying nozzles relate to the supply of the air for acceleration and the injection of the accelerator additives.

The compressed air is admitted either transversely to the dense concrete stream or at the circumference of the nozzle (Figure 9.18). Where the compressed air is injected before the nozzle, the concrete is picked up by the air current and torn into coarse pieces. A narrow spray jet with high placement velocity is produced so that relatively large placement ranges can be achieved. Spraying between reinforcements is also possible due to the geometric form of the spray jet. It should be noted, however, that high placement velocities result in segregation of the material at the application surface.

Efforts are being made to achieve a better mix of the wet concrete with the accelerator. Good results have been obtained with extension hoses up to 6 metres long mounted on the nozzle body (Figure 9.19). The compressed air/accelerator mix is injected into the dense concrete stream in the nozzle body, the concrete stream is fragmented and transported through the extension (spraying) hose as a thin stream. In addition to providing an additional mixing section for the accelerator additive, this also has the advantage that the nozzle operator only has to guide the light spraying hose with the thin stream concrete, and not the heavy nozzle.

A new approach is to use a double air supply, at the nozzle and at the end of the spraying hose. The accelerator additive is injected at the nozzle body with only part

of the necessary air volume. At the end of the hose, the mixture is then accelerated to the necessary placement velocity with the remaining air. The conventional nozzles with air feed at the circumference can be used for this purpose. As a result of the reduced acceleration of the atomized thick stream at the nozzle body, the pulsating behaviour of the concrete pump can be offset to a certain extent. As with the dry spraying method, there are some nozzles, primarily in the USA, that impart a spiralling impulse to the spray jet.

Special designs for producing steel-fibre reinforced sprayed concrete also exist in the field of wet spraying where the steel fibres are added at the nozzle. A particularly interesting system of this type is the Meyco Cutex process which has been marketed recently by Meynadier AG and which has already been used in the same form in Sweden, Finland and Australia by Ekebro International AB (Sweden). In this method, steel wire is unwound from two coils and continuously admitted at variable speeds into a specially designed spray nozzle. In this nozzle, the steel wires are cut at high speed to previously set lengths and then transported to the application surface with the sprayed concrete. Apart from the advantages described above of the fibre addition at the nozzle, this system also offers the benefit that the fibre length which is otherwise limited by processing factors, can be increased considerably. The positive effects of longer fibres on the material properties of the steel-fibre reinforced concrete can thus be obtained without processing problems.

9.5 Automatic nozzle operation

The nozzle operation is of particular importance in the production of sprayed concrete. Concrete quality and rebound are determined by the perpendicular impact of the sprayed concrete jet on the surface, by maintaining an optimum spraying distance and by the form of the nozzle movement (Guthoff, 1991). It is difficult to meet these requirements satisfactorily by manual nozzle operation in either dry or wet spraying. The demands on the nozzle operator are particularly severe with overhead spraying where he is also exposed to very unpleasant working conditions.

In view of this, a move away from the manual nozzle operation seems necessary. With the introduction of spraying manipulators, efforts have been made to achieve improvements in the criteria of material quality, rebound rate and dust control (see Figure 9.20).

Manipulators

The use of manipulators makes it possible to remove the nozzle operator from the immediate danger area of sprayed concrete application. This provides protection from rebound and falling rock in unsecured zones as well as a reduction in the exposure to the health endangering dust and accelerator additives. The nozzle operator is also relieved of the severe physical load resulting from the recoil forces at the nozzle and from the weight of the hose during the wet spraying process. Furthermore, the time-consuming operation of scaffolding erection can often be eliminated because of the greater reach offered by manipulators (Handke, 1985).

The reduction in rebound rate resulting from the optimum nozzle operation technique (Diecken, 1990; Guthoff, 1991), the increased throughput and consequent higher utilization of the equipment as a whole all contribute to an increase in cost-

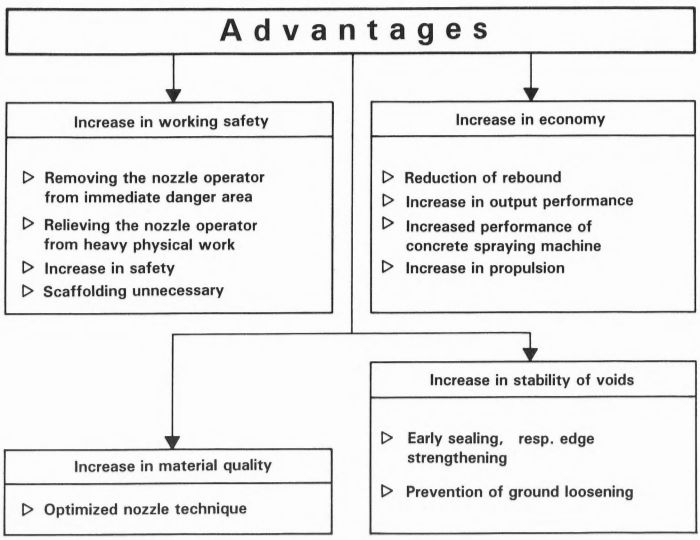

Figure 9.20 *Advantages of the use of spraying manipulators.*

effectiveness. With manipulators, placement rates of up to around 20 m³/h can be achieved.

Disadvantages include the increased observation distance of the operator and the large amount of equipment required. As the nozzle operator is some metres away from the point of application, his view of the work is hindered considerably, particularly with high dust development, so that difficulties are encountered in ensuring an optimum spraying technique. These problems are often increased by the complex control of the kinematics.

The large amount of equipment required when using manipulators requires equally high investment, so that their use is only economical where large volumes of concrete are to be placed. Furthermore, the manipulators on the market today have limitations in confined spaces because of the large space they themselves require. Further development work is therefore required to develop and improve the manipulators and robots.

The manipulators available can be classified on the kinematics of their boom system. The simplest system, the pivoting and inclining telescopic boom, permits raising and lowering of the boom arm via hydraulic cylinders, extension via the telescoping facility and pivoting via a ring gear which provides the link between the boom and the carrier system (Maidl, 1990). To achieve the necessary longitudinal advance when using the horizontal nozzle guidance and still maintain a constant nozzle distance from the face, this system is frequently mounted so that it can move on the carrier system. Without this, it would be necessary to have a pivoting, inclining and telescoping adaptation of the boom system. The mobility is achieved via a rail system which is mounted on a height-adjustable platform. Figure 9.21 shows a system from the Swedish manufacturer, Stabilator, with this type of manipulator.

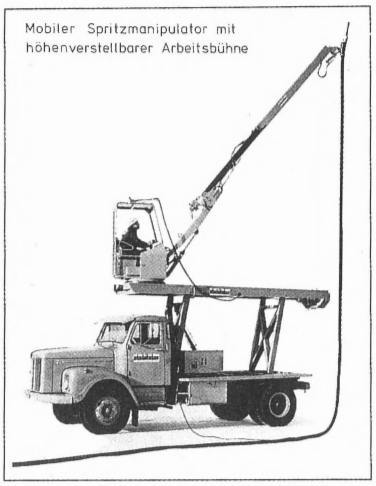

Figure 9.21 *Pivoting and inclining telescopic boom.*

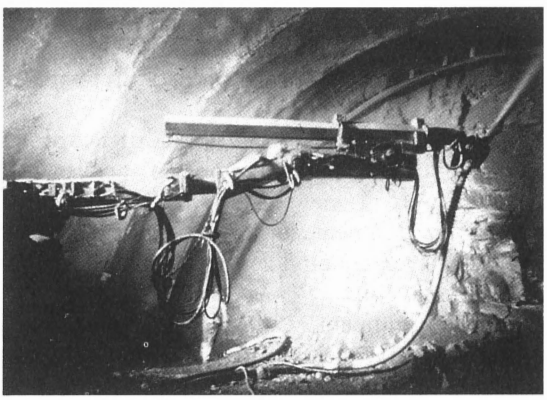

Figure 9.22 *Pivoting and inclining boom in combination with a telescopic slide.*

Starting from this basic system, the second system has an additional telescoping slide (Figure 9.22). Pivoting and balancing cylinders ensure an automatic lateral and vertical parallelism of the slide relative to the axis of the cavity. Horizontal guidance of the nozzle is achieved by the longitudinal advance of the slide alone (*ibid.*).

The upper arm of the third system, the double pivot arm design (Figure 9.23), again shows the basic system of a pivoting and tilting telescopic boom. The lower arm is raised and lowered via hydraulic cylinders. An additional telescoping facility offers a greater working range. The pivot of the two arms is formed by a cabin housing the nozzle operator's control desk. A parallelogram technique ensures that the cabin is always guided parallel to the travelling surface of the carrier system.

The basic principle of all the systems described is the facility to pivot about a

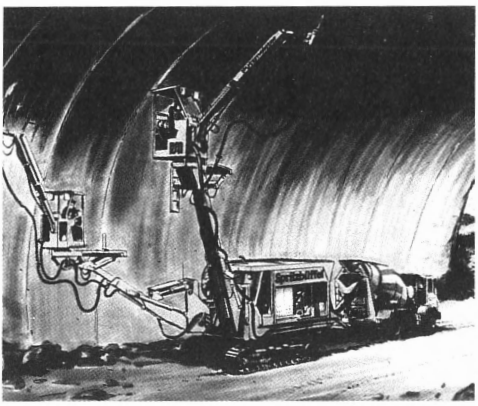

Figure 9.23 *Drawing of double pivot arm construction.*

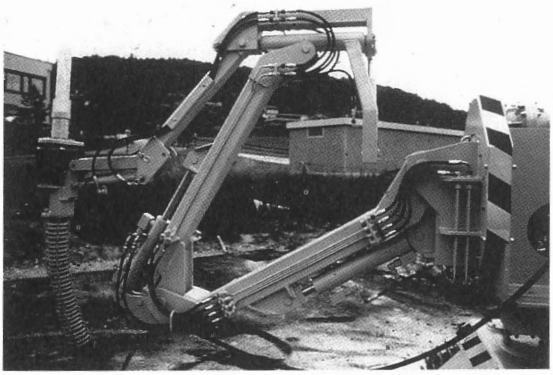

Figure 9.24 *Boom configuration which can pivot about its longitudinal axis.*

vertical axis. The systems described below allow the boom to pivot about a horizontal axis and thus permit an exactly vertical nozzle guidance and the lining of circular profiles. The boom configuration illustrated in Figure 9.24 consists of one main arm and two auxiliary arms. The main arm allows pivoting about the horizontal axis and it is raised and lowered via hydraulic cylinders. The pivot mounting of the lower of the two auxiliary arms permits the angle of inclination to be varied, thus allowing longitudinal advance of the upper auxiliary arm. In addition, this auxiliary arm can be rotated about its own longitudinal axis.

Another system which allows pivoting about a horizontal axis is the 'sliding tree' set-up (Figure 9.23) comprising a straight telescoping arm which can rotate about a horizontal axis. The connection between the telescoping arm and carrier system is formed by a sliding tree which allows a longitudinal advance.

Spraying robots

The harsh working conditions of the nozzle operator can only be partially eliminated using manipulators, because he/she must still be within sight of the nozzle. Any further improvements in working environment are likely to require the development of robots within the sprayed concrete industry.

Compared with other branches of engineering, the use of programmable robots for concrete spraying is still in its infancy. This can be attributed primarily to the difficulties in transferring technology developed for the controlled environment of a factory into a form suitable for use in the harsh conditions of a construction site. The frequent need for one-off production, the wide range of product geometries and in particular the very adverse working conditions all impose exacting requirements on any fully automated robotic system.

Fundamental investigations into sprayed concrete technology have shown that the nozzle guiding technique has a significant influence on the material quality, the rebound and the dust development. Optimum guidance is only likely to be possible using a spraying robot (Guthoff, 1991).

The Japanese system (Figure 9.25) is the first in which a spraying robot guides the spraying nozzle according to previously input cross-section data. The latest Japanese development (Figure 9.26) offers automatic nozzle guidance and an electronic position determination system using two laser beams. However, the use of these first robot-like devices has so far been limited to a few special fields of application.

For the first time outside Japan, work on the development of a spraying robot has been advanced at the Ruhr University, Bochum. The sprayed concrete spraying

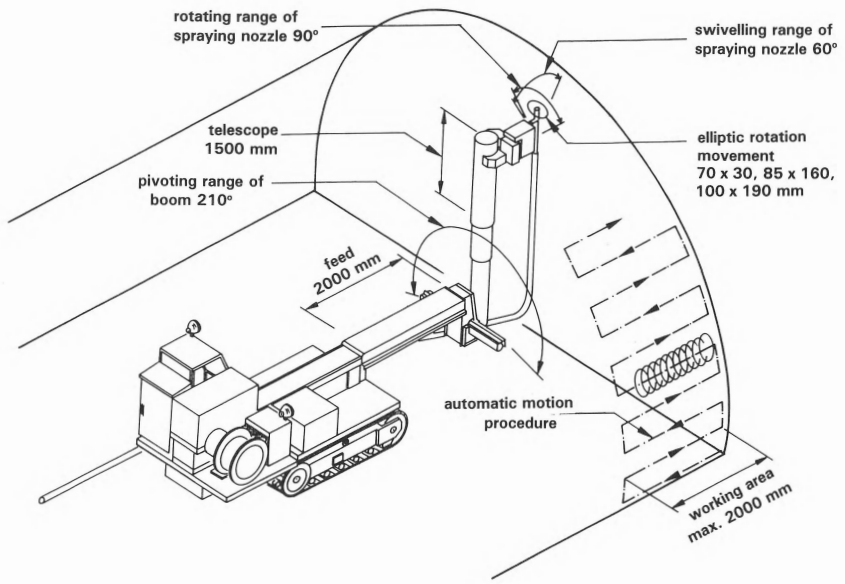

Figure 9.25 *Sliding tree with pivoting telescopic boom.*

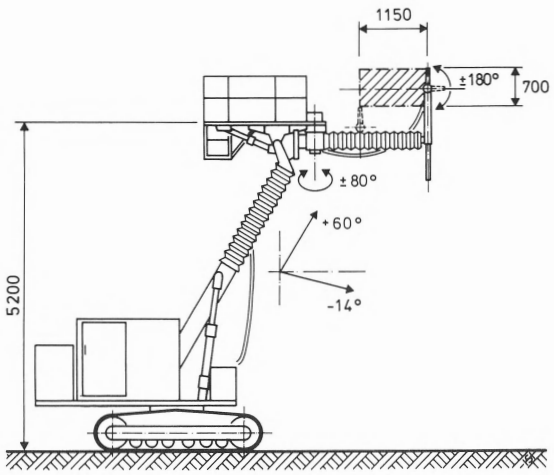

Figure 9.26 *Spraying robot, Japan.*

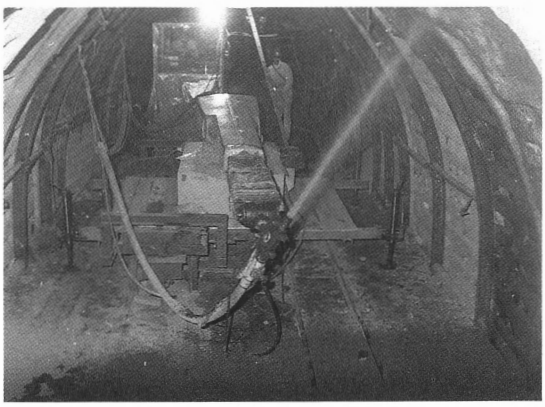

Figure 9.27 *Spraying robot of the Ruhr University in Bochum undergoing trials in the Tremonia experimental pit in Dortmund.*

robot, SAM, was developed for use on the sprayed concrete trial rig of the Ruhr University in Bochum for investigations into the optimum performance of a sprayed concrete application. The facilities on the sprayed concrete test rig permit the effects of individual parameters, e.g. nozzle distance from the face or intrinsic nozzle movement, to be investigated whilst keeping all other conditions constant.

On the basis of the information gained from these investigations, it has already been possible to demonstrate the suitability of SAM for site operation in the Tremonia experimental pit in Dortmund (Figure 9.27). Further details on the robot and the development work can be found in Maidl (1992). Using the spraying robot it is possible to carry out certain special applications of sprayed concrete, for example the spraying of tunnel inner shells where a relatively well defined working

surface exists and where no program control system with sensors is required.

Before a spraying robot can be used directly in the face area of a tunnel construction, certain problems still have to be solved. These are primarily related to the control system, and include the sensor link for the nozzle-to-face measurement, and the ergonomic design of the interface between man and robot. Clearly inter-disciplinary cooperation between construction engineers, ergonomic scientists and automation engineers is needed in order to advance the use of robots in sprayed concrete construction.

9.6 Auxiliary equipment

In all applications, the quality of the sprayed concrete produced is heavily dependent on the abilities of the operating personnel. This is particularly true in the dry spraying process where the nozzle operator is responsible not only for achieving the optimum spraying technique (distance to face, spraying direction) but also for maintaining the desired w/c ratio of the sprayed concrete.

Efforts are now being made to automate many of the current manual activities by developing appropriate auxiliary equipment. Apart from improving the process technology, greater automation offers benefits with respect to occupational health and safety, economy and, last but not least, quality.

Automatic feeding of accelerator additives

Exact metering of accelerator additives is important in concrete production. Whereas an insufficient amount of accelerator results in an inadequate early strength, too much accelerator can cause considerable reductions in the final strength of the sprayed concrete. Automatic metering of the accelerator additive is therefore desirable for both wet and dry spraying.

There are also medical aspects which make automatic metering of the accelerator additives expedient. Handling of accelerator additives can (depending on their composition) cause burns to skin, mucous membranes and the eyes. Direct contact

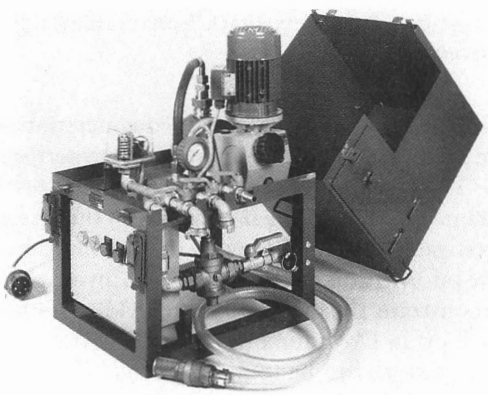

Figure 9.28 *Metering pump, Meyco Mix 100 (Meynadier AG).*

Table 9.2 *Accelerator addition*

	Dry spraying method		
	ahead of machine	in machine	at nozzle
powder accelerator	by hand Metering device, (for example on conveyor belt)	metering device (for example in the rotor chamber)	-
liquid accelerator	-	-	Metering pump for the make-up water
	Wet spraying method		
powder accelerator	-	-	-
liquid accelerator	-	-	Metering pump (e.g. with pressurized addi tive tank via mixer at the nozzle

with these additives for the operating personnel can be minimized by using automatic metering devices. Table 9.2 outlines the options available for accelerator addition in both dry and wet-mix processes.

Accelerator additive feed in the dry spraying process
In the dry spraying process, dry and liquid accelerator additives can be admixed, either at the nozzle or in the material stream ahead of or in the spraying machine. The addition of accelerator additives in the mixer should be avoided as this creates a risk of premature setting.

The injection of liquid accelerator additives at the nozzle during the dry spraying process is achieved with a metering pump (Figure 9.28). The additive is mixed into the dry material flow together with the make-up water. It is difficult to add an exact percentage relative to the cement, however, because of the constantly varying delivery rates through the pneumatic line. Measurement of the instantaneous flow rate is not possible at present. A relatively exact metering of the accelerator additive for the dry spraying method is possible at the transport screw for charging the spraying machine (Figure 9.29) or at the spraying machine proper, as a near constant material flow can be assumed here.

Accelerator additive feed in the wet spraying process
During the wet spraying process, the accelerator additive is added in liquid form directly at the nozzle. This offers a better metering of the accelerator additive since, apart from the change-over phases at the pipe links with double-piston pumps, a near constant material flow at the nozzle can be assumed. A pressurized additive tank with liquid accelerator has proved to be a simple and suitable automatic metering system.

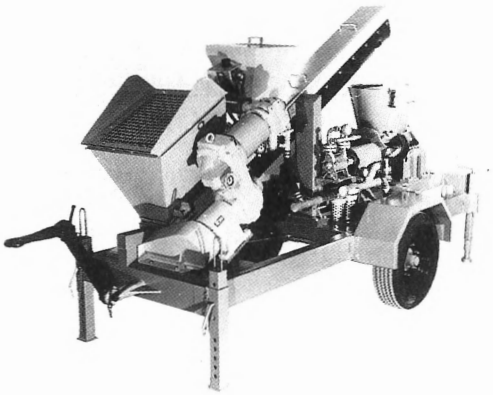

Figure 9.29 *Metering unit Meyco DG (Meynadier AG) for addition to the transport screw.*

With the double-piston pumps used almost exclusively today in the wet spraying process, liquid additive can be metered precisely by linking the oil hydraulic circuits of the spraying machine and the additive metering pump.

Auxiliary equipment for preventing dust development

In addition to the design measures for reducing dust development at the three main components of a sprayed concreting system (mixer, spraying machine and nozzle), there is a number of other measures that can be taken, particularly in the dry spraying method.

Since the optimum intrinsic moisture content of the mixture contributes significantly to reducing dust, oven-dry material is dampened with water before it is charged into the spraying machine (Figure 9.30). The dry material is drawn off from the silo by means of a screw conveyor. The screw serves as a transport screw and also as a mixing screw for the water which is added through several nozzles during the material transport. Because of this prewetting, part of the fine dust is bound before it is actually charged into the spraying machine, thus contributing to

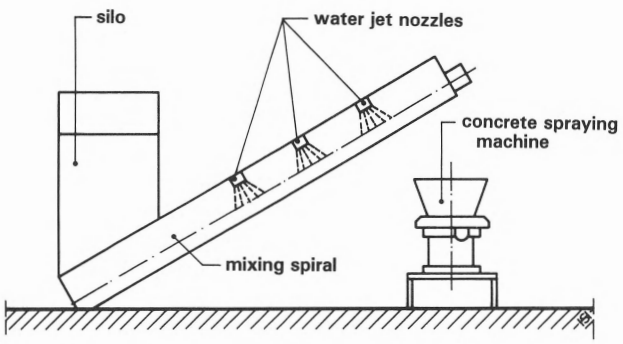

Figure 9.30 *Prewetting system for increasing the inrinsic moisture content of the mixture.*

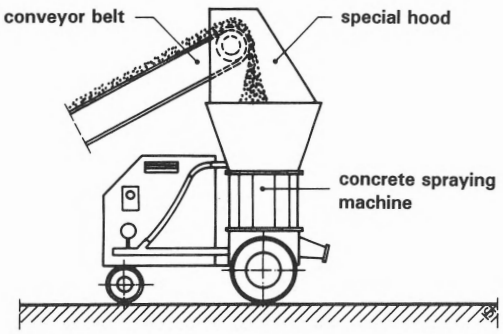

Figure 9.31 *Dust reduction in the machine area using a special hood.*

a reduction in the dust level in the machine area.

Additional hoods on the charging hopper of the spraying machine (Figure 9.31) and on rotor-type spraying machines, an additional sealing sleeve and exhaust gas dedusting system can all contribute to a reduction in dust levels in the machine area.

9.7 Equipment for repair work

Because of its flexibility, the sprayed concreting process is being used more frequently for repairing buildings damaged by fire or environmental pollution. The dry spraying method has obvious advantages for repair work where frequent movement of the spraying system and a stop/start capability are needed. Often in repair only small volumes of concrete are needed and so small machines with low throughputs are required. This also means a reduction in the air volume required for the pneumatic transport.

The small amount of material to be sprayed and the complicated and often time-consuming spraying around reinforcements means that manual (rather than automated) spraying is the norm for repair work. There is available a wide range of equipment designed especially for repair work. For example, the rotor-type dry spraying machine, Rotaflow 25, manufactured by ELE International, is compact and easily maintained. The principle of this machine is explained in Figure 9.32. The maximum placement rate of approximately 3 m^3/h achievable with this mobile unit is quite sufficient for repair work.

An interesting variant is the Meyco Repjet, a mobile unit for repair and maintenance manufactured by Meynadier AG. It comprises all the equipment necessary for the processing of sprayed concrete and also equipment for other work necessary during the rehabilitation of concrete such as removal of the old concrete, sandblasting and washing with pressurized water. A similar development from the Schürenberg GmbH is the Sanier-Express Type 208. This specially configured unit for repair and rehabilitation work offers a standard trailer with the spraying machine and its own power supply with a diesel motor. There is also adequate space on the trailer for loading small items of site equipment, accessories or sandblasting equipment. Despite the low weight and flexibility of the system, a theoretical delivery rate of up to 5.0 m^3/h is possible.

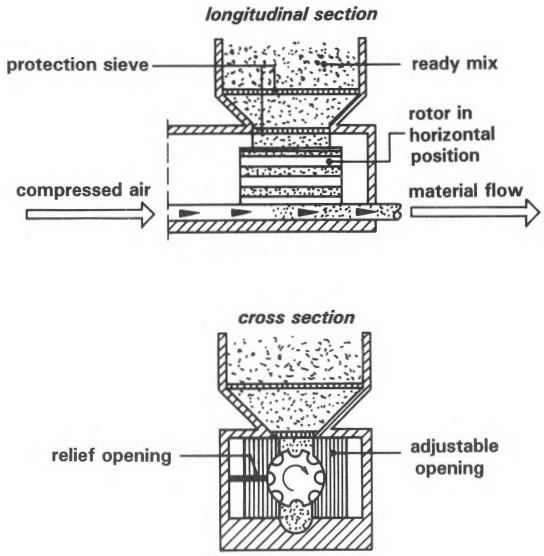

Figure 9.32 *Rotaflow 25 dry spraying machine (ELE International Ltd.).*

Another mobile unit is the ride-on spraying unit (Figure 9.33). This repair unit has all the necessary equipment (spraying machine, high-pressure water pump, hoses) and the requisite energy sources (compressed air, electrical power) on board. With the large volume water tank and the facility of transporting concrete materials on the trailer, everything needed for small repair jobs is contained within the unit.

A special feature of sprayed concrete repair work is that the material used often used has a maximum particle size of less than 4 mm; the sprayed material is thus a mortar rather than a concrete. The Betojet 250 EHM wet spraying machine manufactured by Putzmeister has been designed specially for the processing of silica fume



Figure 9.33 *Mobile spraying unit with SBS spraying machine (Schürenberg GmbH)*

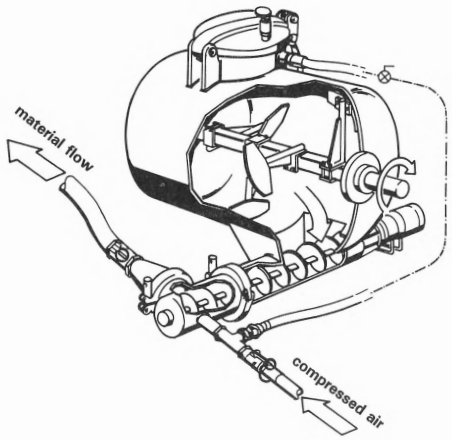

Figure 9.34 *Wet spraying machine, Betojet 250 EHT, with mixer (Putzmeister GmbH).*

modified concrete and mortar (Figure 9.34). This machine has an integral forced-action mixer to mix the dry aggregates with water to produce ready-mixed concrete with a defined w/c ratio. The principle of thin slurry transport is used to convey the material which generally has a very low w/c ratio. The machine achieves a delivery rate of 1–2 m^3/h using the integral mixer. By filling the pressure chamber from a mobile mixer, it is possible to increase the placement rate to 3–4 m^3/h.

Polymer-modified sprayed concretes are also used for repairs and rehabilitation work; these are materials to which a single or multi-component epoxy resin or methyl acrylic resin is added. Polymer-modified sprayed concretes have a number of significant advantages for repair work. The modulus of elasticity and the shrinkage can be reduced and the density and adhesion strength can be increased. In addition, it is possible to reduce the w/c ratio by an appropriate addition of the liquefying resin. They are also characterized by a minimal risk of cracking and

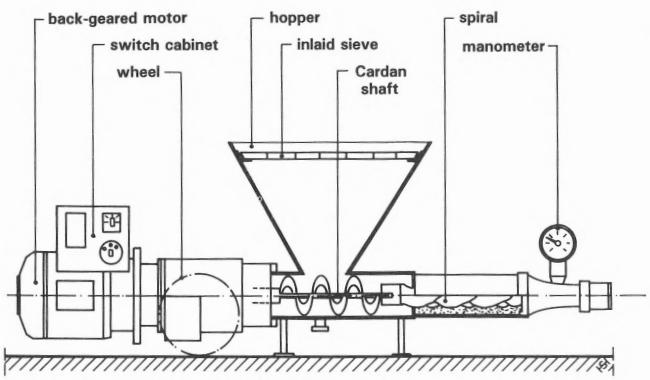

Figure 9.35 *Wet spraying machine MC-SP 213 (MC-Bauchemie, Müller GmbH & Co.).*

water drawing, particularly from old concrete. One particular disadvantage of these materials is, however, the high demands made on the personnel during the metering and application. Shortcomings in workmanship frequently result in a poor quality of the repair and rehabilitation work (Rosa, 1988; Koehne, 1983). Polymer modified concrete is often supplied ready mixed in sacks in order to eliminate the influence of the operating personnel on the metering of the resin. In the dry spraying process, it is also possible to add the resin in a water-emulsified form at the nozzle.

Polymer-modified sprayed concretes are used in both wet and dry spraying (Schorn, 1985). Figure 9.35 shows a small and compact wet spraying machine developed by the MC-Bauchemie, Müller GmbH & Co. for use in repair work on frames and lattices. The machine has a very low tare weight of around 70 kg and delivers material at a maximum rate of 13 l/min from a 50 litre hopper.

9.8 Special requirements for work in mines

Sprayed concrete and steel-fibre reinforced sprayed concrete have also found significant use in mining. Typical fields of application are:

- lining of large diameter boreholes;
- localized securing at the face, when digging shafts and passing faults;
- reinforcing, repairing and corrosion protection of steel arch supports.

In mining, very high demands are made on equipment safety and flexibility. Long set-up times or frequent failure of a system due to its high complexity or susceptibility to faults are, for economic reasons, quite unacceptable. The dry spraying method is therefore commonly used because of its lower equipment complexity (higher flexibility) and high operational reliability. The wet spraying method has not been widely used to date due to its relative inflexibility. Also there are moves to remove the nozzle operator from the health-endangering environment close to the spraying surface. A wide range of auxiliary equipment is used to minimize dust development (see Section 9.6). At the spraying machines, considerable extra effort has to be made as kiln-dry material is nearly always used. Because of the long (and often vertical) transport routes, a pre-wetted mixture is usually not feasible.

Particular attention must be paid in mining to explosion prevention, and, when internal combustion engines are used, to the CO content of the exhaust gases (Hinz, 1978). Despite their rather intermittent delivery special spraying machines are used which are pneumatically powered, longer and flat (Pasztur, 1983).

References

Albers, H.J. (1984) Die Neue Österreichische Tunnelbauweise auf dem Bergwerk Nordstern. *Felsbau* 2, Heft 1, S. 32–40.

Blümel, O.W. und Lutsch, H. (1981) *Spritzbeton*. Springer-Verlag, Wien.

Braun, W.M. (1991) Rollschalung für perfekten Spritzbetonauftrag vor Ort. *Tiefbau*, Heft 7, S. 446–447.

Brux, G., Linder, R., und Ruffert, G. (1981) *Spritzbeton, Spritzmörtel, Spritzputz; Herstellung, Prüfung und Ausführung*. R.Müller, Köln-Braunsfeld.

Diecken, U. von (1990) *Möglichkeiten zur Reduzierung des Rückpralls von Spritzbeton aus verfahrenstechnischer und betontechnologischer Sicht*. Dissertation. In: Technisch-wissenschaftliche Mitteilungen des Institutes für Konstruktiven Ingenieurbau, Ruhr-Universität Bochum, Heft 2.

Distelmeier,H. (1985) Methoden zur Reduzierung der Einflußfaktoren bei der Herstellung und Anwendung von Spritzbeton. *Spritzbeton-Technologie*. S. 53–60. Internationale Fachtagung Innsbruck-Igls.

Egger, H.R. (1985) Wird das Trockenspritzverfahren durch das Naßspritzverfahren abgelöst? *Spritzbeton-Technologie*. S. 1518. 1. Internationale Fachtagung Innsbruck-Igls.

Eurotunnel Trans Manche Link (1989) Channel Tunnel: Specification for Material and Workmanship. Chapter 9 in *Ground Suport in Tunnels and Shafts*.

Feistkorn, E. (1985) Stand der Spritztechnik. *Glückauf*, 121. Nr. 2, S. 126–133

Guthoff, K. (1991) *Einflüsse automatischer Düsenführung auf die Herstellung von Spritzbeton*. Dissertation. In: Technisch-wissenschaftliche Mitteilungen des Institutes für Konstruktiven Ingenieurbau, Ruhr-Universität Bochum, Heft 7.

Handke, D. (1985) Stand der Entwicklung von Spritzmanipulatoren. Dissertation. In: Technisch-wissenschaftliche Mitteilungen des Institutes für Konstruktiven Ingenieurbau, Ruhr-Universität Bochum, Heft 6.

Handke, D. (1987) *Kriterien zur Beurteilung und Verminderung der Staubentwicklung bei Spritzbetonarbeiten im Tunnelbau*. Dissertation. In: Technisch-wissenschaftliche Mitteilungen des Institutes für Konstruktiven Ingenieurbau, Ruhr-Universität Bochum, Heft 3.

Hinz, D. (1978) *Verfahrenstechnische Probleme bei der Anwendung von Spritzbeton unter Tage*. Diplomarbeit Ruhr-Universität Bochum.

Koehne, H.D. (1983) Anwendungen von Kunsthartspritzbeton zur Bauwerkssanierung. *Tiefbau, Ingenieurbau, Straßbau*, Heft 9. S. 530–537

Lauffer, H. (1987) Das Naßspritzverfahren Baustellenerfahrungen und Kostenvergleiche. *Spritzbeton-Technologie*. S. 75–80.2. Internationale Fachtagung Innsbruck-Igls.

Maidl, B.R. (1984) *Handbuch des Tunnel- und Stollenbaus, Band I. Konstruktionen und Verfahren*. Verlag Glückauf GmbH, Essen.

Maidl, B.R.(1990) Spritzbetonroboter im Tunnelbau. In: *VDI-Bericht 800, Baumaschinentechnik - Fortschritte durch Mikroelektronik und Automatisierung*, S. 207–236. Tagung Baden-Baden, 21 und 22. Düsseldorf.

Maidl, B.R. (1991) *Stahlfaserbeton*. Verlag Ernst & Sohn, Berlin.

Maidl, B.R. (1992) *Handbuch für Spritzbeton*. Verlag Ernst & Sohn, Berlin.

Nakajima, H., Mio, M., Ichihara, Y and Sagara, Y. (1988) Development of Shotcrete Robots. In: *Proceedings of the 5th International Symposium on Robotics in Construction*. Tokyo, Japan.

Pasztur, R. (1983) Ungarische Erfahrungen mit Naßspritzbeton in der Dünnstromförderung. *Beton und Stahlbetonbau*, 78. Nr. 1, S.6.

Rosa, W. (1988) Erkennen und Abstellen der Ursachen von Betonschäden und deren Instandsetzung mit Spritzbeton. *Instandsetzung und Erhaltung von Bauten aus Beton und Stahlbeton*. Internationale Fachtagung Innsbruck-Igls.

Ruffert, G. (1984) Förder- und Spritztechnik für Stahlfaserspritzbeton. Berichte des Lehrstuhl für Konstruktiven Ingenieurbau an der Ruhr-Universität Bochum, Heft 42, S. 39–41.

Scherer, J. (1987) Machinentechnische Anforderungen an Spritzmaschinen im Dünnstromverfahren. *Spritzbeton-Technologie*. S. 59–62, 2. Internationale Fachtagung Innsbruck-Igls.

Schorn, H. (1985) *Epoxidharzmodifizierter Spritzbeton*. Technisch-wissenschaftliche Mitteilungen des Institutes für Konstruktiven Ingenieurbau, Ruhr-Universität Bochum, Heft 6.

Schreyer, J. (1986) Stand der Spritzbetontechnik. In: Unfallverhütung beim unterirdischen Hohlraumbau. Vorträge zu der Fachtagung der Tiefbau-Berufsgenossenschaft vom 22. bis 24. in *Hennef, Sonderdruck der Tiefbau-Berufsgenossenschaft*.

SIA 118 Allgemeine Bedingungen für Bauarbeiten.

Wind, H. und Kern, E. (1987) Erprobung von Spritzbetontechniken und ihr Einfluß auf den Baufortschritt der DB-Neubaustrecke Hannover-Würzburg. *Tiefbau*-BG 99, Heft 2, S. 78–84.

10 Construction Practice and Quality Control

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This chapter describes construction practices and quality control for shotcrete (sprayed concrete). The pertinent areas covered under construction practices are: site set-up, crew organization and responsibilities, safety, scaffolds and other equipment, surface preparation, formwork, joints, anchoring and arrangement of steel reinforcement. Batching and mixing, placement, application techniques, shooting position, rebound, overspray, finishing, curing and weather restrictions are also covered, as are tolerances, quality assurance, in-process testing, sampling, in-situ testing, inspection, the core grade system and evaluation. American Concrete Institute (ACI) Committee 506 (1990*a*) in its publication ACI 506R-85, *Guide to Shotcrete*, has produced a detailed report covering many of these items. This chapter highlights the important aspects of construction practice and quality control. The ACI reference should be reviewed in conjunction with this book.

10.1 Site set-up

A key requirement in the proper site set-up of a shotcrete operation is that the equipment is close to the work. In so doing, the hose lengths will be minimized. Shorter hose lengths require a smaller volume of air to move the material. An adequate volume of air is required to ensure the high velocity that is required for good compaction of the shotcrete. Figures 4.2 and 4.7 show the set-ups for dry and wet-mix processes, respectively.

When the work is spread over a considerable area or more than two crews are shooting, the gun and/or pump should be located centrally. The equipment should be positioned so that guns or pumps can be easily charged and the plant should be designed to provide a continuous flow of material to the nozzleman. Other factors that may require attention include dust from the dry process. The contractor as well as the owner should review the local codes and whether the dust from shotcrete has any environmental impact. Enclosures for smaller projects can be erected but on relatively large sites enclosure is usually impractical and can seriously handicap the economics of a project. Owners or construction managers of large projects should alert the contractor to local environmental considerations.

10.2 Crew organization

The success of any shotcrete application depends upon the crew. While many stress that the single most important position is the nozzleman, the whole shotcrete crew

must work like a well oiled machine and exhibit teamwork. This cannot be overstressed, because without a qualified gunman, blowpipe operator and foreman there will inevitably be problems. The minimum size of shotcrete crew should consist of a foreman, nozzleman, finisher, an assistant nozzleman, blowpipe operator, gunman or pump operator, mix operator and labourers. Some of the functions may be combined depending on the type of project. For example, the blowpipe operator may be the assistant to the nozzleman; the finisher may be the nozzleman or his assistant. In addition, the gunman and mix operator may be combined. The responsibilities of each member of the shotcrete crew are discussed below.

Foreman

It is the foreman's duty to plan and organize the crew, work, and sequence of application. He/she also bears the responsibility for safety and quality assurance. Owners or the engineers may require a quality assurance program (QAP). This is the document that specifies the overall performance requirements that must be followed by the shotcrete contractor. Quality control tests, such as mechanical and durability tests, are the back-up needed for acceptance of the work. However, the heart and soul of the QAP is the proper shooting of the shotcrete, making sure that the in-place shotcrete is free of defects, such as rebound or inadequate bonding. The foreman must initiate the QAP and ensure the programme is implemented. Besides being responsible for ordering material, equipment, setting the pace of the work, maintaining crew morale, the foreman should be capable of shooting or being able to fill any position of the crew as required.

Nozzleman

The main responsibility of the nozzleman is to apply the shotcrete properly. The nozzleman is responsible for shooting on correctly prepared surfaces, and ensuring that the equipment, nozzles and lines are in acceptable working order. He/she should also check that the reinforcing is properly anchored, placed and spaced and verify placement of ground wires. The nozzleman controls the water for the dry



Figure 10.1 *Blow pipe operator removing rebound for repair on natural draught cooling tower.*

process and must ensure that the material stream is steady and the applied material is properly compacted and free of defects.

Blow pipe operator/assistant nozzleman

The blowpipe is an air jet operated by the nozzleman's assistant who keeps rebound and other loose, uncompacted material out of the work. Rebound and uncompacted material must not be allowed to accumulate on ledges, corners or behind reinforcement. Figure 10.1 shows a blowpipe operator removing rebound. Blowpipe operators are also responsible for moving hoses, removing sand pockets, keeping reinforcement clean if overspray builds up on steel surfaces and relaying signals between gunman and nozzleman. In addition, they may shoot for short periods while the nozzleman rests.

Gunman

In his role as coordinator of the shotcrete crew the gunman is responsible for being sure the gun is in working order and regulating a constant flow of mixed material to the nozzleman. He/she should ensure that the stream does not pulsate and also coordinate the mixing and delivery operation.

Pump operator

In the wet-mix process, it is the pump operator's responsibility to provide concrete to the nozzleman at the required rate. The pump operator should be fully trained in the operations of the concrete pump. All obstructions on the project should be carefully observed, especially overhead electrical lines.

Familiarity with the equipment is essential and a sound technical appreciation can be obtained from texts such as *Pumping Concrete: Techniqes and Applications* (Cepas, 1991). The pump operator coordinates delivery of concrete and monitors its consistency by observing or directing slump tests.

Mixer operator

The mixer operator is responsible for the batching and mixing of the shotcrete material and the storage of all material components and their accessibility. He/she should ensure that the shotcrete ingredients do not contain foreign substances, that cements are free of lumps and that aggregates do not contain significant amounts of clay or other deleterious substances. Also, the aggregates must have the proper moisture content for shooting.

Labourers

Labourers' duties include maintenance of equipment, hoses, moving hoses and scaffolds. Along with the rest of the crew, they are responsible for house cleaning, maintaining clean work areas and removing rebound, overspray or other loose material. They may also fix loose reinforcement or erect protective barriers prior to and during shooting to keep areas clean of overspray.

Safety

The contractor should provide each worker with a safety guide to be read by each member of the crew. The foreman, as well as each member of the crew, is responsible for the crew's safety. Prior to and during large projects, the foreman should conduct periodic "tool box" sessions concentrating on safety related practices.

Each member of the crew should be equipped with goggles (of the wrap-around type), hard hats and safety shoes. Also, crew members should wear respirators (generally a thin fibre filter type) or a handkerchief may sometimes be satisfactory. Gloves should also be worn. If the nozzleman, assistant nozzleman/blowpipe operator are on scaffolds, safety harnesses must be used. Contractors should consult local and governmental codes (OSHA in the United States) regarding safety requirements and equipment regulations. The foreman should verify that each crew member is properly protected and is conducting his/her work in a safe manner. Hoses should be checked for wear as should any other pneumatic or hydraulic systems. A full discussion of site safety and good practice is given in Chapter 12.

10.3 Scaffolds and other equipment

Scaffolds or other lifts should be stable and allow the nozzleman to move close enough to encase reinforcing steel properly. The equipment should be capable of permitting the nozzleman to move back from the work as work proceeds. The scaffolds, lifts and other equipment should allow unobstructed access to the area being shot. Braces or posts should not be located between the work and the nozzleman. If posts or other obstructions exist within the work, the engineer should



Figure 10.2 *Elevator scaffold used to shoot shotcrete for prestressed composite tanks (Courtesy Crom Corporation, Gainesville, Florida).*

be notified before removal to ensure it is done safely. Some applicators use elevator type rolling scaffolds. This equipment gives the nozzleman a completely unobstructed view of area to be shot. In addition, it can move along the work expeditiously. Figure 10.2 shows a scaffold used on tank construction.

10.4 Substrate surface preparation

The surface of the substrate that will receive the shotcrete depends on the condition and type of surface. An important factor that should be stressed is that even when a substrate surface has been prepared, it can get fouled if it is not properly protected during shooting. Protective barriers or covers should be erected on areas adjacent to work that is being shot. This procedure can minimize rework and the potential for fouling up a surface that has already been prepared. In the following sections the preparation of various substrates is discussed.

Earth

Earth surfaces must be properly compacted and trimmed to line and grade. Earth should not be frozen or spongy. Techniques for reducing excessive absorption of mixing water from the shotcrete into the earth are to either prepare the earth surfaces by wetting with a water spray, or install a moisture barrier system.

Steel

All loose mill scale, rust, oil, paint, grease or other contaminants that may hinder bond development must be removed. Sandblasting is the typical method used to remove contaminants. The surface condition should be such that it meets the requirements detailed in the publication of an appropriate national body, e.g. Steel Structures Painting Council's publication, *Commercial Blast Cleaning, Steel Structures Painting Manual* (1982).

Concrete

A concrete substrate that is to be shotcreted should be thoroughly clean. While there are a number of methods to remove spalled concrete, the following procedures must be adhered to. This will ensure a sound substrate that will have the capability of developing adequate bond with the shotcrete.

All spalled, severely cracked, deteriorated, loose and unsound concrete should be removed completely. Methods such as scarifying, chipping, water and/or sandblasting and grinding are commonly used. Any concrete contaminated with deleterious chemicals or oils should be removed. Edges of repair areas should be sawcut to limit the extent of damage brought on by mechanical impact during removal. If shotcrete is to be applied to a smooth concrete surface, the surface should be roughened by water or sandblasting, grinding or bush hammering. Chapter 4 (Section 4.6) describes the dangers of using excessive mechanical force to roughen concrete, namely the formation of micro-cracks, which can render the surface unsound.

After surfaces have been prepared, the foreman should verify that only sound concrete remains. If a number of days lapse between substrate preparation and shotcrete application, the foreman should check to ensure that the surface has not

slaked or become dirty. In addition, whenever concrete is removed using impact tools such as bush hammers, there is the danger referred to above of damage to the substrate surface. If this damaged layer is not removed, the shotcrete can fail in bond. The foreman should therefore verify that the substrate is free of defects and as an absolute minimum, sound the substrate by striking with a steel hammer.

Prior to shotcrete application, the substrate surfaces should be blown with compressed air (no oil) or vacuumed. This operation should be followed with prewetting the substrate for 24 hours. If there is running water on the substrate concrete or other surfaces, this situation must be controlled. Use of drain pipes, wicks or other such devices can control water flow. If any pressure is permitted to develop behind the freshly applied shotcrete, the potential for debonding is great. This condition can also result in local wash outs.

Masonry

Similar steps are required to that of concrete. However, absorption of water from the shotcrete into the masonry must be controlled. Dampening of the masonry will prevent severe cracks from developing due to the absorptive nature of masonry.

Rock

All loose material, fragments, debris, mud, dirt, deleterious and foreign matter must be removed. Any such material on a rock surface will inhibit bond development.

10.5 Formwork

Formwork for shotcrete is generally similar to that for conventionally cast concrete. However, since shotcrete has the ability of standing up on its own within formwork, hydraulic pressures against formwork may be less. When designing formwork for shotcrete the formwork supplier should be consulted to see if any economic advantage may be gained by using less formwork than that used for conventional cast-in-place concrete. Also, forms must be adequately braced and secured to resist vibration and strain due to the placement of shotcrete. Formwork must also be designed to provide for escape of compressed air and rebound.

Form release agents should not be permitted to touch shotcrete surfaces that will receive additional shotcrete layers as this will interfere with bond development between layers. If such form oil contamination occurs, steps are required to ensure its removal.

10.6 Joints

Both construction and contraction joints are a common feature. Construction joints are stopping places in the process of construction. A true construction joint should bond new concrete to existing concrete and not permit movement. Contraction joints provide for movement in the plane of the element and induce cracking caused by drying shrinkage and thermal stresses at preselected locations.

Construction joints

When a joint is subjected to compressive stress, square joints are typically required. In this case, the nozzleman and blowpipe operator must be extremely careful to remove trapped rebound. With a tapered joint, a plane of weakness must not be constructed. This can be achieved by spraying a joint at approximately 30°, with the front face being cut back square (to avoid the subsequent layer tapering to zero thickness); alternatively the square edge can be formed by spraying against a wooden board, up to half the thickness of the element, fixed firmly off the substrate.

Contraction joints

Contraction joints are usually made either by prepositioned wooden strips that are left in place, or by saw cutting the shotcrete shortly after final set. In some water-retaining structures, water stops are required. It is very difficult to encase waterstops adequately. The foreman should check with the nozzleman to ensure good encasement at waterstops. Rebound can easily accumulate in these areas and the blowpipe operator must be ready to prevent buildup of rebound. ACI Committee 350, *Environmental Concrete Engineering Structures* (1989), provides additional information on the design of contraction joints.

10.7 Steel reinforcement

In this section, anchoring and arrangement of steel reinforcement is discussed. If the reinforcement is improperly anchored or arranged and shooting results in inadequate encasement, than a failure or defects in the shotcrete are very likely. Reinforcement must be anchored and secured so that it will not vibrate during shotcreting. If reinforcement is allowed to move during shotcreting plastic cracks can occur and a plane of weakness may develop at the level of the reinforcement.

Anchors

There are numerous factors involved in determining the type, size and spacing of anchors. These factors are type of application, its design, shotcrete thickness, nature of the original surface and the type, weight, and geometry of reinforcement. Anchors should be checked for pullout and shear. Table 10.1 presents maximum recommended anchor spacing.

Anchoring reinforcement to steel surfaces is typically done using mechanical clips, welding blank nuts to steel, stud welding, slab bolsters or by direct attachment. Clips and bolsters are used to attach mesh directly to steel. Studs or nuts are used to attach reinforcing steel or mesh. Drilling holes in structural members should be avoided. Expansion anchor bolts, steel dowels, powder activated studs, self-drilling fasteners and expansion shields are used to anchor reinforcing to concrete, masonry or rock. Epoxies or other adhesives are used to facilitate pullout strength. The manufacturer of these systems should be consulted for strength limitations, environmental considerations and insertion procedures. Some glues used for fastening are sensitive to seawater or other chemicals. These should be checked prior to their use. ACI Committee 506 (1990*a*) provides additional details on each of these systems.

Table 10.1 *Maximum recommended anchor spacing*

Element	Spacing, on centre both ways
floors	900 mm (36 in)
vertical and inclined surfaces	600 mm (24 in)
overhead	450 mm (18in)

Individual bar chairs, slab bolsters or nails are commonly used to attach reinforcement to wood. Nails should be prohibited if the wood is part of the formwork, and chairs and bolsters should be plastic tipped. Bolsters should be positioned so that they are offset from bars or mesh. Figure 10.3 shows the correct positioning of slab bolsters.

Arrangement of reinforcement

ACI Committee 506 (1990*a*) presents a detailed discussion of reinforcement. This section describes acceptable methods for the arrangement of reinforcement, which make encasement of bars easier and reduce sandpockets behind bars. Bars should not be directly over one another, but staggered (see Figure 10.4*a*). Bars in the horizontal plane should not touch each other; parallel bars should be at least 65 mm (2½ in) apart (see Figure 10.4*b*). Bars should be at least 12 mm (½ in) off the back form for shotcrete without coarse aggregate; for shotcrete with 20 mm (¾ in) maximum size aggregate, this distance should be increased to 50 mm (2 in).

Mesh should be lapped 1½ squares in both directions. In this arrangement, parallel wires should not be tied together. Using this technique limits mesh to two

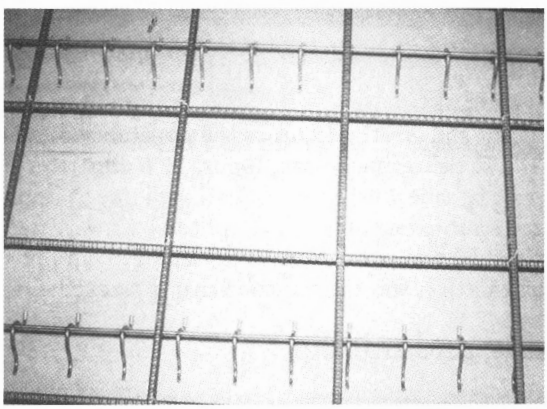

Figure 10.3 *The correct positioning of slab bolsters.*

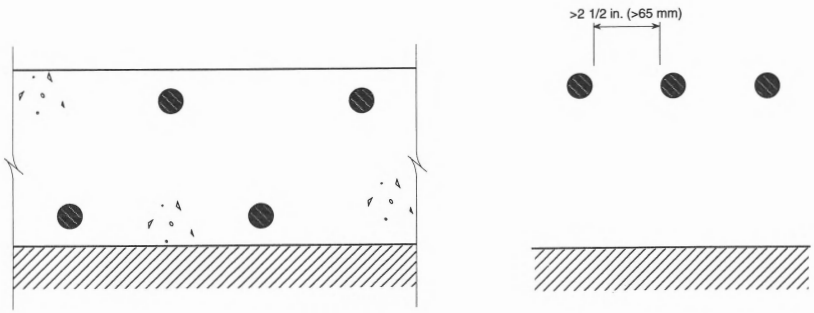

Figure 10.4 *(a, left) Staggered reinforcement (b) Arrangement of reinforcement for parallel bars.*

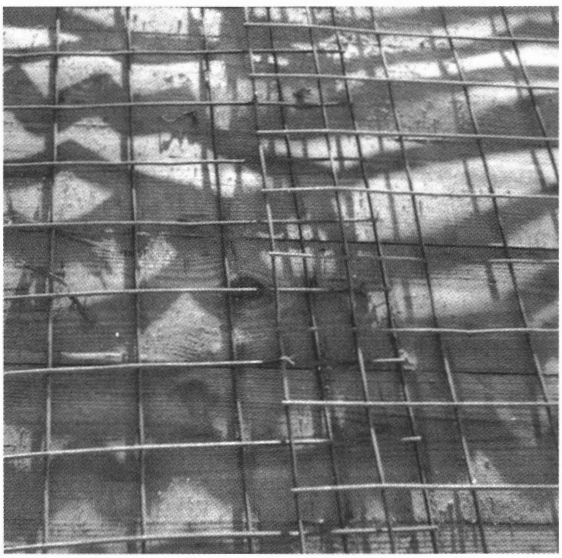

Figure 10.5 *One and a half square mesh overlap.*

layers at any one point and greatly decreases the possibility of sandpockets behind bars. Figure 10.5 shows this arrangement. Figure 10.6 illustrates the likely effect of locating two bars side by side where a void developed due to improper shooting of this poorly arranged reinforcement in which spliced bars were tied together instead of being spaced at least 50 mm (2 in) apart. This arrangement prevented full encasement of bars and the section was so weakened that it cracked during removal.

10.8 Batching and mixing

Without a properly designed, proportioned, batched and mixed shotcrete it becomes difficult to achieve the desired qualities associated with quality concrete. The

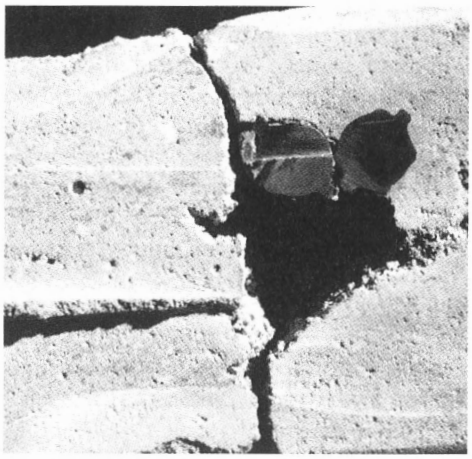

Figure 10.6 *Extreme flaw developed as a result of improperly encasing parallel bars.*

first step is to design the mixture and provide an adequate amount of cementitious material, with nondeleterious aggregates. Admixtures must be compatible with cements and/or mineral admixtures and not degrade the shotcrete or cause loss of strength or durability. Next, the batch quantities should be selected based on production limits and equipment. Batching too much material before it can be used may result in the use of shotcrete which has begun to set. When this occurs, especially in wet-mix shotcrete, retempering of the mix should be avoided. In dry-mix shotcrete caking up can occur and this can result in clogging or nonhomogeneous shotcrete. Only the amount consistent with production should be batched.

Batching

Weight or volumetric batching is acceptable when using cement and aggregate for the dry-mix process, although these must usually be predampened before being introduced to the gun. ASTM C 94 and C 685 cover weight and volumetric batching, respectively. However, greater tolerances may be accepted: cement ± 2%, aggregates ± 4%, and admixtures ± 6% has been found to be acceptable for high production volumetric batching mobile mixing equipment.

To minimize slugging and hose plugging the optimum moisture content of the sand for dry-mix process is 3 to 6%. Aggregates can be dried or predampened to bring these materials into this range. Large fluctuations in aggregate moisture should be avoided. This is especially true when shooting some materials such as latex or silica fume. Rapid-set liquid accelerators are usually introduced at the nozzle with the mixing water. Powdered accelerators are added during batching or mixing.

Mixing

It is wise to screen all material exiting the mixer to avoid lumps in the shotcrete. This helps to reduce plug-ups. In the dry-mix process, the materials should be

mixed thoroughly until streaks are gone. This is necessary to avoid sand pockets and laminations. To determine the optimum predampening use the "ball-in-hand" test in which some shotcrete material is squeezed in the hand; if it crumbles than more water is needed for predampening; if it holds together, or cracks but remains whole, there is a sufficient amount of moisture. If moisture comes off in your hand then the mix contains too much moisture.

A mix that has dried out or caked must be discarded. Rebound should not be used. With the wet-mix process, a mix that is difficult to pump should be discarded. The wet-mix process should be treated in a similar way to a pumping project.

10.9 Shotcrete placement

Since the quality of in-place shotcrete is very dependent upon how it is placed, it cannot be overstated that the whole crew must act as a team. The quality of shotcrete depends greatly on the gun operator and nozzleman, control of mix water, air pressures, nozzle velocity and nozzling techniques. The gun operator should provide the nozzleman with a steady flow of material. The gun operator should prevent slugging, plugged lines and mixes that result in excessive rebound. When the nozzleman has to make changes in the water, he should direct the stream away from the work until changes are made.

When pumping shotcrete, the pump operator should provide an even rate of concrete flow to the nozzle. The pump operator should never put additional water into the mixer hopper if some concrete has been discharged and used as this may reduce the durability of the shotcrete. If changes in mix water are required the ready-mix supplier and/or engineer should be consulted before changes are made.

It has been found that for the dry-mix process just enough water is added at the nozzle to produce a slight glistening. It is the author's opinion that a wetter mix, without sagging, produces a more compact shotcrete, with fewer internal defects. Drier mixes produce more rebound and are more susceptible to sand pockets. Drier mixes create finishing difficulties and can increase the potential for laminations.

Nozzling

A nozzle distance of 0.6–1.8 m (2–6 ft) is generally acceptable, but shorter distances create greater compactive effort resulting in higher density and strength. Shotcrete may be applied in single thicknesses or layers. Overhead work is applied in layers generally 25–50 mm (1–2 in.) in thickness. Greater thicknesses of shotcrete, without the use of accelerators or silica fume, may sag and cause dropouts. Horizontal work, one of the more difficult shooting positions, is generally applied in single layers and caution must be exercised in the removal of rebound. In vertical and overhead work rebound falls to the ground, while in horizontal work such as swimming pool slabs, the rebound is easily trapped in the work causing sand pockets and subequent cracking. As a general rule, the nozzle should be perpendicular to the receiving surface. At times, the nozzle can be slightly off the 90° target, but never more than 45°. The further the angle from 90°, the greater the rebound and less the compaction. In addition, shooting at too great an angle results in uneven surfaces that have rolls and folds. It has been found that by rotating the nozzle in a series of oval or circular patterns reduces the effect of slugging. It is also advisable to outline

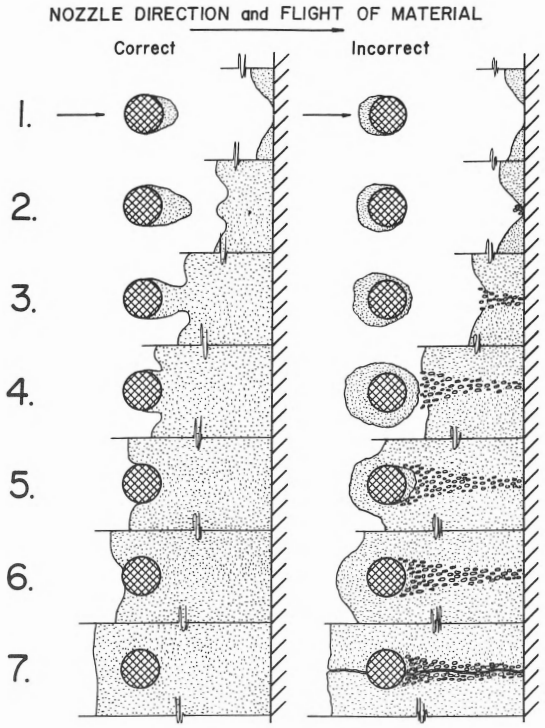

Figure 10.7 *Correct and incorrect method of encasing reinforcement.*

the work, i.e. choose an area that is not too large, apply shotcrete to the perimeter of the area and then work the rest of the area. By confining an area it becomes more manageable. This technique reduces dry spots within the work. When shooting through and encasing reinforcement the nozzle should be held closer than normal and at a slight upward angle. In the author's opinion, the mix should be somewhat wetter than normal when encasing reinforcement. The front face of the bar should remain clean without a build up and the shotcrete should flow around behind the bar producing compacted material around the back of the bar. If the front face is allowed to become dirty it is virtually impossible to encase the bar adequately without voids. Figure 10.7 shows the correct and incorrect method of encasing reinforcement. It is important to note that if a sandpocket develops, a weakened section is created and upon drying, cracks will inevitably form. Long straight cracks parallel to reinforcement are an almost sure indication of sand pockets trapped behind bars causing a weakened section.

Unless it can be shown otherwise through demonstration, it is better to commence shooting walls from the bottom and the work proceed upwards. On rare occasions shooting top-down has been found satisfactory. This method keeps rebound more easily out of the work, but before using this method the applicator should demonstrate on a mock-up wall that he can do it successfully.

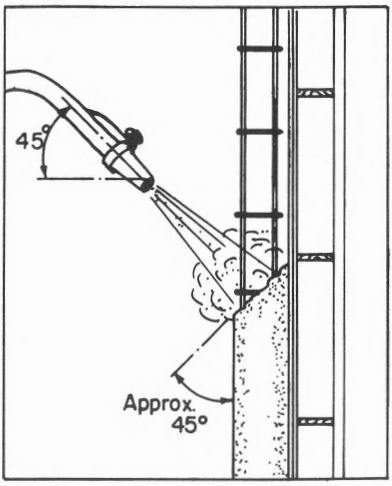

Figure 10.8 *Bench gunning.*

When applying thick single layers in excess of 150 mm (6 in), *bench* gunning is generally used. In this method the layer is built up at a slope of approximately 45° (see Figure 10.8). When shooting internal corners, the corners should be shot first. Then the corners should be built up as the layers become thicker. This method helps prevent rebound and overspray from filling these areas. In addition, using a blowpipe is extremely helpful in reducing accumulation of rebound in these areas.

When shooting multiple layers, the preceding layers should first be allowed to harden slightly or stiffen. All loose, uneven or excess material should be brushed or scraped away. If a surface is allowed to harden it should be treated for cleaning purposes as a construction joint. The surface should be open, rough and highly textured as this will promote a better bond between layers.

When a member contains two layers of steel it is advantageous to delay the placement of the outer layer until the first layer of steel is embedded. The next layer is then placed and shotcrete applied as described above. In shooting overhead work, the thickness should be limited to be consistent with the mix design and equipment. Thicknesses greater than 50 mm (2 in) are hard to place successfully without sags and dropouts. Overhead shooting requires the nozzle to be perpendicular to the receiving surface. Thickness of placement is highly dependent on slump (wet-mix) and the texture of receiving surface.

Work should be suspended during inclement weather. High winds can cause separation of the nozzle stream. If temperatures approach freezing and the work is unprotected, work should be stopped. Rain can cause washouts or sloughing; light mist is acceptable but if any doubt exists as to the quality of the work then the construction should be suspended.

Rebound and overspray

Rebound is defined as shotcrete which is leaner than the original mixture which ricochets off the receiving surface and falls by gravity either to the ground or gets trapped into the work. Overspray is lean shotcrete that is carried by the air stream

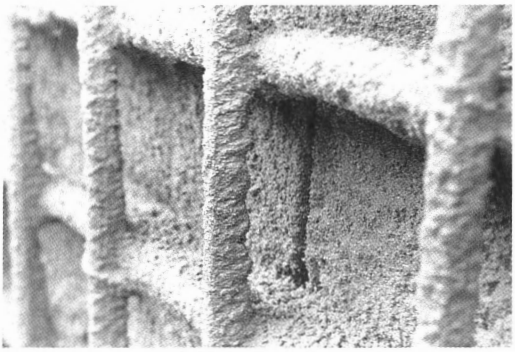

Figure 10.9 *Overspray on reinforcement.*

and deposited away from the intended receiving surface and typically clings to surfaces such as reinforcement, pipes, previously cleaned and prepared surfaces. Rebound and overspray are unwanted and can cause significant defects in the shotcrete. Overspray leaves an unconsolidated thickness of low quality shotcrete.

Overspray should be removed before it is allowed to harden and is a particular problem when using latex-modified shotcrete. Hardened overspray that is covered up will undoubtedly reduce the bond between layers and could result in delamination and failure. However, if overspray remains fresh and soft it can generally be consolidated with additional shotcrete without causing problems. Figure 10.9 shows overspray on reinforcement. All shotcrete has some overspray that can be controlled by proper shooting techniques.

Rebound occurs with all shotcrete, but the smaller the amount, the better quality the shotcrete. Dry, leaner mixtures have greater rebound than wetter and richer mixtures. Rebound should be controlled and removed from the work usually with a blowpipe. Since rebound is approximately 90% aggregate, the greater the rebound the richer the in-place shotcrete becomes. Figure 10.10 shows a core illustrating rebound trapped in the slab of a swimming pool which often results in cracks in the shotcrete.

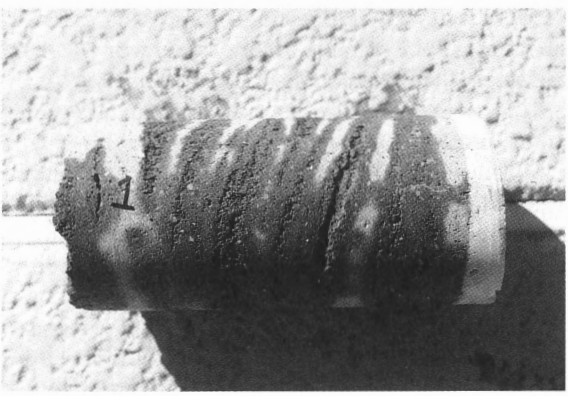

Figure 10.10 *Rebound trapped within the slab of a swimming pool.*

10.10 Finishing, curing and climate

The natural gunned texture is the preferred finish. Additional manipulation can result in a weakened surface, cracks, a reduction in cohesion and bond between shotcrete and reinforcement. The three main types of finish are described below, namely natural, flash/finish coats and final finishes.

Finishes

A natural gun finish requires the least amount of rework and is the most durable. However, natural finishes leave a textured and possibly undulating surface. If better alignment is required, the surface can be screeded, followed by floating.

If finer finishes are required, a flash coat can be used. The flash coat is a thin surface coating up to 6 mm (¼ in) thick containing a mixture with a fine sand. A finish coat is used for thick walls. They are used to provide greater uniformity in appearance and texture and are typically 6 to 25 mm (¼ to 1 in) thick, applied just after screeding. Flash and finish coats can be finished in several ways. Wood float, rubber float, brush and steel trowels can provide various textures. A crucial aspect of the specification and production of the surface finish are the construction tolerances, described below.

Tolerances

Due to the nature of shotcrete and its unique finishes there are certain limitations on tolerances that must be recognized. The approach proposed by Kolf and Gebler (1993) is discussed below.

Because of the finishing techniques required in shotcrete construction, some tolerances must be larger than those achievable with formed construction. However, this allowance for increased tolerances need not diminish the serviceability, durability, or integrity of a structure. Tolerances provide an indication of the expected finished product and can identify applications where additional effort and cost may be required, or where a particular construction method may be inappropriate. Therefore, knowledge of tolerances that are consistently achievable is needed by owners and specifiers so that project requirements can be stated clearly. ACI Committee 506 (1990*b*) states "tolerances up to 50 percent larger than those permitted for formed surfaces may be suitable for shotcrete work." A revision proposed to the Committee states that tolerances should conform to ACI Committee 117 (1990) recommendations, except that tolerances for concrete dimensions should be increased by a factor of 2 for shotcrete. Some cover requirements for reinforcing steel specified by ACI Committee 506 (1990*b*) are substantially less than those given by ACI Committee 301 (1989). Specified tolerances on cover for reinforcement are equivalent to those given by ACI Committee 117. The revision proposed to ACI Committee 506 cites ACI Committee 301 for concrete cover dimensions and ACI Committee 117 for cover tolerances.

The ACI Committee 506 recommendations provide some guidance on achievable tolerances for shotcrete construction. However, a more definite specification is necessary to avoid ambiguity and potential reduction in quality through reduced cover over reinforcing steel, reduced member thicknesses, or other dimensional

Table 10.2 *Recommended tolerances for shotcrete construction* (Kolf and Gebler, 1993, with added metric modifications)

	Tolerance in mm (in)			
	Class A	**Class B**	**Class C**	**Class D**
*Surface finish (Flatness)**	6 (¼)	10 (⅜)	16 (⅝)	25 (1)
Cross-sectional thickness ≤ 300 mm (12 in)	-6 (-¼)	-6 (-¼)	-6 (-¼)	-6 (-¼)
	+6(+¼)	+10(+⅜)	+16(+⅝)	+25(+1)
Cross-sectional thickness > 300 mm (12 in)	-6 (-¼)	-10 (-⅜)	-10 (-⅜)	-10 (-⅜)
	+6(+¼)	+10(+⅜)	+16(+⅝)	+25(+1)

* surface flatness is defined as the measured depression below a 3 m (10 ft) straightedge placed on the finished surface.

variations. In fact, most tolerances provided by ACI Committee 117 for cast-in-place construction should apply to shotcrete construction.

Tolerances for placement of reinforcing steel, cover over reinforcing steel, and overall alignment of structural members should be consistent with those given by ACI Committee 117 for cast-in-place construction. Possibly the only tolerances that require distinct values for shotcrete construction are cross-sectional dimensions and surface finish (or flatness). However the revision proposed to ACI Committee 506 does not include a reference to tolerance or finishing. In addition, factoring of concrete dimensional tolerances could potentially reduce construction quality by allowing excessive reduction of concrete cover or member thicknesses.

Table 10.2 presents a possible format for specifying tolerances in shotcrete construction. These tolerances would be as required by ACI Committee 117 for cast-in-place concrete, except as modified in the table. An additional mandatory specified item would be the class of shotcrete required for the work. ACI Committee 117 describes classes of construction for floor finish tolerances and permissible formwork offsets. The idea of classes can also be applied to shotcrete. Recognized classes of construction allow the specifier or owner to select from a range of achievable options. Tighter tolerances often require different construction methods resulting in increased construction costs. The table recommends tolerances for the following suggested classes of shotcrete construction:

Class A – Consistently achievable by techniques other than gun finish techniques. May require increased effort resulting in higher in-place costs.

Class B – Consistently achievable by techniques other than gun finish, such as trowel or float finishes, without unusual effort.

Class C – Consistently achievable by gun finish techniques. May require increased effort resulting in higher in-place costs.

Class D – Consistently achievable by gun finish techniques without unusual effort.

Increased effort could refer to the use of a flash coat, a shorter spacing of ground wires or other techniques. Flash coats are thin final coats of shotcrete containing finer aggregate and applied by gunning from a greater distance than normal. Ground wires are wires stretched tight to mark the finish surface location in shotcrete work. Shotcrete is usually applied to a thickness slightly past the ground wires, and then screeded back to the required surface.

The use of a 3 m (10 ft) straightedge to measure flatness allows a direct comparison with tolerances for floor finishes. However, for some shotcrete applications, use of a shorter straightedge may be more appropriate. Member thickness tolerances presented in the table incorporate the same minus tolerances presented by ACI Committee 117 for cast-in-place construction. The intention is to avoid excessive effects on design parameters and maintain consistency with tolerances for cover over reinforcing steel. Cumulative tolerances that reduce member thicknesses and depth of reinforcing steel can reduce member strength, especially for thin shotcrete sections. Tolerances that increase member dimensions increase the self-weight and also can reduce the effective live load capacity. Designers and specifiers should account for the potential added dead weight that results from shotcrete application within "plus" tolerances.

Curing

Curing is essential to the hydration process which provides concrete with its strength and durability. The best curing is moist curing. The length of curing should be at least 7 days and at a favourable temperature (>5°C, or 40°F). Curing compounds are acceptable provided no additional shotcrete is applied to that surface. For a natural gun finish or flash finish the curing compound should be applied at a heavier rate than finer finishes, approximately double being normal. If the relative humidity is greater than 85% throughout the curing period, natural curing may be acceptable provided other climatic conditions (wind, sun) are satisfactory. However, for shotcrete surfaces exposed to severe conditions such as freezing and thawing and/or deicer chemicals, natural curing may be insufficient to develop adequate near-surface strength. In such cases, moist or membrane curing is recommended.

A curing compound may be applied to reduce the rapid drying out of shotcrete at the end of moist curing. The curing compound reduces drying and the potential for shrinkage cracking.

Hot and cold weather shotcreting

Wet-mix shotcrete is more susceptible to hot weather than dry-mix because it is a pumped concrete. Slump loss, retempering, strength loss, increased setting rate and air content control are problems often associated with hot weather shotcreting. Mix ingredients should be tested for compatibility at elevated temperatures and the proper choice of materials can often alleviate slump loss and problems due to increased water demand. Keeping shotcrete cool and hose lines protected can have a

beneficial effect on the shotcrete process. Shotcrete pumped mixes can be kept cool and retarders can be used expeditiously, except for overhead work. Other ingredients such as pozzolans can be effective in minimizing high temperature effects but a preconstruction mock-up should be made to assure that the mix can be shot and that strength and durability requirements are met.

The temperature range of shotcrete should be maintained between 10°and 38°C (50°and 100°F). Once a temperature range is selected, the shotcrete temperature should not vary by more than ±5°C (±10°F). The smaller the range the better for uniform shotcrete quality.

Shotcrete should be protected against freezing. Gunning can be allowed to proceed at or above 5°C (40°F), but work should be discontinued below 5°C (40°F). Once in place, the shotcrete can be cured with low atmospheric pressure saturated steam at relatively low temperatures (50°C, 120°F, or slightly less). A curing compound is an acceptable alternative if steam curing is impracticable. Water curing should not be used in a freezing environment. The temperature during curing should be maintained above 5°C (40°F).

10.11 Quality assurance

Past experience has shown that the key elements to be incorporated into a quality assurance programme include prequalification of the project nozzleman and an on-site quality control programme. Discussed in this section are the various elements necessary for a shotcrete quality assurance programme. Many of these points are discussed further by Gebler *et al.* (1991).

Prequalification of the nozzleman

Prequalification of the nozzleman involves a demonstration of skill in constructing test panels. Test panels must incorporate anticipated job conditions such as the approximate reinforcement configuration, directions of placement and a mix design appropriate to the project. Unreinforced panels may also be shot as a supplement to reinforced panels.Test panels usually measure approximately 750 × 750 × 100 mm (30 × 30 × 4 in) and should be fabricated (Figure 10.11) in the anticipated shooting positions (i.e., vertical, horizontal and/or overhead).

Cores from the test panels should be removed from intersections of reinforcement and from unreinforced areas. All cores should be graded visually and several cores that do not contain reinforcement should be used for compressive strength testing or for other performance tests. The visual examination can be based on a grading system first proposed by Crom (1985). Each of the core grades 1 to 5 is shown in Figures 10.12 to 10.16, respectively. A core grade of 1 or 2 is generally used for acceptance of a nozzleman on projects demanding high quality workmanship. Some projects may allow relaxation of this acceptance criterion.

The visual core grading system is subjective. Nevertheless, since the grading criteria are explicit, good correlation between independent gradings has been achieved by engineers experienced with shotcrete. To increase objectivity, the gradings of several engineers can be averaged.

Other durability tests on samples from the preconstruction panels can be specified as required. Tests such as freeze/thaw and sulphate resistance can be made to

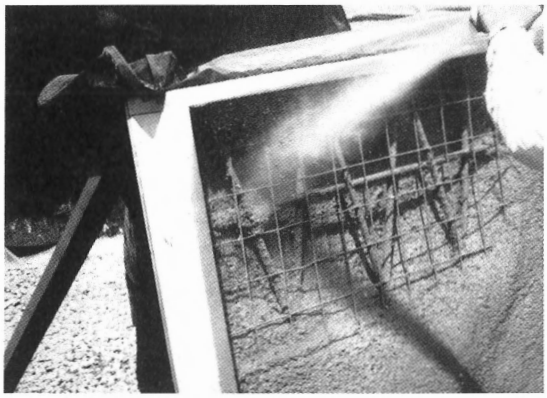

Figure 10.11 *Test panel fabrication. Notice the reinforcement in the panel which is identical to that in the actual structure.*

verify the potential performance of shotcrete. Some of these tests are covered in other chapters, including Section 6.5. Prequalification tests are used to establish the competency of the nozzleman. Active project quality control is then used to judge consistency of placement throughout the project.

Quality control

A comprehensive on-site quality control programme should be conducted throughout the duration of the project. An engineer experienced in shotcrete should oversee workmanship and should have the authority to reject the work as it proceeds.The quality control programme should include the following, which are described below: review of shop drawings; mechanical sounding of work; tensile bond strength testing of in-place work; other in-situ testing; and fabrication of daily test panels.

(i) Shop drawing review
Structural design should incorporate the requirements of the shotcrete construction. In addition, proper reinforcement fabrication and placement details are vital to a successful shotcrete project. Reinforcement drawings should be reviewed for support details and types, and the number and locations of splices. Reinforcement should be adequately supported to prevent movement during installation of shotcrete. Splices should be staggered and offset whenever possible and the total number should be kept to an absolute minimum.

(ii) Mechanical sounding
All shotcrete work should be sounded mechanically for the presence of delaminations. A common method of sounding is tapping with a steel hammer. Sounding should be performed two to three weeks after placement (or later) to allow for shrinkage of the shotcrete. It is helpful while striking the shotcrete to put a hand on the work to help detect debonded areas. This technique adds a little more sensitivy to sounding.



Figure 10.12 *Grade 1 core. The core shall have a good paste content throughout, without laminations, sand areas or large hollows. Small air bubbles to a maximum dimension of 1/16 in (1.3 mm) are quite normal and acceptable. They are dispersed at random without interconnection. There are no sand pockets, hollows or shadows behind any crossed reinforcing bar sections.*

Figure 10.13 *Grade 2 core. The core shall have a good paste content of dense material meeting the same standards as Grade 1 except there may be one or two small tight laminations (i.e. the sand shall be bonded sufficiently by cement paste that it cannot be easily raked out),or sandy areas. Dimensions of laminations or sandy areas shall not exceed 1/8 in (3 mm) in thickness and 1 in (25 mm) in length. The height, width or depth of any void shall not exceed 3/8 in (10 mm). Tight shadowing or slightly porous areas lean in paste behind the reinforcing steel shall not exceed 1/2 in (13 mm) in any dimension, except along the length of the reinforcing bar.*



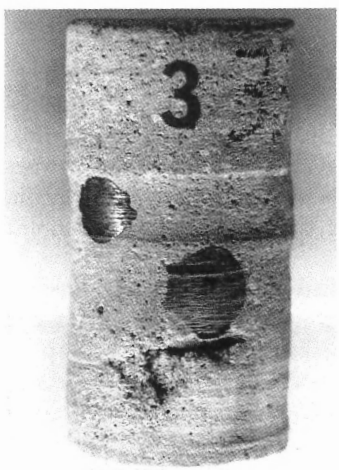

Figure 10.14 *Grade 3 core. The core shall meet the same standards as Grade 2, but in addition may have no more than two laminations or sandy areas with dimensions exceeding 3/16 in (5 mm) in thickness and 1 1/4 in (32 mm) in length, or one major void, sand pocket, shadow or lamination containing some loosely bonded sand not to exceed 1/8 in (16 mm) in thickness and 1 1/4 in (32 mm) in length. The flaws may occur anywhere in the core, but will usually be found below the reinforcing steel and may be completely through the core behind the reinforcing bar.*



Figure 10.15 *Grade 4 core. The core shall meet the same standards as Grade 3 but may have two major flaws, such as described for Grade 3 or may have one flaw with a maximum dimension of 1 in (25 mm) thickness and 1½ in (38 mm) in length.*



Figure 10.16 *Grade 5 core. Any core which has more imperfections than core grades 1 to 4 shall be classified as Grade 5.*

(iii) Tensile bond strength

Tensile bond strength tests can be performed directly on the structure. This method provides quantitative tensile bond strengths between shotcrete layers or between the shotcrete and the substrate. The data should be analysed judiciously by the engineer to determine acceptability. If bond is critical, then the specification should state minimum tensile bond strengths.

To perform tensile bond tests, a core bit is used to drill through the finished shotcrete layer into the substrate concrete or shotcrete. A steel disc is attached to the top of the core with epoxy resin. The epoxy resin is allowed to develop adequate strength so that failure during the test does not occur at the steel disc/epoxy resin interface. The test set-up is shown in Figures 10.17 and 10.18. During testing, a tensile pull-off load is applied to the plate through a loading rig and hydraulic ram. Extreme care must be exercised in drilling to ensure good results. Any eccentricity



Figure 10.17 *Tensile bond strength test equipment.*

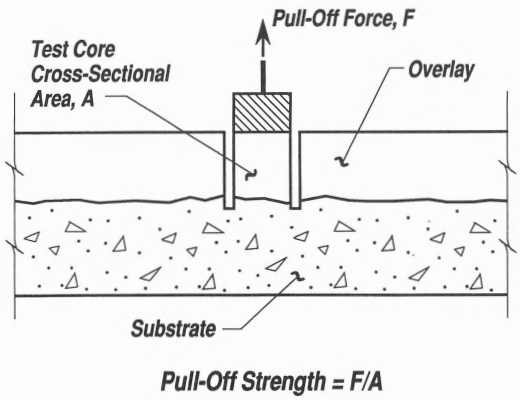

Figure 10.18 *Diagram of set up for tensile bond strength test.*

or wobble in the core barrel during coring can produce low results due to imposed bending stresses. The failure plane must be examined to determine whether it is at the bond plane (yielding a bond strength) or in the shotcrete or substrate (giving a material tensile strength value). If failure occurs at the bond line and the tensile bond value is less than the specified minimum, the engineer should review cleaning operations, amount of reveal in the substrate and/or quality of the substrate material. If composite action is critical, direct shear tests may also be conducted. Alternatively, correlation between tensile bond and direct shear test results can be developed to facilitate field testing.

(iv) In-situ testing

There are several in-situ testing techniques for evaluation of the quality of in-place shotcrete. Aside from obtaining cores and undertaking mechanical or durability tests, there are non-destructive tests available to evaluate shotcrete quality.

Often sand pockets, sand lenses or trapped rebound occur in the shotcrete due to a variety of causes. When defects in shotcrete are suspected, cores should be obtained. The core grading system can be used to evaluate and accept or reject in-place shotcrete (see Section 10.11 above). A freeze/thaw test can also be used to ascertain in-place quality of shotcrete when sand lenses or other defects are thought to be present. Drilled cores are subjected to ASTM C 666 (1990), *Standard Test Procedures for Rapid-Freezing and Thawing of Concrete.* If cores fail to achieve the durability factor established in the specification or separate at laminations, sand pockets or sand lenses, then there is reason for rejection. Figures 10.19 and 10.20 illustrate a core with sand lenses and lamination before and after being subjected to a freeze/thaw test. Note that failure occurred at the sand lenses.

There are several nondestructive tests (NDT) using sonic devices, thermography or X-rays to evaluate the condition of shotcrete. They should be used with caution, especially if personnel (technicians and/or engineers) are not experienced with

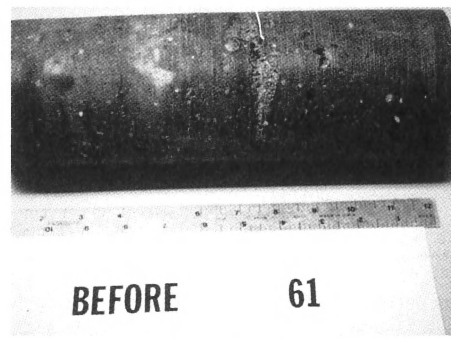

Figure 10.19 *Core showing lamination and sand lens before subjecting it to the freezing and thawing test.*

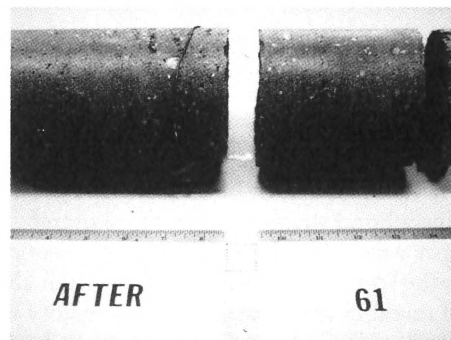

Figure 10.20 *Core after subjecting it to freezing and thawing. Note that the core split at the sand lens.*

shotcrete. Furthermore, care must be used when interpreting NDT results, which should be verified by core testing when serious problems are identified. It is advisable that NDT alone should not be the sole basis for rejection and the specification should state clearly what constitutes acceptance/rejection. It is inappropriate to state merely that a cause for rejection is that the shotcrete lacks uniformity, or has voids or laminations. Almost all conventionally placed concrete contains some minor nonuniformity and of course, voids. The use of the core grade system can give helpful limits on internal defects. This system can be used in specifications and when properly used and administered can be a vital tool in assessing in-place shotcrete. This approach also alerts the contractor, before application, to the amount of defects that will be tolerated and the quality that the engineer/owner is expecting.

(d) Daily test panels

Test panels should be fabricated on a daily basis to provide cores for visual grading, compressive strength testing or other durability tests. Reinforcement configuration and placement position of the test panels should simulate in-place work to be done that day. If cores from daily test panels are found to be defective, then cores should be extracted from in-place material installed on the corresponding day.

While this programme may seem excessively cautious, and costly, it is justified. The shotcrete process is very dependent on the skill of the shotcrete crew and potentially subject to a range of defects if the crew does not operate in a workmanlike manner. The contractor has the obligation to reassure the owner/engineer that the in-place shotcrete is up to standard and will meet the design requirements.

Shotcrete and the 85% f'_c rule

Recently there has been much discussion in the USA regarding the validity of 0.85 f'_c rule for shotcrete acceptance. Gebler and Schutz (1990) discuss the reasons why the 0.85 f'_c rule is not valid for shotcrete. Allowing a 15% strength reduction of in-place shotcrete is simply unjustified. In conventional concrete, a drilled core is compared to a standard mould-cast cylinder and the conditions and limitations allowing the 85% compressive strength reduction are valid. In shotcrete, a drilled core is compared to a similar drilled core and the 85% rule is unjustified. There is no sound engineering reason or published literature to support the 85% rule for shotcrete. It is recommended that construction specifications should not permit the 85% compressive strength factor for shotcrete.

Usually shotcrete produces relatively strong concrete. It does not suffer from low-strength related problems but more from nozzling (placement) problems. If strengths are significantly lower than expected, an in-situ inspection of shotcrete placing procedures and evaluation of in-place shotcrete is warranted as there may be serious in-place defects. Low strength shotcrete may warn of other problems.

References

ACI Committee 117 (1990) *Standard Specifications for Tolerances for Concrete Construction and Materials* (ACI 117-90), American Concrete Institute, Detroit, Michigan, 12 pp.

ACI Committee 301 (1989) *Specifications for Structural Concrete for Buildings*, (ACI 301-89), American Concrete Institute, Detroit, Michigan, 34 pp.

ACI Committee 350 (1989) *Environmental Engineering Concrete Structures* (ACI 350R-89), American Concrete Institute, Detroit, Michigan, 24 pp.

ACI Committee 506 (1990*a*) *Guide to Shotcrete* (ACI 506 R-85), 1985 Revised 1990. American Concrete Institute, Detroit, Michigan.

ACI Committee 506 (1990*b*) *Specification for Materials, Proportioning, and Application of Shotcrete* (ACI 506.2-77) 1983, revised 1990, American Concrete Institute, Detroit, Michigan, 8 pp.

American Society for Testing Materials (1990) *C 666-90, Standard Test Method for Resistance of Concrete Rapid Freezing and Thawing*, ASTM, Philadelphia, PA.

American Society for Testing Materials (1993) *Standard Specification for Ready Mixed Concrete,* C94-92a, ASTM, Philadelphia, PA.

American Society for Testing Materials (1993) *Standard Specification for Concrete made by Volumetric Batching and Continuous Mixing*, C685-92a, ASTM, Philadelphia, PA.

Cepas, R.A. (1991) *Pumping Concrete: Techniques and Applications*, 2nd edition.The Aberdeen Group, Addison, Illinois.

Crom, T. (1985) *Dry Mix Shotcrete Nozzling* The Crom Corporation, Gainsville, Florida, 40.

Gebler, S. and Schutz R. (1990) Is 0.85 f Valid for Shotcrete? *Concrete International*, **12**, (9). American Concrete Institute, Detroit, Michigan, 67–69.

Gebler, S., Kolf, P., Seegebrecht, G., Litvin, A., and Vincent J. (1991) Shotcrete: Surveillance for Durable Structures - Case Histories. *Second CANMET/ACI International Conference on Durability of Concrete*, Montreal, Canada, ACI SP-126, Volume II, 869–900.

Kolf, P. and Gebler, S. (1993) Shotcrete Application Tolerances, *Concrete Construction*, **38**, (4), 287–289.

Steel Structures Painting Council (1982) *Commercial Blast Cleaning.* Steel Structures painting Manual, 2, SSPC-SP6.

11 Special Sprayed Concretes

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11.1 Introduction

Historical background

The dry-mix sprayed concrete process developed by Carl Akeley in the United States around 1910 (American Concrete Institute, 1990), comprised simply sand, Portland cement and water. The process was given the proprietary trade name *Gunite* and was in reality a means for applying mortar pneumatically. From 1910 to 1970, there was remarkably little change in the dry-mix sprayed concrete process. In the 1950s a rotary barrel-feed-type gun was developed in the United States and subsequently improved upon by manufacturers in Switzerland. This enabled coarse aggregates to be incorporated into the dry-mix designs, so that more *concrete-like* sprayed concretes could be applied.

The wet-mix sprayed concrete process was developed after the second world war. Early mix designs were typically formulated with Portland cement, sand, coarse aggregate (usually not more than 15 mm maximum size) and water. Accelerators were added to aid adhesion and thickness of build-up on vertical and overhead surfaces and there was some limited use of supplementary cementing materials such as fly ash and blast furnace slag. Other than these adaptations in mixture formulation, and some improvements in wet-mix sprayed concrete equipment, there were no major changes in wet-mix sprayed concrete technology prior to the 1970s.

The 1970s and 1980s, however, saw development of a number of special sprayed concretes which have now found increasing application in sprayed concrete projects worldwide. These developments have stemmed largely from the desire of owners, engineers and contractors to improve on the quality and durability of in-place sprayed concrete, to increase the productivity and economy of the sprayed concrete process and to expand the range of possible sprayed concrete applications. This chapter is devoted to a review of these special sprayed concretes.

Why the need for special sprayed concretes?

While conventional dry and wet-mix sprayed concretes have served industry well for many decades, there has always been room for improvement, both in mixture formulations, the equipment and application procedures. For example, conventional sprayed concrete has been quite limited in the thickness that could be applied in a single pass, particularly when applied to overhead surfaces. This has necessitated

the building up of sprayed concrete in multiple layers, with layer thickness on overhead surfaces typically being limited to about 50–75 mm with dry-mix sprayed concrete and even less with wet-mix sprayed concrete, unless accelerators are used. Most accelerators, unfortunately, have adverse effects on the properties of the hardened sprayed concrete, such as:

- reduced compressive and flexural strength (Morgan, 1992);
- increased porosity and permeability (Beaupré *et al.*, 1993);
- increased drying shrinkage capacity and hence restrained shrinkage cracking potential (Morgan and Neill, 1991);
- reduced durability, particularly for sprayed concretes subjected to cycles of freezing/thawing and/or exposure to deicing chemicals (Beaupré *et al.*, 1993).

The need for multiple layer construction impacts adversely on productivity and hence economy of the installation. Also, improper preparation of an existing sprayed concrete layer, prior to application of the next layer, can result in reduced bond between layers and, in extreme cases, failure of the sprayed concrete installation (Morgan and Neill, 1991). Thus there has long been a need to be able to enhance the thickness of build-up in a single pass, without having to resort to the use of high addition rates of accelerators. The incorporation of silica fume in both dry and wet-mix sprayed concrete has gone a long way to satisfying this need.

Plain, unreinforced sprayed concrete, like conventional unreinforced concrete, is a relatively brittle material, with limited capacity to resist tensile stresses and strains without cracking and possible disruption. Mesh, or conventional reinforcing steel bars have traditionally been incorporated in the sprayed concrete installation to mitigate brittleness. In the 1970s, however, there was a new development in reinforcing: the incorporation of steel fibres in the sprayed concrete mixture (Henager, 1981). It was found that steel fibres improved the crack resistance, ductility, energy absorption (toughness) and impact resistance of the sprayed concrete. Fibre-reinforced sprayed concrete has proven to be much more *user friendly* than mesh-reinforced sprayed concrete.

The sections which follow review the advances in sprayed concrete technology, as influenced by the use of silica fume and steel fibre reinforcement. In addition there is brief review of other special sprayed concretes, such as:

- the use of high early-strength cements;
- the use of polypropylene fibre reinforcement;
- the use of special chemical admixtures in wet-mix sprayed concretes.

11.2 Cementing materials

Prior to the 1980s most sprayed concrete was made with Portland cement as the cementing material. The exception was high alumina cement, which has long been used in refractory applications (Glassgold, 1991). Since that time a variety of special rapid setting and/or high early-strength-gain cements have been used in sprayed concrete (Morgan, 1991*a*; Gebler, 1989). Such cements have been used in order to achieve effects similar to those accomplished with sprayed concrete accelerators, but without the adverse side effects of accelerators.

A range of different types of such special cements is commercially available. They all exhibit specific characteristics and can seldom be used universally for all

dry and wet-mix sprayed concrete operations. The most rapid setting cements are more suited to site batching operations and cannot be used in central mix or transit mix batching and supply, with long retention times prior to discharge. Some types of high early-strength-gain cements, which require at least a 10 minute contact period with water and mixing to mobilize the plasticizers and alkali activators in their formulation, can only be used in the wet-mix sprayed concrete process (Morgan, 1991*a*). The contact time with water in the dry-mix sprayed concrete process is too short to properly activate the cement.

11.3 Supplementary cementing materials

Fly ash

Fly ash is used in sprayed concrete for many of the same reasons it is used in conventionally cast concrete. It:

- improves the workability and pumpability of wet-mix sprayed concretes made with harsh aggregates, or sands deficient in fine sizes;
- reduces the heat of hydration, and consequently the potential for thermally induced cracking, in thick sprayed concrete applications (e.g. underground bulkhead construction);
- improves sulphate resistance (when properly selected fly ashes are used);
- controls alkali-aggregate reactions and
- produces more economical mixtures.

A recent innovation is the development of high volume fly ash wet-mix sprayed concrete, containing 40–60% fly ash by mass of cement. Water-reducing admixtures and high dosages of superplasticizers are used to produce mixtures with very low water/cementing materials ratios (Malhotra *et al.*, 1989; Morgan *et al.*, 1990; Langley and Dibble, 1990). The resulting wet-mix sprayed concrete has good volume stability (low drying shrinkage capacity), good freeze/thaw durability (when properly air-entrained), and very low chloride permeability compared with conventional wet-mix Portland cement sprayed concrete. To date such shotcrete has been used mainly in conjunction with polypropylene fibre reinforcement, in predominantly downward shooting applications. Examples include capping and sealing waste piles, pyritic slates and shales, slaking ground and other acid-leachate generating sites. In such applications the generally slower setting time and rate of early strength gain is not of concern. Of more interest is the longer term permeability and durability of the sprayed concrete installation.

The use of fly ash in dry-mix sprayed concrete has been fairly limited; mainly restricted to providing additional fines to enhance adhesion and cohesion of the sprayed concrete mixture, in situations where excessively high cement contents are to be avoided (Morgan, 1988*a*).

Silica fume

Perhaps the most significant advance in sprayed concrete technology since the 1970s has been the use of silica fume. Its use in wet-mix sprayed concrete was pioneered in Norway in the 1970s (Garshol, 1990). It was found that the substitution of

7–15% by mass of the Portland cement with silica fume imparted a number of benefits to the sprayed concrete including:

- improved adhesion (sticking to a surface) and cohesion (ability of plastic sprayed concrete to stick to itself);
- ability to build up greater thicknesses of shotcrete with elimination of, or reduction in accelerator addition rates;
- improved properties in the hardened sprayed concrete, particularly compressive and flexural strength.

The greatest improvements in the wet-mix, silica fume modified sprayed concrete are achieved when water reducing and superplasticizing admixtures are added to the mixture, to control water demand and reduce the water/cementing materials ratio (Morgan and Wolsiefer, 1992). Extensive laboratory research and field studies carried out in Canada in 1983 (Morgan *et al.*, 1987; Morgan, 1988*b*) demonstrated that even more pronounced benefits could be achieved with dry-mix sprayed concrete, compared to wet-mix silica fume sprayed concrete, through incorporation of silica fume in the mixture. These benefits included:

- substantial improvement in the adhesion and cohesion of the plastic sprayed concrete;
- build up of thick layers in a single pass on vertical surfaces (600 mm or more) and overhead surfaces (as much as 400 mm) with little or no accelerator added;
- improved resistance to wash-out where freshly applied sprayed concrete was subjected to running water or tidal cycling;
- improved economy, through substantial reductions in rebound and increased rates of productivity, through single layer construction;
- improvements in properties of the hardened shotcrete, such as compressive and flexural strength;
- enhanced durability, particularly with respect to: freeze/thaw resistance, deicing salt scaling resistance, reduced penetration of chloride salts and improved resistance to chemical attack.

The sections which follow provide information concerning the design, supply, application and performance of wet and dry-mix sprayed concretes modified with silica fume.

11.4 Admixtures

Accelerators

Accelerators have long been added to sprayed concretes (both wet and dry-mix) in order to increase the thickness of build-up in a single pass and thus enhance productivity; and to reduce the time to initial set and increase early (8 to 24 hour) strength development.

While accelerators can be quite effective in imparting these characteristics to sprayed concrete, there is a penalty to be paid. As previously mentioned, their use nearly always results in reduced strength at later ages (Gebler *et al.*, 1992; Morgan, 1992; Schutz, 1982), and the permeability and durability of the sprayed concrete can also be adversely affected (Gebler *et al.*, 1992; Beaupré *et al.*, 1992). The extent of strength reduction depends on a variety of factors, including the particular type

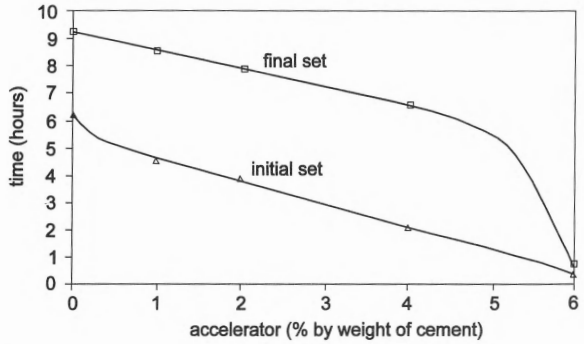

Figure 11.1 *Influence of a sprayed concrete accelerator on setting time (Morgan, 1992).*

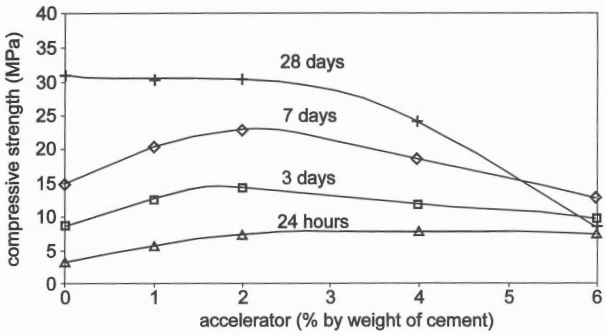

Figure 11.2 *Influence of a sprayed concrete accelerator on strength development (Morgan, 1992).*

of accelerator used and the rate of addition. As a general rule, strength reductions tend to be most pronounced with accelerator types and addition rates which promote flash setting (Schutz, 1982; Morgan, 1992). Figure 11.1 shows the influence of a particular accelerator on the setting time of wet-mix sprayed concretes. Figure 11.2 shows the resulting reduction in compressive strength with increasing accelerator dosage. There is almost a 50 per cent reduction in compressive strength at 28 days for the mixture with 6 per cent accelerator, which displayed very rapid setting.

Also, it is well-known that most accelerators will significantly increase the drying shrinkage of Portland cement concretes (Morgan, 1974) and field observations have verified this same influence in sprayed concretes. Figure 11.3 shows cracks up to 1.25 mm wide in a bridge abutment in Alberta, Canada, repaired with an accelerated, dry-mix, sprayed concrete (Morgan and Neill, 1991).

Fortunately, with the advent of silica fume, it is no longer necessary to rely solely on accelerators for build-up of thick layers of sprayed concrete in a single pass. It should, however, be noted that the incorporation of silica fume in the sprayed concrete does not substantially reduce the time to initial and final set. In projects where high early (8 hour) strengths are required, it may still be necessary to use some accelerator, albeit at reduced rates. Alternatively, special high early-strength cements (Gebler, 1989; Morgan, 1991*a*) may be used. As a general recommendation,

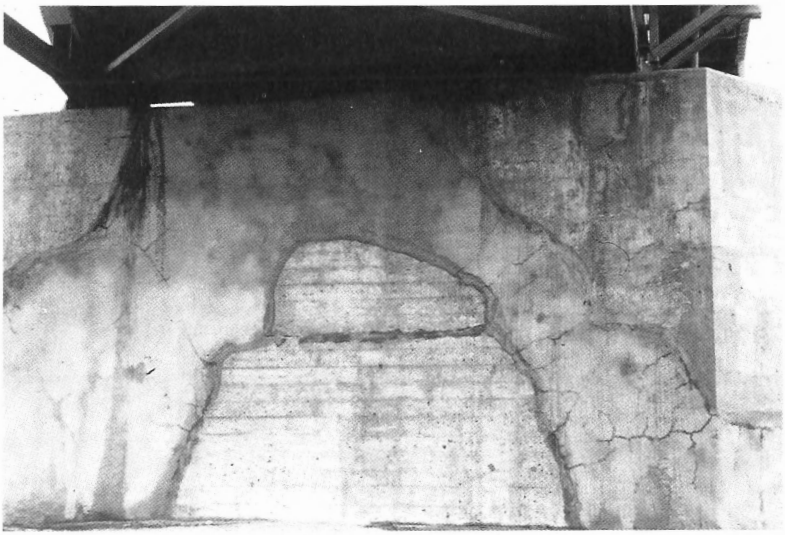

Figure 11.3 *Restrained shrinkage cracks in a bridge pier repaired with accelerated dry-mix sprayed concrete.*

accelerators should not be used in sprayed concretes, unless considered essential to the construction process.

Chemical admixtures

Chemical admixtures for conventional concrete, such as water reducers, superplasticizers, retarders and air entraining admixtures are commonly used in sprayed concretes. They are added to the mixture for the same basic reasons they are used in conventional concretes. There are, however, some significant differences in their use in sprayed concretes.

Air entraining admixtures are added to wet-mix sprayed concretes to enhance the freeze/thaw durability and deicing chemical scaling resistance. Experience has shown, however, that for wet-mix sprayed concrete as much as one half of the air content at the point of discharge into the sprayed concrete pump, is lost on impact with the receiving surface (Morgan, 1989; Gilbride *et al.*, 1988). As a result it is often necessary to start with air contents as high as 8 to 10 percent in the sprayed concrete at the point of discharge into the pump, in order to achieve satisfactory parameters of the air void system in the hardened in-place sprayed concrete (Beaupré *et al.*,1993).

Conventional wisdom suggests it is not possible to entrain air in dry-mix shotcrete. However, recent work at Laval University in Quebec (*ibid*) has shown that it is possible to entrain adequate air in dry-mix sprayed concrete by adding an air entraining admixture to the mix water injected at the nozzle. Such air entrained dry-mix sprayed concrete showed good resistance to deicer chemical scaling (*ibid*).

Water-reducers are commonly used in wet-mix sprayed concretes to control water demand of the mixture, with the attendant benefits that this imparts; reduced shrinkage, reduced water/cementing materials ratio and hence increased strength and reduced permeability. Both water-reducers and superplasticizers are recom-

mended for use in wet-mix sprayed concretes made with silica fume. Silica fume has an inherently high water demand (because of its extreme fineness) and so the use of superplasticizers, in particular, is considered important to control water demand of the mixture and thus enable the full benefits of silica fume to be achieved (Morgan *et al.*, 1987; 1988*a*).

Conventional liquid water reducers and superplasticizers are not used in dry-mix sprayed concrete, since the majority of the mix water is added at the water ring at the nozzle. There is simply not enough time for the water reducing properties of the admixtures to be mobilized in the short time it takes from water injection at the nozzle, to impact of the mixture with the receiving surface. The addition of dry powdered superplasticizer to prebagged, dry-mix sprayed concrete is not recommended. If the powdered superplasticizer becomes mobilized in the in-place sprayed concrete, it can result in sloughing.

11.5 Fibre reinforcement

Steel fibre

Prior to the 1970s sprayed concrete was reinforced with conventional concrete reinforcing steel, welded wire mesh fabric, or in some instances even chain link mesh or chicken wire. These latter two types of reinforcement are normally not recommended, as they are not conducive to thorough encapsulation in the sprayed concrete process. Expanded diamond mesh lath has also been used, but mainly in applications using ferro-cement.

The pioneering work of Lankard in the USA in 1971 (Henager, 1981) showed that steel fibre reinforcement was very compatible with the sprayed concrete process. While this technology had its origins in the development of pseudo-ductile sprayed concrete for use in lining rock slopes and support of underground openings in tunnels and mines, steel fibre reinforced sprayed concrete (SFRSC) soon started to find applications in remedial works and construction of a variety of different types of structures (Henager, 1981; ACI, 1984; Morgan, 1991*b*).

There is a variety of different types of steel fibres which have been used in sprayed concrete. Various different processes are used for manufacturing steel fibres, including: cutting cold drawn wire, slitting steel sheet, milling steel blocks and the melt-extraction process.

The most useful parameter describing steel fibres is the aspect ratio, which is defined as the ratio of length/equivalent diameter. The most important aspects controlling the performance of steel fibres in sprayed concrete are the aspect ratio and volume concentration. The higher the aspect ratio and volume concentration of steel fibre, then theoretically the better is the performance of the SFRSC with respect to parameters such as impact resistance, toughness, ductility, crack resistance and residual load carrying capacity after cracking. Unfortunately, the higher the aspect ratio and volume concentration of the fibre, the more difficult the SFRSC becomes to mix, convey and shoot. Thus there are practical limits to the amount of fibre which can be added to SFRSC, and the amount varies with different proprietary fibre types.

In the 1970's, a wide variety of different fibre types were promoted, with fibre

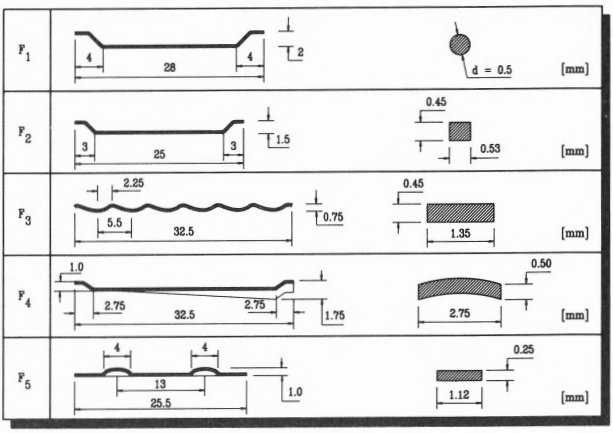

Figure 11.4 *Examples of different types of steel fibres used in sprayed concretes (Banthia, 1992).*

sizes varying from 12 × 0.25 mm and an aspect ratio of 50, to 64 × 0.76 mm and an aspect ratio of 83. Most of these fibres were straight. They were difficult to mix, convey and shoot and post first-crack performance (as measured by the toughness test) was less than impressive. Manufacturers then devised a variety of means of improving the *effective aspect ratio* of steel fibres, by techniques such as crimping the fibres, introducing bent or enlarged ends, making special deformations on the fibres, or increasing roughness of the fibre surface texture.

By the 1980s very few straight fibres were used in SFRFC any more. The most common fibres now used are deformed in one way or another and have typical fibre lengths ranging from about 25 to 40 mm and aspect ratios ranging from about 40 to 60. Figure 11.4 shows some of the proprietary fibre types currently in use in SFRSC. Fibre addition rates vary between about 50 and 80 kg/m^3, with 60 kg/m^3 being commonly used in tunnelling and mining applications (Rose, 1985; Wood *et al.*, 1989; Ramakrishnan, 1985; Morgan 1991*c*).

Polypropylene fibre

For nearly two decades, steel fibre was almost the only fibre used in sprayed concrete. In the late 1980s, however, polypropylene fibre started to find use. Both discreet monofilament and fibrillated fibres have been used. Initially they were used at very low addition rates of about 1 kg/m^3; i.e. at about the same addition rate as for conventional concrete. At these low addition rates, the benefits of polypropylene fibre are limited mainly to providing enhanced resistance to plastic shrinkage cracking and providing some *green-strength* to freshly applied sprayed concrete, i.e. making the sprayed concrete less susceptible to sags and tears during finishing operations.

A more recent development has been the use of sprayed concretes with high volume addition rates of fibrillated polypropylene fibres in wet-mix sprayed concrete (Malhotra *et al.*, 1989; Morgan *et al.*, 1989, 1990; Langley and Dibble, 1990). In these studies and subsequent field applications, polypropylene fibres were added to wet-mix sprayed concrete at addition rates of between 4 and 7 kg/m^3. At these

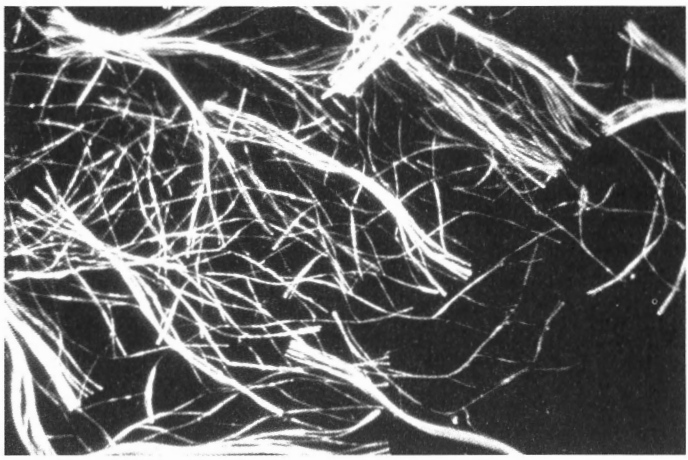

Figure 11.5 *Collated, fibrillated polypropylene fibre used in wet-mix sprayed concrete.*

higher fibre addition rates a pseudo-ductile material is produced which can provide similar load vs. deformation characteristics in flexure to certain steel mesh and steel fibre reinforced sprayed concretes (Morgan, 1989). The fibrillated polypropylene fibres used have ranged in length from 20 to 40 mm. Figure 11.5 shows one type of commonly used fibrillated polypropylene fibre.

While low addition rates (up to 1 kg/m^3) of polypropylene fibre have been added to dry-mix sprayed concrete, the higher addition rates cannot be effectively incorporated in the dry-mix process. The wetting of the mixture at the nozzle is simply not capable of adequately coating and embedding the fibres in the cementitious paste in the short mixing time before the material impacts with the receiving surface. A *snow* of unincorporated fibres is then produced in the return air-stream during nozzling operations, and actual in-place fibre contents remain low.

11.6 Mixture proportioning

Cementing materials

Sprayed concrete mixture proportioning is governed by the same principles which apply to conventional concrete mix design; i.e. Abram's law applies and the prime factors controlling strength and quality are the water/cementing materials ratio, degree of consolidation and (in wet-mix sprayed concrete) air content. There are, however, some typical differences in proportioning of sprayed concretes compared to conventional cast concretes. Sprayed concretes typically have higher cementing materials contents; values ranging from 400 to 500 kg/m^3, as batched, are typical (Morgan *et al.*, 1987). In-place cementing materials contents tend to be even higher, particularly in dry-mix sprayed concrete, because of the higher mass of aggregate (compared with the cement) in rebound materials. These higher cementing materials contents are necessary to facilitate adhesion and build-up of sprayed concretes.

Aggregates

The other major difference between sprayed concrete and conventional concrete is in the gradation of the aggregates used. ACI 506R-90 (1990) recognizes three different sprayed concrete aggregate gradations. These are listed in Table 11.1. Gradation No. 1 is essentially a conventional concrete sand gradation and is commonly used in what is sometimes referred to in the United States as *Gunite* mixtures; i.e. fine aggregate, dry-mix sprayed concrete. Gradation No. 2 is probably the most widely used sprayed concrete aggregate gradation and is commonly used in both wet-mix and dry-mix sprayed concretes. It comprises about 25 to 30 percent by mass of a 10 mm maximum size coarse aggregate and 70 to 75 percent by mass of a concrete sand. Gradation No. 3 contains a blend of 20 mm maximum size coarse aggregate and concrete sand, and is not often used in sprayed concrete. It is occasionally used in applications requiring large volume placements of thick sections, such as pneumatically placed underground bulkheads and plugs.

Clearly most sprayed concrete mixtures have considerably less coarse aggregate and finer composite aggregate gradations than conventional cast concretes. Some agencies have attempted to design and apply sprayed concretes with combined aggregate gradations approaching those of conventional concretes, but this is counterproductive. Much of the excess coarse aggregate is lost as rebound during the application process and total rebound increases to unacceptably high levels. This is particularly true of the dry-mix sprayed concrete process, but also applies (albeit to a lesser extent) to wet-mix sprayed concrete.

Supplementary cementing materials

Fly ash is used as a replacement or addition to Portland cement, at rates in the range of 15 to 25 per cent by mass of Portland cement (Morgan, 1988*a*), although amounts as high as 60 per cent have been used in high volume fly ash systems (Malhotra *et al.*,

Table 11.1 *ACI 506R-90, Table 2.1, Gradation limits for combined aggregates for sprayed concretes*

Sieve Size, U.S. Standard Square Mesh	Percent by Weight Passing Individual Sieves		
	Gradation No. 1	Gradation No. 2	Gradation No. 3
¾ in. (19 mm)	–	–	100
½ in. (12 mm)	–	100	80–95
⅜ in. (10 mm)	100	90–100	70–90
No. 4 (4.75 mm)	95–100	70–85	50–70
No. 8 (2.4 mm)	80–100	50–70	35–55
No. 16 (1.2 mm)	50–85	35–55	20–40
No. 30 (600 μm)	25–60	20–35	10–30
No. 50 (300 μm)	10–30	8–20	5–17
No. 100 (150 μm)	2–10	2–10	2–10

1989; Langley and Dibble, 1990). Fly ash is used mainly in wet-mix sprayed concretes, and for many of the same reasons that it is used in conventional cast concrete.

Silica fume has been used in sprayed concretes at rates varying from 5 to 15 per cent by mass of Portland cement. At the lower addition rates (5 percent) effects on the properties of the plastic shotcrete are modest; only slight improvements in adhesion, cohesion, thickness of build-up, resistance to wash-out and reduction in rebound are achieved. At the higher addition rates (up to 15 per cent), improvements in plastic properties can be quite dramatic, particularly in the dry-mix sprayed concrete process. In Canada a number of cement companies produce and market preblended Portland-Silica Fume cements, with about 7.5 to 8.5 per cent silica fume (by mass of Portland cement) in the blend. Such cements are widely used in both wet and dry-mix sprayed concretes, particularly in infrastructure rehabilitation, mining and tunnelling applications.

Admixtures

Water-reducing admixtures are normally used in wet-mix sprayed concretes to control water demand of the mixture. They are usually added at the same rates at which they are used in conventional concretes. They are not used in dry-mix sprayed concretes. Superplasticizers are recommended for use (in addition to water reducers) in wet-mix sprayed concretes containing silica fume. They are added at similar addition rates to the amounts used in conventional cast concretes; i.e. 500 ml to 1000 ml/100 kg cement. However, care should be taken not to overdose with superplasticizer as this can result in mixtures with poor stability in-place and a tendency to sag and slough.

Accelerator addition rates can vary considerably, depending on the particular accelerator being used and the specific effects sought. Where very rapid stiffening of the mixture is required, accelerators are sometimes added at rates sufficient to promote *flash-set*. This may be as high as 6 to 8 per cent by mass of cement for chemical-set accelerators, which act by promoting very rapid chemical reactions with the cement with the immediate evolution of heat of hydration; e.g. accelerators based on sodium, calcium and potassium aluminates and carbonates, and triethanolomine.

Accelerators based on thixotropic (gluing) action, such as sodium silicates (water-glass), are added at even higher rates (Garshol, 1990), with values in the range of 10 to 15 per cent by mass of cement being common. In the construction of large diameter, twin-track rail tunnels for the Deutches Bundesbahn in Germany, using the New Austrian Tunnelling Method (NATM), water-glass addition rates approaching 20 per cent by mass of cement were used to facilitate the robotic placement of wet-mix sprayed concrete in thick overhead sections.

Accelerator addition should, however, be kept to the absolute minimum required to facilitate the construction process, because of the adverse affects of the accelerator on the properties of the hardened sprayed concrete. This is particularly true for accelerator addition rates which promote flash set or instant stiffening (Lukas and Kusterle, 1990). Finally, it should be cautioned that the effectiveness of accelerators can be very cement-specific. A particular accelerator may work well with a given brand of cement, but not with another brand of the same cement type.

Table 11.2 *Typical remedial sprayed concrete mixture* (Proportions at the nozzle, kg/m^3)

Material	Mix Description			
	Wet-Mix		Dry-Mix	
	Plain	Silica Fume	Plain	Silica Fume
Portland cement, CSA Type 10	400	350	425	375
Silica Fume	-	47	-	50
10 mm coarse aggregate*	460	485	495	490
Concrete sand*	1260	1215	1215	1205
Water	170	177	165	165
Water-reducing admixture	Yes	Yes	-	-
Superplasticizer	-	Yes	-	-
Air-entraining admixture	Yes	Yes	-	-
TOTAL:	2290	2274	2300	2285

*Proportions based on SSD aggregates

Preconstruction testing should be conducted to evaluate the effectiveness of specific combinations of cements and accelerators.

Typical sprayed concrete proportions

Typical sprayed concrete mixture proportions for both wet and dry-mix sprayed concretes, as used in tunnelling and mining, and infrastructure rehabilitation applications in North America, are given in Table 11.2 (Morgan, 1992). It should be appreciated that these are *as-batched* mixture proportions; in-place proportions will differ, because of rebound, particularly for dry-mix sprayed concretes.

11.7 Batching, mixing and supply

Dry-mix Sprayed Concrete

The special dry-mix sprayed concretes described in this chapter have been batched, mixed and supplied by a range of different systems, including the following:

- central or transit mixer batched, with transit mixer supply;
- site-batching, using either volumetric or mass-batching techniques;
- dry-bagged premix materials, supplied in small paper bags (30 kg typical) or large synthetic cloth bulk bin bags (1600 kg typical).

There are advantages and disadvantages to each of the above systems. The following is a brief description of the pros and cons of the different systems.

Transit mixer supply

While central or transit mixer batching and transit mixer supply has been quite widely used for conventional sprayed concretes, it is considered the least desirable system for special sprayed concretes such as silica fume modified mixtures. Experience has shown that the more fresh the dry-mix sprayed concrete (i.e. the shorter the time from first contact of moisture with the cementing materials, until the time of impact on the receiving surface) the better the quality of the plastic and hardened sprayed concrete. With longer periods of time before discharge numerous small pellets of non-homogeneous material can be formed in the transit mixer. This can result in a reduction in the adhesive and cohesive quality of the sprayed concrete. Lesser thicknesses of build-up are achievable on vertical and overhead surfaces and the degree of rebound increases significantly. Properties of the hardened sprayed concrete, such as permeability and strength can also be adversely affected.

With conventional transit mix supplied sprayed concrete the time from batching (first contact of moisture with cement) to completion of discharge should not exceed 45 minutes. In hot weather, shorter times to completion of discharge may be required. With silica-fume modified dry-mix sprayed concrete there can be an even greater propensity to the formation of pellets with extended mixing time and even shorter periods to completion of discharge may be required.

Site batching

Site batching remains the predominant means of supply of conventional dry-mix sprayed concrete in North America. It is also well suited to supply of special sprayed concretes, such as silica fume modified mixtures, provided properly calibrated dispensing systems are used. Site-batched sprayed concrete usually has the advantage of a shorter time from first contact of water with the cementing materials, to time of application, compared to transit mixer supply. Site batching can be accomplished either by mass batching, volumetric batching, or a combination of the two systems. If volumetric batching is utilized, it is important that there are regular



Figure 11.6 *Supply of dry-mix, silica fume modified sprayed concrete to a bridge rehabilitation project in Quebec, Canada.*

mass calibration checks to ensure that the design mixture proportions are being batched. Both stationary and mobile volumetric batching units are used. Figure 11.6 shows a mobile batch unit supplying dry-mix, silica fume modified sprayed concrete to a bridge rehabilitation project in Quebec, Canada.

Premix supply

Dry-bagged premix supply is particularly well suited for special dry-mix sprayed concretes, as they often contain more numerous ingredients than conventional dry-mix mixtures. For example, dry-bagged premix mixtures commonly used in tunnelling and mining applications in Canada typically contain: Portland cement, silica fume, 10 mm maximum size coarse aggregate, concrete sand, steel fibres, dry-powdered accelerators and sometimes dust suppressants. All ingredients are precision mass-batched in a controlled batch-plant environment. With site batching, and particularly volumetric site batching, there is always a danger of mis-batching of one or more of the ingredients in such multiple-component mixtures.

Another major advantage of dry-bagged premix supply is the very short time from first contact of moisture with the mixture, until it impinges on the receiving surface. Being *bone-dry* it is necessary to premoisturize the sprayed concrete prior to discharge into the sprayed concrete gun. Figure 11.7 shows 30 kg bags of dry premixed material being added to a premoisturizer auger, where water is added to raise the moisture content to 3–6 per cent (4 per cent being typical). If the bone-dry ingredients are not premoisturized it becomes more difficult to uniformly wet-out the sprayed concrete with the water addition at the nozzle. This can result in increased production of dust (both at the gun and at the nozzle), increased rebound and the danger of formation of incompletely wetted-out in-place shotcrete; i.e. so-called sand lenses.

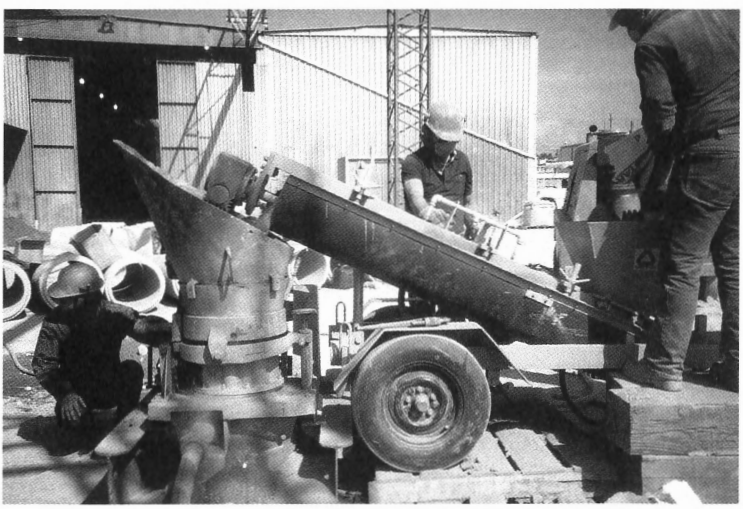

Figure 11.7 *Dry-bagged premixed sprayed concrete being added to a premoisturizer auger, prior to discharge into a dry-mix sprayed concrete gun.*



Figure 11.8 *Bulk bin bag supply of dry-bagged, premix sprayed concrete for rehabilitation project of the Jordan River Dam on Vancouver Island, British Columbia.*

Small (30 kg) paper bags have been used for supply of premixed materials, but the system which is now finding widespread use in North America is supply in large synthetic cloth bulk bin bags (1600 kg typical). Dry bagged premix has proven popular for use in support of underground openings in tunnelling and mining applications and in sprayed concrete repair of infrastructure. Figure 11.8 shows bulk bin bag supply of a dry-mix, steel fibre reinforced, silica fume modified sprayed concrete for repair of the Jordan River Dam on Vancouver Island, British Columbia, Canada.

Dry-bagged supply is particularly well suited to remote sites with difficult access. It can be transported long distances by truck, train, barge, ship and even helicopter. Being totally dry the material can be used at any time after batching. The bags do, however, have to be transported and stored so as to prevent moisture from causing prehydration of the cement. Also, during periods of cold weather the bags should be stored in a protected location. The in-place sprayed concrete temperature at the time of application should not be allowed to fall below 5°C; otherwise rebound tends to increase and the sprayed concrete may be slow in setting and developing strength.

Wet-mix sprayed concrete

Any of the batching, mixing and supply systems used for conventional concrete production can be used for wet-mix sprayed concretes. Mixtures have been batched and supplied using all of the following systems:

- central mix batched, with transit mixer supply;
- transit mixer batched and supplied;
- volumetric site batching in mobile batcher units.

Ingredients such as silica fume and steel fibre reinforcement can be added at the batch plant or on site. Silica fume has been added in all the following ways:

- as a liquid slurry (typically with about a 50 per cent silica fume solids content) with or without superplasticizer;
- as a dry uncompacted or compacted silica fume powder with or without a dry powdered superplasticizer;

Table 11.3 *Properties of the plastic wet and dry-mix sprayed concretes in Table 11.2*

Property	Mix Description			
	Wet-Mix		Dry-Mix	
	Plain	Silica Fume	Plain	Silica Fume
Slump, mm	50	50	–	–
Air content, %,				
Before shooting	8.5	6.4	–	–
After shooting	4.8	3.9	–	–
Thickness to sloughing, mm				
Overhead application	80	130	65	380
Vertical application	300	330	200	460
Overhead rebound, %	15	13	46	20
Vertical rebound, %	4	3	42	20

- as an ingredient of a blended Portland/silica fume cement (typically 8 per cent by mass silica fume in the blend).

Steel and polypropylene fibre reinforcement can be added to wet-mix sprayed concrete in the same ways as for fibre reinforced concretes. They can be added at the batch plant, or at the site. Special fibre dispensers have been developed for site addition of steel fibres to volumetric mobile batching units.

When adding steel fibres to wet-mix sprayed concrete the temptation to retemper the mixture excessively with water must be avoided. SFRSC will appear much stiffer than conventional plain sprayed concrete and will produce much lower slumps after fibre addition, when tested using the standard slump test. But visual appearance and the slump test are not good indicators of the true workability of SFRSC; mixes that appear stiff and have a low slump can still pump and shoot well. Excessive retempering with water can result in segregation and fibre balling in the plastic SFRSC and a reduction in the quality of the hardened SFRSC.

If accelerators are used they must be added in a liquid form at the nozzle. Special accelerator dispensing units have been developed which are driven by the hydraulics of the wet-mix sprayed concrete pump. The accelerator addition is calibrated and timed to coincide with the surge of the pistons in the sprayed concrete pump, so that uniform accelerator dosage is achieved.

11.8 Application and plastic properties

Dry-mix sprayed concrete

The plastic properties of dry-mix sprayed concrete are determined by the propor-

Table 11.4 *Air content in plastic and hardened wet-mix sprayed concrete and parameters of the air void system (Beaupré, 1993)*

Mix No.	Description	Air-entraining admixture, ml/kg	Fresh sprayed concrete		Hardened sprayed concrete		
			Air content, %		Air content %	Spacing factor, mm	Specific surface, mm^2/mm^3
			Before shooting	After shooting			
AW 1a	Plain	0.93	8.8	4.4	4.9	306	18.6
AW 1b	Plain	0.46	7.0	4.1	4.6	322	18.1
AW 1c	Plain	0	4.4	3.3	5.8	412	12.6
AW 1d	Plain	0	4.3	3.2	4.0	501	12.2
AW 1pf	Poly Fibre	0.58	6.2	4.2	5.1	312	15.6
AW 1S5	5% Silica Fume	0.46	6.8	4.0	5.2	323	17.3
AW 1S	10% Silica Fume	0.58	7.4	4.3	5.6	248	21.6

tions of the dry material in the mixture, the amount of water added at the nozzle and the nozzling technique. The optimal amount of water required is to a degree self-policing. If too much water is added, the sprayed concrete will tend to sag or slough. If too little water is added, the mixture is not properly wetted-out, and an excessive amount of dust tends to be generated (both at the gun and the nozzle) and rebound increases. There is also a danger of the formation of dry, incompletely consolidated layers (usually referred to as sand lenses) in the sprayed concrete. Dry-mix sprayed concrete adheres best, shows the least rebound and best hardened properties when shot at the wettest stable consistency. An experienced nozzleman is the best judge of this optimal state.

With conventional dry-mix sprayed concrete (without accelerators or silica fume) the thickness of build-up in a single pass attainable on vertical or overhead surfaces is usually limited to about 50–80 mm. On horizontal surfaces much thicker sections can be shot in a single pass, particularly if the shotcrete consistency is kept stiff (e.g. 40–50 mm slump) or the bench-gunning technique is used.

With silica fume and/or accelerator addition, much greater thicknesses of build-up are possible. See for example the test results in Table 11.3 for the dry-mix sprayed concrete with proportions detailed in Table 11.2. In thickness to sloughing tests (Morgan, 1992) the substitution of 11.5 per cent by mass of cement of silica fume resulted in increases in thickness to sloughing from 65 to 380 mm on an overhead surface and 200–460 mm on a vertical surface.

In this same study the incorporation of silica fume in the mixture reduced the amount of rebound from 46 to 20 per cent on an overhead surface and 42 to 20 per cent on a vertical surface (Table 11.3). Similar reductions in the amount of rebound achieved through the use of silica fume have been recorded on a variety of projects.

Table 11.5 *Properties of the hardened wet and dry-mix sprayed concretes in Table 11.2*

Property	ASTM test procedure	Mixture description			
		Wet-mix		Dry-mix	
		Plain	Silica fume	Plain	Silica fume
Compressive strength, MPa	C39				
at 24 hours		15	22	30	34
7 days		28	45	44	49
28 days		44	63	54	60
Flexural strength, MPa	C78				
at 7 days		3.8	4.9	–	–
28 days		5.3	6.7	7.4	8.4
Boiled absorption % at 28 days	C642	6.6	5.9	4.9	2.7
Volume of permeable voids, % at 28 days		14.3	12.9	11.2	6.3
Air content, %	C457	5.0	3.3	4.3	3.9
Specific surface, mm^{-1}		23	18	16	21
Spacing factor, mm		0.25	0.36	0.35	0.26
Drying shrinkage, length change, % at 64 days	C341	0.105	0.088	0.072	0.061

Rebound in steel fibre reinforced sprayed concrete

Rebound can be defined as the material which ricochets off the impacted surface and falls to the ground during the sprayed concrete application process. When the dry-mix sprayed concrete stream first impinges on the receiving surface, nearly all the coarse aggregate and a significant amount of steel fibre rebound. This continues until a sufficient thickness of mortar has built up to enable bedding-in of the impinging coarse aggregate and steel fibres.

As the shotcrete layer thickens, less coarse aggregate and fibre rebound (Ryan, 1975). Thus it has been found that in-place fibre retention is least in thin (50 mm or less) sprayed concrete layers. In 100 mm thick sprayed concrete layers, it was found (Morgan, 1991*b*) that for as-batched steel fibre contents of 60 kg/m^3, in-place steel fibre contents ranged from about 35–45 kg/m^3.

In a systematic study of dry-mix sprayed concretes, made with 5 different types of steel fibre, fibre rebound varied from 35 to as much as 78 per cent (Banthia, 1992). It was found that the percentage of fibre rebound was substantially affected by fibre geometry. Banthia proposed a term *specific projected fibre area* (i.e. fibre projected area in mm^2 per unit fibre mass) to explain the propensity of certain fibre

types to rebound more than others. Figure 11.4 shows the types of fibres investigated. As a generalization, lighter or more foil-like fibres tend to rebound more than heavier, more needle-like fibres.

In addition to fibre type and geometry, there are a number of other factors which can influence fibre rebound in dry-mix sprayed concretes, including:

- aggregate gradation: coarser aggregate gradations can increase overall and fibre rebound;
- consistency (degree of wetness): fibre rebound tends to be higher in mixtures sprayed at a drier consistency; and
- shooting technique: the air pressure and distance of the nozzle from the surface and nozzle orientation must all be optimized.

In summary any factors which increase overall dry-mix sprayed concrete rebound will also tend to increase the percentage of fibre rebound. Further discussion of material and fibre rebound is given in Section 4.5 of Chapter 4.

Wet-mix sprayed concrete

The plastic properties of wet-mix sprayed concrete are largely determined by the quality of the mixture supplied to the delivery equipment. If the mixture is too wet the nozzleman will have difficulty in making the sprayed concrete stick to the receiving surface. If the mixture is too stiff, pumping and shotcrete consolidation difficulties may be experienced. Wet-mix sprayed concretes have been applied at consistencies varying from 20 mm to 150 mm slump, but usually the slump is in the range of 40 to 80 mm. The lower end of this slump range is generally used for sprayed concretes applied to overhead surfaces, or where thick vertical sections are to be constructed. Mixtures with slumps greater than 80 mm would normally only be used for predominantly downward shooting; e.g. construction of canal linings.

Silica fume modified wet-mix sprayed concretes can be applied to greater thicknesses before sloughing on vertical and overhead surfaces than conventional sprayed concretes. The beneficial effect of silica fume on thickness of build-up is, however, not as pronounced as in dry-mix sprayed concrete (Table 11.3).

Rebound with properly designed wet-mix sprayed concretes is usually very low, irrespective of whether silica fume is used or not. In the study summarized in Table 11.3 rebound on vertical surfaces was only 3 to 4 per cent and on overhead surfaces 13 to 15 per cent; clearly much lower than for dry-mix sprayed concretes.

In a study of steel-fibre reinforced wet-mix sprayed concretes (Banthia *et al.*, 1993), somewhat higher overall rebound was found on vertical surfaces. Values ranged from 9 to 15 per cent for the five different types of steel fibre reinforced mixtures evaluated. The as-batched mixtures had steel fibre contents of 60 kg/m^3. In-place steel fibre contents ranged from 50–55 kg/m^3; i.e. fibre rebound ranging from 11.5 to 18.3 per cent. This is clearly much lower fibre rebound than occurs in the dry-mix sprayed concrete system.

Wet-mix sprayed concretes exposed to cycles of freezing and thawing and/or deicing chemicals should be adequately air entrained to provide durability (Morgan, 1989; Beaupré *et al.*, 1993). It is necessary to start with sufficiently high air contents in the mixture supplied to the pump, since as much as half the as-batched air content is lost during the sprayed concrete shooting and pneumatic consolidation process. In the study summarized in Table 11.3 the air content of the plain sprayed

concrete reduced from 8.5 to 4.8 per cent on shooting; the air content of the silica fume modified sprayed concrete reduced from 6.4 to 3.9 per cent (Morgan, 1992).

The results of a systematic study of special wet-mix sprayed concretes made with and without silica fume, fibres, air-entraining admixtures and accelerators, (Beaupré *et al.*, 1993) are summarized in Table 11.4. The reduction in air content on shooting is readily apparent. The greatest reduction occurs in the higher initial air content mixtures. However, these mixtures characteristically end up with the highest in-place air contents, lowest spacing factors and best resistance to deicing chemical scaling. In summary, the benefit of air-entrainment in wet-mix sprayed concrete is well demonstrated.

11.9 Properties of hardened sprayed concrete

General

Sprayed concretes tend to have higher contents of cementing materials and lower coarse aggregate contents than conventional cast-in-place concretes, with the following consequences:

- compressive and flexural strengths tend to be higher;
- water demand is usually greater in the sprayed concrete mixtures (particularly wet-mix sprayed concretes); this results in higher drying shrinkage capacity in the sprayed concretes;
- good durability can usually be achieved, if proper mixture proportioning and application procedures are used.

Typical hardened properties of wet and dry-mix sprayed concretes, both with and without silica fume, are given in Table 11.5. The mixture proportions and plastic properties for these sprayed concretes are given in Tables 11.2 and 11.3 respectively (Morgan, 1992). It should be appreciated that the mixture proportions given are the as-batched mixture proportions; the in-place proportions will not be very different for wet-mix sprayed concretes, because of the low inherent rebound in this process. The in-place cementing materials content will, however, be higher for in-place dry-mix sprayed concrete, because of aggregate rebound. Some engineers have attempted to design leaner (lower cement contents) sprayed concrete mixtures, to counteract this influence. This, however, can be counterproductive, as lean sprayed concrete mixtures often display excessive rebound and the quality of the in-place sprayed concrete can be adversely affected. Concerns regarding high shrinkage capacity and the potential for restrained shrinkage cracking are best addressed by the incorporation of fibre reinforcement in the mixture, or the use of suitably designed conventional reinforcement.

Compressive and flexural strength

Compressive strengths developed in dry-mix sprayed concretes are usually high. Table 11.5 shows the results of one particular study *(ibid.)*. Plain mixtures developed compressive strengths of 30 MPa at one day, 44 MPa at 7 days and 54 MPa at 28 days. Compressive strengths in the silica fume modified mixture were some 4 to 5 MPa higher at all ages. These dry-mix sprayed concretes were produced under ideal, controlled testing conditions.

A review of the construction records of a number of large sprayed concrete projects in Western Canada showed that average 28 day compressive strengths for silica fume modified, dry-mix sprayed concretes (with and without steel fibre reinforcement) were in the range of 45 to 55 MPa.

Traditionally, wet-mix sprayed concretes were considered inferior to dry-mix sprayed concretes for their strength potential. This was largely because of the higher water demand in wet-mix sprayed concretes for a given cementing materials content (and hence higher water/cementing materials ratio). With the advent of superplasticizers and silica fume, however, this is no longer true and it is now possible to produce wet-mix sprayed concretes with even higher strengths than dry-mix sprayed concretes. This is well demonstrated in the study summarized in Table 11.5. The plain wet-mix sprayed concrete is of lower strength than the plain dry-mix sprayed concrete. By contrast the 28 day compressive strength of the wet-mix silica fume modified sprayed concrete is higher than in the dry-mix silica fume modified mixture. Even higher compressive strengths, of 80 MPa or more, are possible with appropriate addition rates of superplasticizer and silica fume. Gebler, at a recent American Concrete Institute Conference described a project where such a high strength shotcrete was used for repair of an abrasion-damaged concrete lining in a large diameter steel pipe in a project near Las Vegas, Nevada.

Results of tests by several researchers (Morgan *et al.*, 1987, Morgan, 1991*b*; Banthia *et al.*, 1993) show that small improvements in compressive strength can result from the addition of steel fibre to sprayed concrete mixtures. Improvements are, however, only a few MPa and thus compressive strength enhancement is not a good reason for adding steel fibres to sprayed concrete. Polypropylene fibre addition, by contrast, results in reductions in compressive strength, with the strength reduction increasing as the fibre addition rate is increased, as shown in Table 11.6 (Morgan, 1989).

Table 11.6 *Physical properties of hardened polypropylene fibre reinforced wet-mix sprayed concretes.*

Fibre dosage kg/m3	0	4	6
Compressive strength at 28 days, MPa	47.4	41.9	39.6
Flexural strength at 28 days, MPa	5.4	4.7	4.6
ASTM C1018 Toughness Index			
I_5	-	2.5	3.3
I_{10}	-	4.6	6.5
I_{20}	-	6.5	10.2
Residual strength, %			
20 (I_{10}-I_5)	-	41	64
10(I_{20}-I_{10})	-	20	37
ASTM C642			
Boiled absorption, %	6.8	7.9	8.8
Volume permeable voids, %	14.9	16.9	18.6

Flexural strengths in sprayed concrete are usually quite high. For silica fume modified sprayed concretes values in the range of 6 to 8 MPa at 28 days are common in both wet-mix and dry-mix systems. Even higher flexural strengths can be achieved with high addition rates (60–80 kg/m^3) of certain types of steel fibre reinforcement (Morgan, 1991*b*). By contrast, high addition rates of polypropylene fibre reinforcement result in reductions in flexural strength (Table 11.6: Morgan, 1989).

Toughness

The main reason for incorporating fibre reinforcement in sprayed concrete is to impart some toughness to an otherwise relatively brittle material. Fibre reinforcement improves the ductility, energy absorption, impact resistance and crack resistance of sprayed concrete. Fibre addition enables the sprayed concrete to continue to carry stresses beyond matrix cracking, which helps maintain structural integrity and serviceability of structures under load.

A variety of different test procedures have been developed to measure and quantify the toughness of fibre reinforced composites. There are numerous references in the literature on the subject (Kasperkiewicz and Skarendahl, 1990; Gopalaratman *et al.*, 1991; Johnston, 1990; Banthia and Trottier, 1993; Chen *et al.*, 1993). The most common methods used to characterize the toughness of fibre reinforced sprayed concretes have been the American Society for Materials Testing ASTM C1018 and the Japan Society of Civil Engineers JSCE SF-4 Test Methods. Definitions of toughness parameters calculated from these two test methods are given in Figures 11.9 and 11.10. There is, however, considerable controversy regarding the suitability of

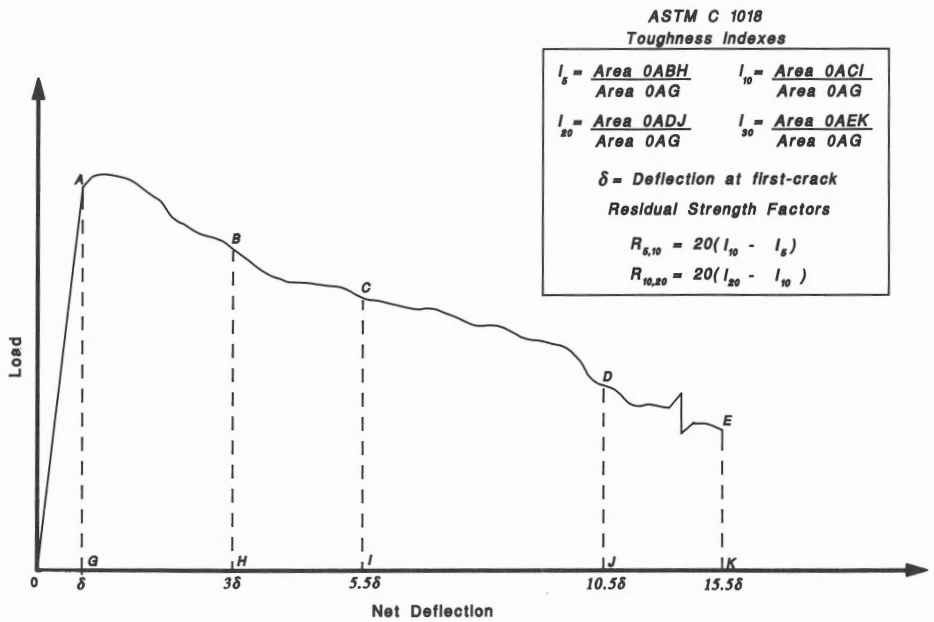

Figure 11.9 *ASTM C1018 toughness parameters.*

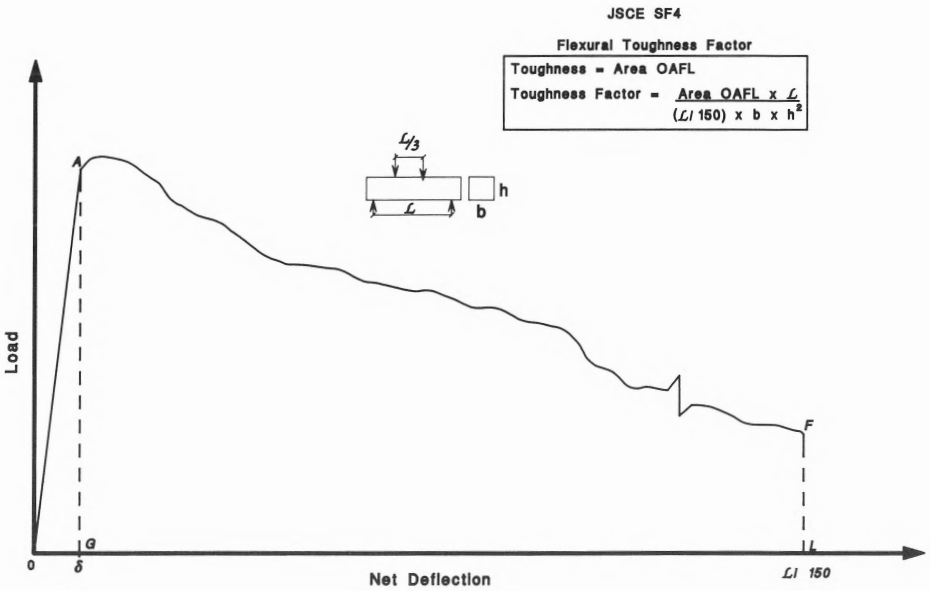

Figure 11.10 *JSCE SF-4 toughness parameters.*

these and other test methods for characterizing the toughness of fibre reinforced concrete composites. Banthia and Trottier (1993) have gone on record as stating: *"The current methods of characterizing the toughness of fibre reinforced concrete, however, have proven to be largely inadequate and have caused a great deal of dissent and confusion"*. They have proposed an alternative technique which he considers capable of characterizing toughness in a more objective manner.

Most of the toughness characterization of fibre reinforced sprayed concretes reported in the literature is based on the ASTM C1018 test (Morgan, 1991*b*; Banthia *et al.*, 1994; Banthia and Trottier, 1993). In this test, parameters called *toughness indexes* and *residual strength factors* are calculated from an instrumented third point load test on flexural prisms. Toughness index values have been used for specification purposes in numerous sprayed fibre reinforced concrete projects in North America (mainly in tunnel lining applications). Difficulties have, however, been experienced in obtaining reproducible results between different laboratories using different loading machines and deflection measuring equipment.

Banthia has reviewed the reasons for these difficulties, and they are highlighted below. The current ASTM C1018 procedure permits the use of deflection measuring systems which include extraneous deflections; i.e. settlement in the support system. This results in deflections at first crack which can be as much as 30 times greater than the theoretically calculated first crack deflection. Since the toughness indices I_5, I_{10}, I_{20}, etc. are based on multiples of first crack, the calculated toughness index values can be seriously in error if the first crack measurements include extraneous deflections. ASTM C1018 is currently under revision to address this concern. Early toughness index values for sprayed concretes reported in the literature

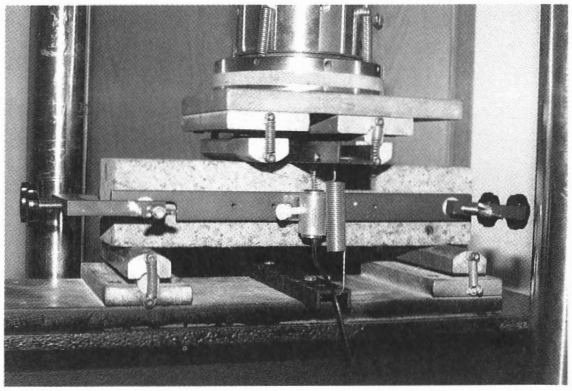

Figure 11.11 *Toughness testing of a steel-fibre reinforced sprayed concrete beam, using a yoke to measure deflections.*

should be interpreted with caution, since many results were based on measurements which included extraneous deformations.

Accurate measurement of the true load deflection curve in a toughness test is now possible with the use of a yoke modelled after the JSCE SF-4 test method (Figure 11.11). This enables accurate measurement of the net deflection of the fibre reinforced composite. However, difficulty may still be experienced in establishing the first crack point, which is defined in ASTM C1018 as *the point on the load-deflection curve at which the form of the curve first becomes non-linear (approximately the onset of cracking in the concrete matrix...).* The problem with this definition is that matrix cracking is a progressive phenomenon and non-linearity can develop well before the peak load, even in sprayed concretes without fibre reinforcement (*ibid.*). This makes the interpretation of first crack deflection somewhat subjective and can lead to different interpretations between individual operators, which can significantly influence calculated toughness index values.

Another problem in the ASTM C1018 test relates to the stiffness of the particular testing machine used. After peak load, energy is released from the testing machine into the specimen and depending on factors such as stiffness of the testing machine and the fibre volume in the test specimen, instability can result (*ibid.*). This is particularly evident in low fibre volume mixtures and/or mixtures with high matrix strengths. Calculated results for I_5, I_{10} and even I_{20} toughness index values can fall within this area of instability in the load vs. deflection curve and result in erroneous data.

The Japanese JSCE SF04 test method is not dependent on determination of first crack deflections and hence is free of problems associated with this measurement in the ASTM C1018 test. It is based on determination of the total area under a load vs. deflection curve, up to a predetermined deflection, as shown in Figure 11.10. Two parameters are calculated; toughness, which is expressed in kNmm units and toughness factor, which gives an equivalent flexural strength value for the entire load vs. deflection curve and is expressed in MPa. These parameters are also influenced by post-peak load instability, but to a much lesser extent than ASTM C1018 toughness index values. The main drawback of the JSCE SF-4 method is that toughness values

are dependent upon the geometry of the specimen. Also, the chosen end-point deflection of span/150 has been criticized as being much greater than acceptable deflection/serviceability limits for most fibre reinforced concrete applications.

Irrespective of the toughness measuring system used, it is apparent that for a given rate of fibre addition, certain fibres are much more effective in enhancing toughness than others (Morgan, 1991*b*; Banthia *et al.*, 1992; Banthia and Trottier 1993). With steel fibres, high tensile strength drawn wires with hooked ends have proven very effective. Other deformed shapes have also produced reasonable toughness values; the lowest performance has been with straight, lower tensile strength, or low ductility fibres. Thus it is not sufficient to simply specify a fibre type and addition rate. Appropriate toughness values should be specified and the fibre type and addition rate should be selected to meet the specified performance requirements.

Permeability

The ASTM C642 test for determination of boiled absorption and volume of permeable voids is not often used to quantify cast-in-place concrete quality. It is, however, quite commonly used in sprayed concrete specifications in North America. This test is particularly useful in identifying sprayed concrete that is less than adequately consolidated, or sprayed concrete which has been damaged by excessive addition of accelerators. Figure 11.12 (Morgan *et al.*, 1987) gives suggested indicators of sprayed concrete quality, based on the ASTM C642 test. Recent research at Laval University (Beaupré *et al.*, 1993) has shown a correlation between values of boiled absorption and volume of permeable voids, and deicing chemical scaling resistance. Dry and wet-mix sprayed concretes with high values of boiled absorption and permeable voids display high scaling in the ASTM C672 test.

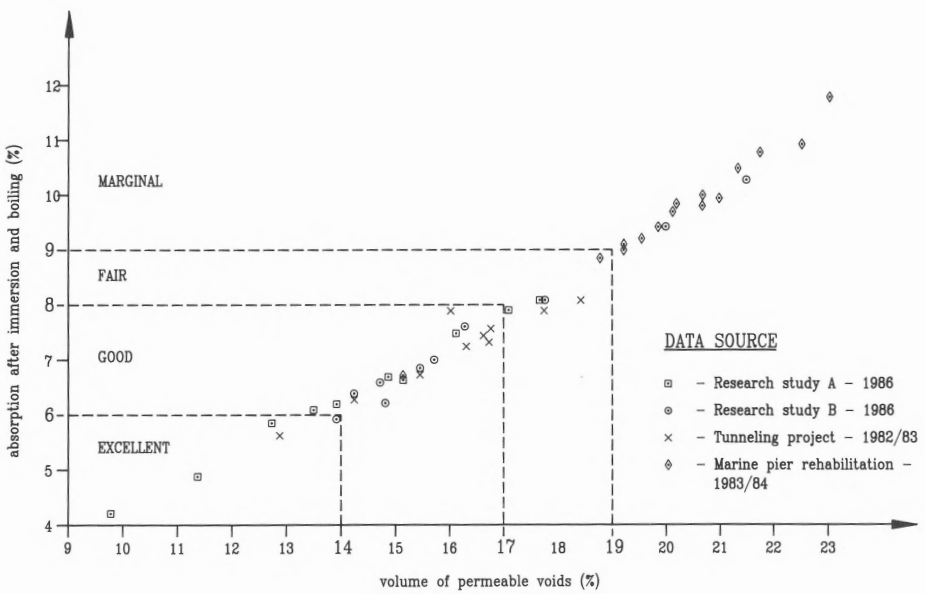

Figure 11.12 *Suggested indicators of sprayed concrete quality, based on the ASTM C642 test.*

Another test which is used in North America to characterize sprayed concrete permeability is ASTM C1202. This test measures the resistance of concretes to penetration by chloride ions, based on a current passed through a test core over a given period of time; i.e. measures coulombs passed. The addition of silica fume to both wet and dry-mix sprayed concretes has been found to be highly effective in reducing the coulomb rating by a magnitude or more (Wolsiefer and Morgan, 1993). This is indicative of silica fume addition reducing markedly the permeability of sprayed concrete to chloride ion intrusion. Silica fume addition is thus highly beneficial in protecting embedded reinforcing steel and other ferrous metals in sprayed concrete installations from such corrosion. Silica fume modified sprayed concrete has thus been the material of choice in numerous marine structures and bridge rehabilitation projects (Morgan, 1988*b*; Morgan and Neill, 1991).

Corrosion resistance of steel fibre reinforced sprayed concrete (SFRSC)

The corrosion resistance of SFRSC is governed by the same factors which influence the corrosion resistance of conventionally reinforced concrete or sprayed concrete. As long as the matrix retains its inherent alkalinity and remains uncracked, deterioration of SFRSC is not likely to occur. It has been found (Hoff, 1987) that good quality steel fibre reinforced concrete, even when exposed to conditions conducive to reduced alkalinity, such as atmospheric pollution, deicing chemicals, or a marine environment, will only carbonate to the depth of a few mm over a period of many years. Steel fibres in the immediate surface layer rapidly corrode to the depth of surface carbonation, causing some rust-coloured surface staining. However, the interior fibres immediately beneath the carbonated surface layer remain totally protected, provided the SFRSC remains uncracked.

In the event of cracking, the fibres exposed in the crack are subjected to corrosive influences. How long the fibres remain capable of load transfer across the crack depends on factors such as crack width and depth, type and diameter of fibre used and the severity of the corrosive environment. Several studies (*ibid.*) have shown that provided the crack width remains in the range of 0.03–0.08 mm, carbon steel fibres will not oxidize, even after many years of exposure. Other studies have

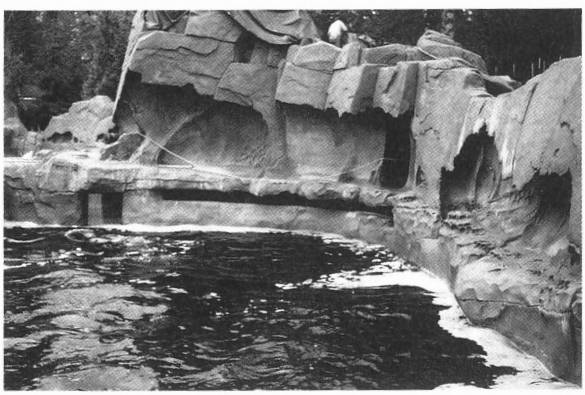

Figure 11.13 *Artificial West Coast rockscape at the Vancouver Public Aquarium constructed with wet-mix steel-fibre reinforced, silica fume sprayed concrete.*

shown that although corrosion takes place in a moist marine environment when crack widths are in the range of 0.10–0.30 mm, much of the composite strength can still be maintained, because steel fibres can tolerate a considerable reduction in diameter from corrosion before failing and permitting unrestricted crack opening.

One of the major advantages of SFRSC over mesh-reinforced sprayed concrete in severe exposure environments is that SFRSC will not support the classic galvanic cells which are sometimes the cause of corrosion and deterioration in mesh reinforced sprayed concrete. The fibres, being discontinuous and discrete, are protected by the alkaline matrix, and provide no mechanism for propagation of corrosive activity.

If the presence of steel fibres in the sprayed concrete is viewed as undesirable, then a thin surface coating of plain sprayed concrete (sometimes called a flash coat, or finish coat) can be applied to the SFRSC. This system was used to good advantage in construction of the artificial west coast rockscape around the killer whale pool addition at the Vancouver Public Aquarium, British Columbia, Canada (Figure 11.13). After nearly 10 years of exposure in this aggressive marine and freeze/thaw environment, there has been no rust staining or deterioration. The sprayed concrete is a wet-mix, steel fibre reinforced, air entrained, silica fume sprayed concrete, with a plain finish coat (carving mix).

Durability

An appreciation of the potential freeze/thaw durability of sprayed concrete can be obtained by extracting cores from the in-place sprayed concrete and determining the air content and parameters of the air void system using the ASTM C457 test procedure. In dry-mix sprayed concrete it appears that the natural air content, specific surface and spacing factor are such that freeze/thaw durable concrete can be produced (Morgan, 1989; Beaupré *et al.*, 1993). This is dependent upon the use of good quality, freeze/thaw durable aggregates; sufficiently high strength mixture designs, which produce low values of boiled absorption and volume of permeable voids; and good shooting technique, such that the sprayed concrete is free from defects such as sand lenses, excessive voids of incomplete consolidation, or entrapped rebound and overspray.

The resistance of dry-mix sprayed concrete to frost attack and scaling from exposure to deicing chemicals can be further enhanced by addition of an air-entraining admixture to the mix water added at the nozzle, and the incorporation of silica fume in the mixture (Beaupré *et al.*, 1993). This technology has been used to good effect in Quebec, Canada, for repair of salt-attacked and deteriorated highway bridges and elevated freeway structures.

For wet-mix sprayed concrete exposed to freeze/thaw cycles or deicing chemicals, it is essential that air-entraining admixtures are used, such that the parameters of the air void system in the in-place sprayed concrete are satisfactory. Guidance as to what constitute acceptable parameters of the air void system are provided in the referenced texts by Morgan (1989) and Beaupré *et al.* (1993).

In a nationwide survey of the durability of sprayed concrete rehabilitation treatments of some 60 bridges in Canada (Morgan and Neill, 1991) only two examples of freeze/thaw deterioration of sprayed concrete were noted. Both occurred in conventional wet-mix sprayed concrete in Nova Scotia. In one case the sprayed con-

crete in a bridge abutment was poorly consolidated (because of improper shooting angles) and had deteriorated to rubble from exposure to seeping deicing chemicals. In the second case localized frost attack had occurred in sprayed concrete applied to a rock bridge abutment with inadequate provision for drainage of seeping groundwater. The author has witnessed examples of severe frost attack in dry-mix sprayed concrete on the upstream face of an old Ambersen buttress dam, where overspray and rebound were incorporated into the finished sprayed concrete during rehabilitation of the dam. The sprayed concrete had turned to rubble in places. Similar deterioration has been reported in prestressed concrete tanks constructed with conventional dry-mix sprayed concrete (Schupak and Poston, 1989).

Finally, it should be cautioned that the use of accelerators, particularly at high addition rates, can compromise the resistance of the sprayed concrete to deterioration from frost and deicing chemical attack (Beaupré *et al.*, 1993).

Drying shrinkage and cracking

Results of drying shrinkage studies on wet and dry-mix sprayed concretes, with and without silica fume are shown in Figure 11.14 (Wolsiefer and Morgan, 1993). The wet-mix sprayed concrete displayed higher shrinkage than the dry-mix sprayed concrete. This is to be expected, given the higher water demand in a wet-mix sprayed concrete, for a given cementing materials content. Interestingly in this particular study the silica fume modified sprayed concretes displayed lower drying shrinkage than the conventional Portland cement sprayed concretes.

Fibre reinforcement has proven effective in mitigating plastic shrinkage cracking in fibre reinforced concretes (Grzybowski, 1989). In hardened concretes, fibres are effective in distributing cracking and restraining crack widths. Figures 11.15

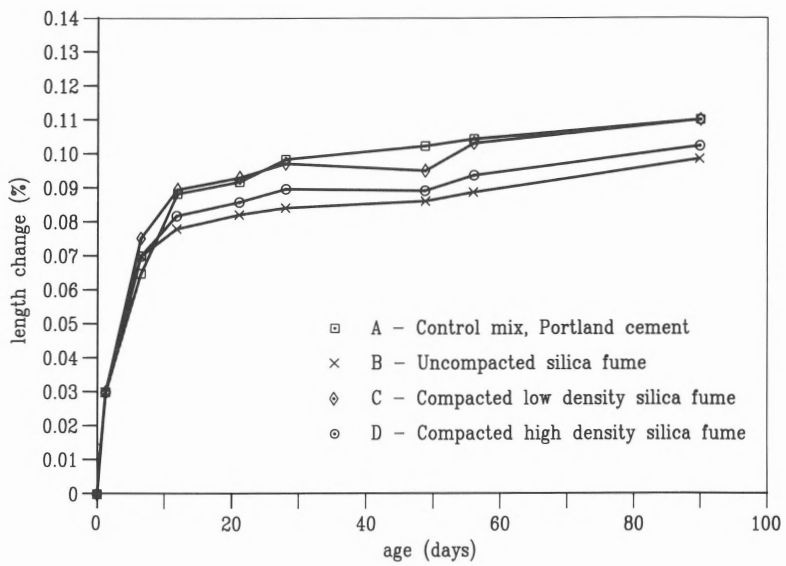

Figure 11.14a *Drying shrinkage of wet-mix shotcrete with and without silica fume.*

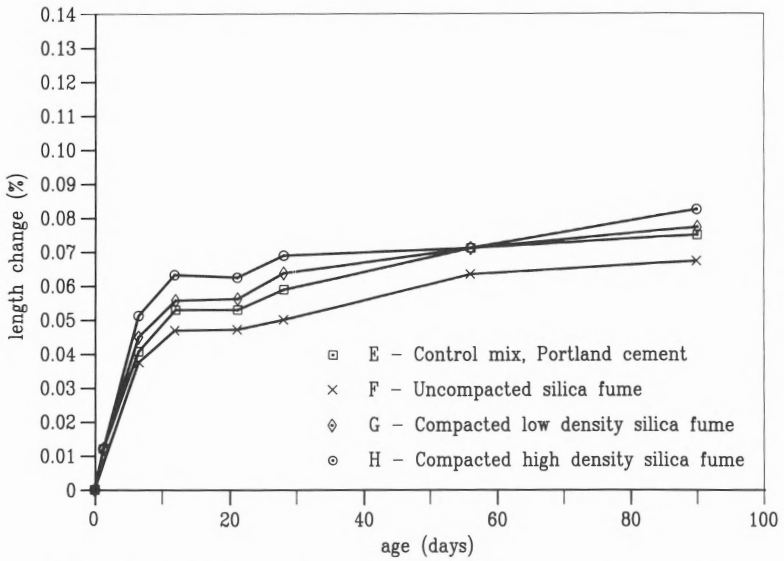

Figure 11.14b *Drying shrinkage of dry-mix shotcrete with and without silica fume.*

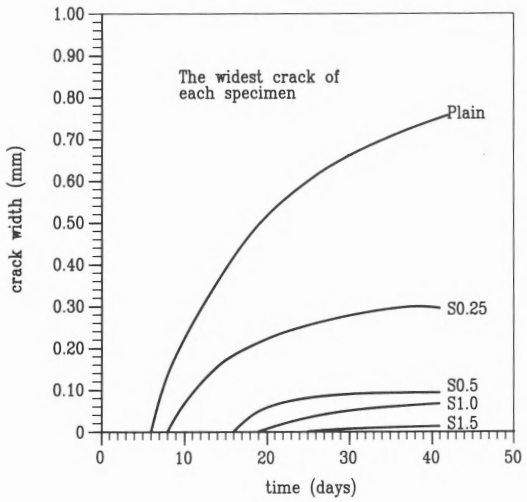

Figure 11.15 *Crack width development with time in steel-fibre reinforced concretes. Obtained from restrained ring shrinkage tests (Gryzbowski, 1989)*

and 11.16 show the influence of steel and polypropylene fibres, respectively, in restraining crack widths, as determined in a ring shrinkage test (*ibid.*) It is apparent that for a given volume percentage of fibres, steel fibres are more effective in restraining crack widths than polypropylene fibres.

Fibre reinforcement has been found to be effective in sprayed concrete applications in the field in minimizing cracking. Figure 11.17 shows a bridge pier jacketed

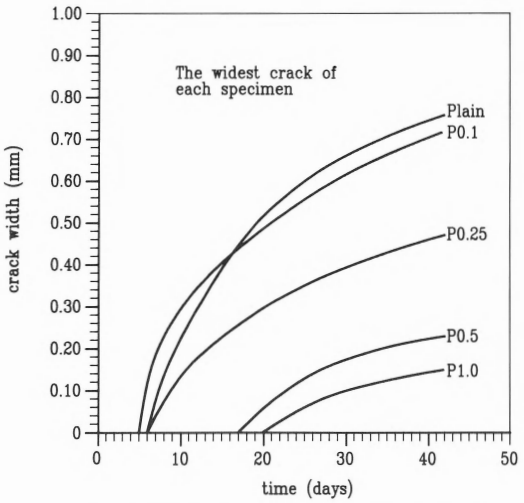

Figure 11.16 *Crack width development with time in polypropylene-fibre reinforced concretes. Obtained from restrained ring shrinkage tests (Gryzbowski, 1989).*

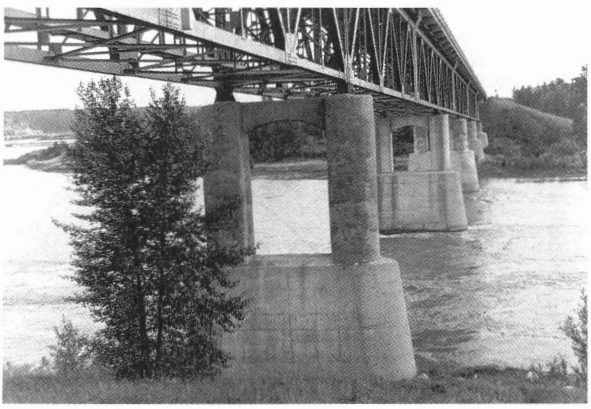

Figure 11.17 *Bridge pier in Alberta, Canada, jacketed with a dry-mix steel-fibre reinforced silica fume sprayed concrete.*

with a steel fibre reinforced, dry-mix, sprayed concrete in Alberta, Canada. The installation was almost free of any visible cracks, in spite of the work being done in a windy, drying environment. This method has also been used to cap an acid-generating exposed slate bedrock in a new highway construction project in Nova Scotia, Canada. The work was done with a polypropylene fibre reinforced wet-mix sprayed concrete and there were remarkably few drying shrinkage cracks.

Accelerators increase drying shrinkage and hence the potential for restrained shrinkage cracking. They should only be used in sprayed concrete if considered essential for completion of the work; e.g. immediate ground support in underground openings. In summary, sprayed concretes characteristically display higher drying

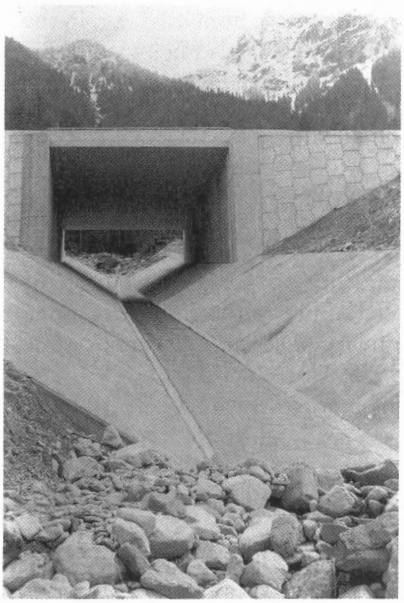

Figure 11.18 *Creek channelization to protect bridge abutment on a highway in British Columbia, Canada, using wet-mix steel-fibre reinforced silica fume sprayed concrete.*

shrinkage capacity than conventional structural concretes, because of the higher cementing materials content. Fibre reinforcement can be effective in minimizing plastic and restrained shrinkage cracking in sprayed concretes.

11.10 Applications

New construction

Special sprayed concretes have been used for a wide variety of new construction applications. Examples include high erosion/abrasion resistant creek channel linings. Figure 11.18 shows a wet-mix, steel fibre reinforced, silica fume, sprayed concrete channel lining for protection of a bridge abutment, on a new highway construction project in British Columbia, Canada.

Special sprayed concretes have also proven popular in construction of artificial rockscapes in aquariums, zoos, exhibits and golf courses. Figure 11.13 shows an artificial west coast rockscape constructed at the Vancouver Public Aquarium killer whale pool, using wet-mix, steel fibre reinforced silica fume sprayed concrete. Silica fume modified sprayed concretes have been used in construction of air-formed domes for bulk storage and recreational facilities. They have been applied to metal lath, to construct walls for acoustic insulation in film studio sound stages and many other new construction applications.

Special sprayed concretes have been used for slope stabilization, often in conjunction with active or passive rock or soil anchors, in numerous railway, highway and pipeline projects. Silica fume modified sprayed concretes with steel or poly-

propylene fibre reinforcement have been used, e.g. in the stabilization of a ravelling highway rock cut on the Trans Canada Highway, in British Columbia, completed with a polypropylene fibre reinforced wet-mix, silica fume sprayed concrete.

Support of underground openings

Perhaps the most widespread use of special sprayed concretes has been for support of underground openings in tunnelling and mining applications. Morgan and Wood (1990) provide some 50 examples of the use of special sprayed concretes for support of underground openings in Canada. The majority of these projects were completed with dry-mix, steel fibre reinforced, silica fume, sprayed concretes. The following is a brief summary of some of the applications (Vandewalle, 1990; Rose, 1985; Ramakrishnan, 1985; Morgan, 1991*c*):

- initial ground support (often with rock bolts) in tunnel construction;
- final tunnel lining in road, rail and water pressure tunnels;
- rehabilitation of railway rock tunnels with deterioration in rock quality;
- ground support for shafts, adits and chambers in hydroelectric and mining projects;
- ground support in mining drifts, raises and declines;
- construction of underground bulkheads and ventilation seals in mines;
- lining of ore bins, crusher stations and safety bays in mines.

Rehabilitation of infrastructure

Conventional sprayed concretes have been used for decades for repair of deteriorated infrastructure. Special sprayed concretes have further enhanced the utility of this repair methodology. Silica fume modified sprayed concretes, both with and without fibre reinforcement have been used to repair deteriorated marine structures; for repair of hydraulic structures, such as dams, canals, locks, large diameter concrete lined pipes, and metal culverts. They have also been used for seismic

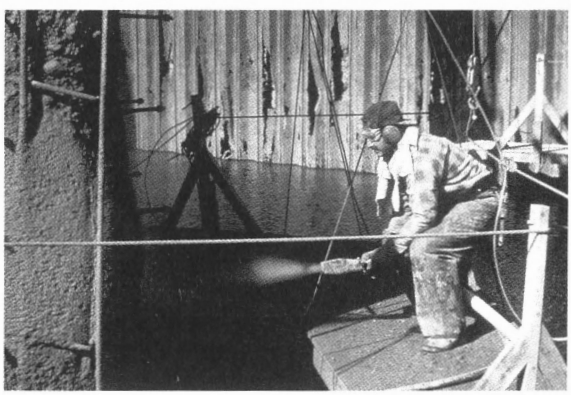

Figure 11.19 *Repair of intertidal zone of an ice-scoured transmission tower caisson in the Skeena River estuary, northern British Columbia, using dry-mix, steel-fibre reinforced silica fume sprayed concrete.*



Figure 11.20 *Rehabilitation of berth faces in the Port of Saint John, New Brunswick, using wet-mix, steel-fibre reinforced silica fume sprayed concrete.*

retrofit and to rehabilitate deteriorated bridges, industrial facilities, cooling towers, smoke stacks, and reinforced concrete structures in pulp and paper mills and the chemical and petroleum industries.

Silica fume modified sprayed concrete has proven to be particularly useful for repair in the intertidal region in marine structures, because of the enhanced wash-out resistance the silica fume imparts to the sprayed concrete (Gilbride, 1988; Morgan, 1992). Figure 11.19 shows repair of the intertidal region of a transmission tower caisson in the Skeena River estuary, northern British Columbia. Up to 600 mm of dry-mix, steel fibre reinforced sprayed concrete was applied in a single pass in repair of the caissons (Anderson, 1987).

Concrete berth faces in the Port of Saint John, New Brunswick, Canada, are subjected to some of the most severe environmental exposure of any concrete structures in the world. With a tidal range of 8.5 metres and winter temperatures which fall as low as -30°C, the intertidal regions of the berth faces are subjected to over 200 freeze/thaw cycles most winters. The original 60 to 80 year old, non-air-entrained mass concrete berth faces have suffered severe deterioration from the combined effects of freeze/thaw attack, salt water exposure and alkali aggregate reactivity (Gilbride, 1988). Figure 11.20 shows rehabilitation of the berth face from a floating barge, using air-entrained, steel fibre reinforced, wet-mix silica fume shotcrete. This shotcrete has so far proven to be highly durable in this aggressive marine exposure environment.

Special sprayed concretes have been used for rehabilitation of deteriorated dams, such as the old Ambersen buttress dam built on Vancouver Island, British Columbia, in 1913. The dam had deteriorated from ice and frost action and extensive use was made of dry-mix, steel fibre reinforced silica fume sprayed concrete in a major seismic retrofit project undertaken on this structure (Morgan, 1992).

Special spayed concretes are now being used widely for repair of deteriorated bridge structures (Morgan and Neill, 1991). Most such work has been completed using the dry-mix sprayed concrete system, because the repair areas are often small and the work is of a stop-start nature. Prebagged materials have proven particularly expedient. Silica fume modified sprayed concretes have proven to be less sus-

ceptible to plastic shrinkage cracking than the latex modified sprayed concretes that were sometimes used for repair of bridge elements subjected to deicing chemicals and frost attack. Restrained shrinkage cracking has been minimized by incorporation of fibres in the mixture, as previously discussed.

11.11 Future developments

The development of fibre reinforcement and utilization of silica fume marked major advances in sprayed concrete technology. There is, however, still room for further enhancement of the sprayed concrete process. Rebound and dust continue to cause problems in the dry-mix sprayed concrete process. While the addition of silica fume to the mixture reduces rebound, there is still scope for improvement. One European innovation holds promise; the introduction of the silica fume as a slurry together with the mix water at the water-ring at the nozzle, either with or without a liquid accelerator (Herfurth and Nilsen, 1990). This system is reported to reduce substantially the formation of dust in the dry-mix sprayed concrete process and result in a product which has very low rebound. Others (Schreyer, 1990; Yoshida and Fukuchi, 1990) have added dust suppressants to minimize dust production; more work is, however, needed in this area, since many of the dust suppressants tried have resulted in a downgrading of the physical properties of the hardened sprayed concrete.

There is a need for more research into the use of high early-strength cements, with rapid setting characteristics, for use in lieu of accelerated sprayed concretes. Such research is needed because of the detrimental effects of accelerators on the physical properties of the hardened product (e.g. increased shrinkage, increased permeability, reduced resistance to deicing chemicals and reduced later-age strength, etc.). For mass sprayed concrete applications, where heat of hydration is of concern (e.g. underground plugs), binary or ternary systems using lesser quantities of Portland cement and greater volumes of supplementary cementing materials, such as fly ash and slag, may prove to be beneficial.

With respect to fibre reinforcement, there is a need to develop fibre types which are specifically optimized for sprayed concrete. Recent research (Banthia *et al.*, 1992) has shown that certain steel fibre types have a much greater propensity to rebound in dry-mix sprayed concrete than other fibre types. Steel fibres should be developed which will provide the least fibre rebound and maximum toughness. More research is needed into the potential for use of other fibre types, such as carbon fibre, in sprayed concrete.

Finally, it is a truism that the quality of a sprayed concrete installation is only as good as the competence of the nozzleman. Even with the best materials, mixture designs and application equipment, the quality of the in-place product is still highly dependent on the competence and attitude of the sprayed concrete nozzleman. Hand nozzling, particularly on large volume, continuous placement operations, can be very physically fatiguing for the nozzleman and this can affect the quality of the work. Robotic nozzling has gone a long way to dealing with this concern for applications such as support of underground openings in tunnels and mines. The Japanese (International Tunnelling Association 1991) are investing considerable effort in automating the sprayed concrete process. More work is, however, still needed

to develop smaller robotic systems which could be utilized for structural sprayed concrete construction and infrastructure remedial applications.

References

American Concrete Institute (1984) ACI 506.1R-84, *State-of-the-Art Report on Steel Fibre Reinforced Shotcrete*, ACI, Detroit, 13.

American Concrete Institute (1990) ACI 506R-90, *Guide to Shotcrete*, ACI Detroit, 4.

Anderson, B.C. (1987) Shotcrete Repairs to Skeena River Crossing Tower Pier Foundations, *Canadian Electrical Association Annual Meeting*, Vancouver, B.C., March, 17.

Banthia, N., Trottier, J-F., Wood, D and Beaupré, D. (1992) Influence of Fibre Geometry on Steel Fibre Reinforced Dry-Mix Shotcrete, *Concrete International*, **14** (5), 24–28.

Banthia, N. and Trottier, J-F. (1993) Test Methods for Flexural Toughness Characterisation of Fiber Reinforced Concrete: Some Concerns and a Proposition, to be published.

Banthia, N., Trottier, J-F., Beaupré, D. and Wood, D. (1994) Steel Fiber Reinforced Wet-Mix Shotcrete:Influence of Fibre Geometry, *Concrete International*, **16** (6), 27–32.

Beaupré, D., Talbot, C., Gendrau, M., Pigeon, M. and Morgan, D.R. (1993) Deicer Salt Scaling Resistance of Dry and Wet Process Shotcrete, *American Concrete Institute, Materials Journal*, to be published.

Chen, L., Mindess, S. and Morgan, D.R. (1993) Toughness Evaluation of Steel Fibre Reinforced Concrete, *Third Canadian Symposium on Cement and Concrete*, Ottawa, 16–29.

Garshol, K., Development of Mechanised Wet Mix Shotcrete Application in the Norwegian Tunnelling Industry (1990) *Shotcrete for Underground Support V*, Uppsala, Sweden, 113–124.

Gebler, S. (1989) Durability of Dry-Mix Shotcrete Containing Regulated Set Cement, *Concrete International, Design and Construction*, **11** (10), 56–58.

Gebler, S., Litvin, A., McLean, W.J. and Schutz, R. (1992) Durability of Dry-Mix Shotcrete Containing Rapid Set Accelerator, *American Concrete Institute, Materials Journal*, **89** (3), 259–262.

Gilbride, P., Morgan, D.R., and Bremner, T.W. (1988) Deterioration and Rehabilitation of Berth Faces in Tidal Zones at the Port of Saint John, *American Concrete Institute, Detroit*, Concrete in Marine Environment, SP-109, 199–226.

Glassgold, L.I. (1981) Refractory Shotcrete - Current State of the Art, *Concrete International, Design and Construction*, **3** (1).

Gopalaratman, V.S. et al, (1991) Fracture Toughness of Fibre Reinforced Concrete, *ACI Materials Journal*, July - August, 339–353.

Grzybowski, M. (1989) Determination of Crack Arresting Properties of Fiber Reinforced Cementitious Composites, *Publication Trita-Bro-8908, ISSN 1100-648X, Department of Structural Engineering, Royal Institute of Technology*, Stockholm, Sweden, 190.

Henager, C.H. (1981) Steel Fibrous Shotcrete – A Summary of the State of the Art, *Concrete International, Design and Construction*, **3** (1).

Herfurth, E.A. and Nilsen, T. (1990) Advances in Dry Shotcrete Technology by Means of Microsilica, *Shotcrete Support of Underground Openings V*, Uppsala, Sweden, 251–261.

Hoff, G.C.(1987) Durability of Fiber Reinforced Concrete in Severe Marine Environment, *American Concrete Institute*, SP-100, Vol. 1., 997–1042.

International Tunnelling Association, (1991) *Shotcrete in Tunnelling, Status Report*, Swedish Rock Engineering Research Foundation, Stockholm, 231.

Johnston, C.D. (1990) Methods of Evaluating the Performance of Fibre Reinforced Concrete, *Materials Research Society Symposium Proceedings*, Vol. 211, Boston, 15–24.

Kasperkiewicz, J. and Skarendahl, A. (1990) Toughness Estimation in FRC Composites, *Swedish Cement and Concrete Research Institute*, CBI Report 4:90, 52.

Langley, W.S., and Dibble, D. (1990) Field Trials of Shotcreting Fibre-Reinforced High Volume Fly Ash (ASTM, Class F) Shotcrete, *CANMET International Workshop on Fly Ash in Concrete*, Calgary, Alberta, 26.

Lukas, W. and Kusterle, W. (1990) The Influence of Water Glass on the Technological Parameters of Shotcrete, *Shotcrete for Underground Support V*, Uppsala, Sweden, 197–212.

Malhotra, V.M., Carette, G.G. and Bilodeau, A. (1989) Fibre Reinforced High Volume Fly Ash Shotcrete for Controlling Aggressive Leachates from Exposed Rock Surfaces and Mine Tailings, *Third CANMET/ACI International Conference on Fly Ash, Slag, Silica Fume and Natural Pozzolans*, Trondheim, Norway.

Morgan, D.R. (1974) The Effects of Lignosulphonate-Based Admixtures on Drying Shrinkage of Cement Paste and Concrete, *First Australian Conference on Engineering Materials*, University of New South Wales, Sydney, Australia, 97–108.

Morgan, D.R. (1988*a*) Use of Supplementary Cementing Materials in Shotcrete, Proceedings, *International Workshop on the Use of Fly Ash, Slag, Silica Fume and other Siliceous Materials* in *Concrete*, W.G. Ryan, Editor, Concrete Institute of Australia, Sydney, Australia, 403–432.

Morgan, D.R. (1988*b*) Dry-Mix Silica Fume Shotcrete in Canada, *Concrete International, Design and Construction*, **10** (1), 24–32.

Morgan, D.R. (1989) Freeze-Thaw Durability of Shotcrete, *Concrete International, Design and Construction*, **11** (8), 78–85.

Morgan, D.R. (1991*a*) High Early Strength Blended Cement Wet-Mix Shotcrete, *Concrete International*, **13** (4).

Morgan, D.R. (1991*b*) Use of Steel Fibre Reinforced Shotcrete in Canada, *First Canadian University - Industry Workshop on Fibre Reinforced Concrete*, Sainte-Foy, Quebec, 164–182.

Morgan, D.R. (1991*c*) Steel Fibre Reinforced Shotcrete for Support of Underground Openings in Canada, *Concrete International*, **13** (11), 56–64.

Morgan, D.R. (1992) New Developments in Shotcrete for Repairs and Rehabilitation, *CANMET International Symposium on Advances in Concrete Technology*, Athens, Greece, May, 675–720.

Morgan, D.R., and Neill, J.N. (1991) Durability of Shotcrete Rehabilitation Treatments of Bridges, *Transportation Association of Canada, Annual Conference*, Winnipeg, Manitoba, September, 36.

Morgan, D.R. and Wolsiefer, J. (1992) Wet-Mix Silica Fume Shotcrete: Effect of Silica Fume Form, *CANMET/ACI International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete*, Istanbul, Turkey, 1251–72.

Morgan, D.R. and Wood, D.F. (1990) Shotcrete For Support of Underground Openings in Canada, *Canadian Tunnelling*, 67–76.

Morgan, D.R., McAskill, N., Carette, G. and Malhotra, V.M. (1992) Evaluation of Polypropylene Fibre Reinforced High-Volume Fly Ash Shotcrete, *ACI Materials Journal*, **89** (2), 169–177.

Morgan, D.R., McAskill, N., Richardson, B.W. and Zellers, R.C. (1989) A Comparative Evaluation of Plain, Polypropylene Fibre, Steel Fibre and Wire Mesh Reinforced Shotcretes, *Transportation Research Record 1226*, Washington, D.C., 78–87.

Morgan, D.R., Neill, J., McAskill, N. and Duke, N. (1987) Evaluation of Silica Fume Shotcrete, *CANMET/CSCE International Workshop on Silica Fume in Concrete*, Montreal, Quebec, 34.

Opsahl, O.A. (1985) A Study of Wet Process Shotcreting Method, *Norwegian Institute of Technology*, Dr. Ing. Study, BML Report No. 85.101, 1985.11.10, Division of Building Materials.

Ramakrishnan, V. (1985) Steel Fibre Reinforced Shotcrete, A State-of-the-Art Report, *US/Sweden Joint Seminar (NSF-STU)*, Stockholm, Sweden, 7–23.

Rose, D. (1985) Steel Fibre Reinforced Shotcrete for Tunnel Linings: The State-of-the-Art, *RETC Proceedings*, 1 Ch.24, 392–412.

Ryan, T. (1975) Steel Fibres in Gunite – An Appraisal, *Tunnels and Tunnelling*, 74–75.

Schreyer, J. (1990) Developing a Dust-Binding Agent for the Dry Spraying Method, *Shotcrete for Underground Support V*, Uppsala, Sweden.

Schupak, M. and Poston, R.W. (1989) Durability of Prestressed Concrete Tanks, *Concrete*

International, Design and Construction, **11** (10), 51–55.
Schutz, R. (1982) Effects of Accelerators on Shotcrete Properties, *Engineering Foundation, Shotcrete for Support of Underground Openings IV*, Paipa, Boyaco, Columbia.
Vandewalle, M. (1990) *Tunnelling the World*, N.V. Bekaert, S.A., Zwevegem, Belgium.
Wolsiefer, J. and Morgan, D.R. (1993) Silica Fume in Shotcrete, *Concrete International*, **15** (4), 34–39.
Wood, D.F., Nickel, G.B. and Borch, N.G. (1989) Developments in the Use of Shotcrete for Tunnel Support, *International Congress on Progress and Innovation in Tunnelling*, Toronto, Canada, Vol. I, 439–447.
Yoshida, Y. and Fukuchi, G. (1990) Site Measurement of Shotcreting Dust, *Shotcrete Support of Underground Openings V*, Uppsala, Sweden, 231-250.

12 Site Safety

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12.1 Introduction

The application of sprayed concrete in itself is a safe construction practice but there are a number of common sense precautions which have to be taken before, during and after the operation. The safe application can be carried out completely within the framework of current legislation of the developed nations and the proposed directives of the European Community as published in November 1992 (EEC 1986, 1992*a*, 1992*b*, 1992*c*, 1992*d*, 1992*e*, 1992*f*, 1992*g*).

This chapter deals with the safe working of plant, the handling of materials, the working environment for operatives and the training required by all who apply and manage sprayed concrete at work. The majority of the chapter applies to both the wet and dry process of application.

12.2 Plant and equipment

The wet process of sprayed concrete application requires the delivery of pre-mixed concrete to the gun which consists of a receiving hopper built over a concrete pump usually powered by a direct drive diesel engine through a gear box. Rotating working parts should be protected by metal guards to prevent limbs from becoming caught in the machinery and these guards should be fixed in such a way that they are always firmly positioned while the plant is working. If the guards are removed for maintenance, they should be replaced before the plant is recommissioned.

In the dry process, smaller items of plant are used which also have rotating parts usually driven by compressed air motors or in some cases 110-volt electric motors. In each case an air compressor or a diesel engine generator is required to power the drive to the gun, and similar precautions are required to prevent accidental entanglement with rotating parts. If generators are used, their power output may be up to 20 KVA and the usual precautions must be taken when dealing with electric cables, plugs and connections.

Ancillary items of plant may also be employed such as constant velocity delivery water pumps, concrete mixers and screw-feed conveyors or pre-dampeners. All plant must be adequately protected.

Most units of site operated plant are driven by diesel engines and bulk deliveries of diesel fuel must be stored adequately on construction sites. Definite rules govern the storage of fuel on sites and these should be applied rigidly .

All plant should be well maintained, kept clean and set in such a position (on level ground) that it can be operated comfortably with good access around it. In dark areas adequate lighting and ventilation should be provided. Many site accidents occur due to someone reaching across moving parts and getting loose clothing, belts or even long hair caught in the machinery. Should ground be uneven, operators can stumble against plant parts which are moving or exhausts which are hot, causing injury.

Dry spray concrete gunning sometimes develops high static electricity charges and it is advisable to positively earth the plant to minimize the possibility of operators receiving an electric shock. Finally, one of the most important pieces of plant in any sprayed concrete operation is the means of communication between the nozzleman and the gun operator. This may be a short wave or VHF radio or a non-powered voice attenuator. The radios may need recharging and should be kept in good order for reliable service.

Similarly, any equipment which is used in conjunction with the plant should be kept in good order. Hoses for compressed air, materials and water must be suited to their respective purpose. Particular attention should be paid to the hose connections as these are vulnerable to misuse. Hoses should be laid out to avoid kinking and not placed where site traffic will be constantly running over them or where personnel could trip over them. It is wise to keep spare connectors and lengths of hose to minimize time lost due to hose failures.

12.3 Materials

Materials may be delivered in bulk for both dry and wet process sprayed concrete and in bags of pre-packed blended materials for the dry process. Site access roads must be adequately constructed to avoid rutting and allow safe travel for trucks delivering up to 20 tonnes of bulk materials, whether ready mixed concrete in truck mixers or bulk sand or cement.

Dry materials should be stored in watertight containers to avoid bags or paper sacks being split, causing fine powders to be blown about which may affect breathing or cause eye damage. Bagged materials are now usually available in 25 kg sacks which are easier to handle than materials in 50 kg sacks which have caused many back injuries due to incorrect handling.

In sprayed concrete jobs where materials are mixed on site, additives may be used to improve the performance of the finished product. Additives to accelerate hardening, improve strength or reduce permeability are now widely available and these chemicals must be labelled, handled and stored properly.

Operatives handling materials in the application of sprayed concrete should be trained in their safe handling. Current legislation (e.g. in Europe the Control of Substances Hazardous to Health, COSHH, regulations) requires employers to ensure that basic instructions are given to each person in the handling of materials used in construction; including materials such as cement and diesel fuel.

12.4 Working environment

Sprayed concrete is a very flexible construction material as it can be applied in small confined spaces or in open exposed sites such as rock slope stabilizations. Wherever

it is used, the spraying environment must be safe for the operators of the plant and those undertaking any surface finishing.

Access scaffolds

With most jobs, access at various levels is usually a necessity (whatever the level – whether it is two metres or 20 metres above or below ground level), and a platform is required which enables the operatives to work in comfort. Many standard scaffolds are too narrow and a minimum width of 1.8 m is desirable (preferably 2 m), to allow maintenance of optimum spraying distances.

Particular attention should be paid to the position of water, air and material hoses on scaffolds to prevent the unwary from tripping or turning an ankle on the hose. Unnecessary scaffold tubes should be removed to allow operatives who will be wearing protective eye visors, helmets and other items of protective clothing as much freedom as possible. Scaffolds and towers should be erected by competent scaffolders and should not be adapted or changed by unskilled operatives. This also applies to access towers and stagings.

Access platforms

Certain situations, such as high inclined rock faces, do not lend themselves to be scaffolded for access. In this case, hydraulically operated access platforms perform a useful role but must be used carefully and by trained operatives. A firm level working area must be prepared for the mobile unit to provide a good foundation for outrigger pads. No risks should be taken to use the plant in windy conditions in exposed positions. Additional labour should be employed to operate the plant and to ensure hoses are free of the plant for safe operation in the elevated platform position.

Confined spaces

Sprayed concrete is often employed in tunnels, man-entry sewers and deep shafts where ventilation may be poor, allowing build-up of toxic gases or a deficiency of oxygen to occur.

All necessary action should be taken to establish that the working environment is safe for work and that it will remain so during the operation. Gas detection equipment should be used in the confined space to check for the presence of toxic gases or oxygen deficiency. Records of gas levels should be maintained. Forced or natural ventilation can also be introduced to ensure continued safe working in confined spaces. Working in live sewers or culverts brings the hazard of sudden increases in flow or chemical spillage which could endanger the lives of operatives. Local conditions should be monitored constantly to check for likely increases in flow. Special arrangements should be made with the emergency services to obtain access to confined spaces in case of incidents.

Disposal of waste

Every sprayed concrete operation generates waste, be it rebound, demolition material, paper sacks, additive containers or general construction rubbish. All materials

should be disposed of safely, away from the site, and within the regulations controlling waste disposal and tipping.

12.5 Work stations

Every sprayed concrete operation has two areas of activity, namely the spraying end, which has been discussed already, and the mixing/gun end where there may be just as many operatives working. In the wet process the pump and the compressor must be set up to enable ready mixed concrete delivery trucks to approach the pump for discharge of their load. If materials are mixed on site the mixer must be set such that it can be operated safely to discharge into the hopper of the pump.

Dry process working requires planning of the plant layout to facilitate mixing of bulk materials on site or the delivery by truck of palletized dry materials. In the latter case a good hard access road must be provided for trucks moving off the highway and if mechanical off-loading by way of forklift truck is employed, the ground should be levelled and hard enough to avoid rutting. By far the best way of delivering the bagged material on pallets is for the delivery truck to have its own off-loading facility operated by the truck driver. Materials delivered in this way can be set down near to the gun to minimize lifting and carrying of bags to the gun.

If at all possible, it is an advantage to provide some open-sided cover (Figure 12.1) for the gun operator to give protection for inclement weather. If the position is exposed then some protection for the prevailing wind is essential to minimize dry powder material blowing about when the bag is split over the gun hopper.

Further considerations regarding the position of work stations should include provision for satisfactory communication. This can be by visual means or short wave radio. If communication is by radio, the work station should be situated away from noisy plant so that the operator can hear instructions from the nozzleman.

The hoses and cables between the gun and the nozzle should be laid out neatly and if possible marked with high visibility tape to prevent site vehicles running



Figure 12.1 *Site layout in the gun area, with a hard clear floor space around the gun. Also, spare hoses are coiled neatly and a dust shroud covers part of the gun. Conditions are dry and the operative is adequately protected and has a cap lamp. There is a lead from the voice attenuator to the nozzleman working underground in the sewer. There is good ventilation.*

over them. Hoses should not be stretched across gaps or hung on scaffolds in such a way that a strain is put upon them by their own self weight and the weight of the contained material. Hose connections can break causing a hazard if high pressure compressed air or water is released.

12.6 Protective clothing

In all construction activities the operatives must be adequately protected from the hazards of the job on which they are working. A variety of clothing is available, designed to give workers adequate protection without limiting the freedom to move and to allow them to undertake their duties without being hindered by the protective measures. All sprayed concrete operatives should be equipped with suitable overalls (Figure 12.2) into which they can change at the start of their day's work and can then be hung out to air and dry at the end of the shift. An all-in-one fabric suit is usually employed although the "throw away" paper suits may have their uses in especially dirty operations. All suits should have close fitting cuffs and legs and the minimum number of pockets, to avoid snagging which would lead to tearing and eventual failure of the suit to provide good protection.

In wet conditions lightweight, waterproof materials are available for work suits which allow the fabric to "breathe", otherwise plain PVC jackets and trousers may be used. Operator comfort should be considered if best production rates are to be achieved. Footwear is another important consideration and all operatives should have appropriate footwear when on a construction site. The footwear should include a protective steel-reinforced toecap and a steel sole plate to give protection to

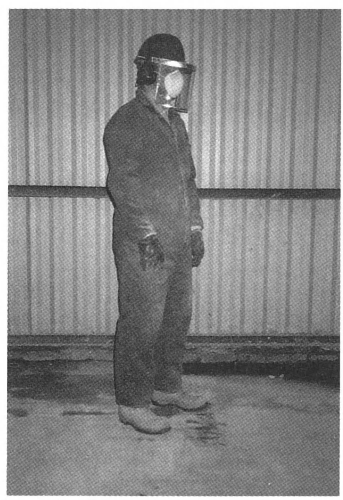

Figure 12.2 *Protective clothing comprising all-in-one fabric coverall with few pockets. The sleeves are pulled over industrial gloves with fabric cuffs. The overall trousers are pulled over the tops of safety boots. The boots should have steel toe caps and steel inserts in the soles.*



Figure 12.3 *Headwear, consisting of a safety helmet with ear defenders, a nose and mouth dust mask and an upward-tilting safety visor.*

the underside of the foot from pointed or sharp objects which could cut or pierce the boot or shoe. Good leather footwear with the necessary safeguards e.g. to BS 1870 (EN 345) and BS 4972 (EN 346), is available as are rubber boots which would be necessary in wet conditions or when working in rivers and culverts.

Headwear is probably the most important piece of protective clothing in construction as many accidents are due to falling objects. Safety helmets should be worn as a matter of course on all construction sites. For sprayed concrete, the design of the helmet should include provision for fixing a visor and ear defenders (Figure 12.3). The standard plastic type of helmet which is constructed to the relevant standards (e.g. BS 5470) is suitable and the gun operator should be able to attach either ear defenders (BS 5108) or ear phones from the radio or voice attenuator. Operatives will need to wear goggles for eye protection if handling dry powder materials but the nozzleman should wear a visor (BS 2092) which is attached to the helmet and can be lifted upwards to give clear vision when spraying is stopped.

With certain additives the plastic visor screen may become smeared and scratched causing poor and distorted vision. To avoid the need for frequent replacement a welder's type of helmet can be used with small toughened glass inserts which can be repeatedly cleaned without scratching the surface, giving longer life. In addition to general facial protection it may be necessary, especially when operating the dry process, to wear a nose mask to prevent inhalation of fine dust particles which may include unwetted cement powder or general dust thrown up by the air stream exhausting to the atmosphere at the nozzle. Various grades of mask are available and the choice of mask is usually governed by the severity of the environment. Cheaper masks may need replacing several times a day so adequate supplies must always be readily available on the site.

Industrial gloves should be worn to protect against rebound and general use in handling hoses, metal nozzles, floats and other tools used in the process.

Although not an item of clothing, it should also be noted that the use of barrier creams may be necessary for anyone with skin that is allergic or sensitive to cement powder. There is often a reaction around the wrist when cuffs inflame the skin and cement causes a reaction which can lead to skin blistering.

It may be necessary for the operatives at the spraying end to be protected against extremes of weather which may also affect the sprayed material. Overhead protection shields the sprayed concrete in place and makes conditions better for the operatives. It prevents rain from washing off the material, and the sun from drying the concrete too quickly. Side protection may be necessary in open and exposed positions to prevent wind from affecting the jet of sprayed concrete.

All protection is designed to make the working conditions and environment safe and more comfortable for the operatives, but it will also improve production outputs, generate higher quality work and give clients the correct impression of the competence of the contractor. Some operatives may decide not to wear certain items of protection but they must be discouraged from discarding any of the more important items such as helmet, eye protection and footwear. Many countries have legislation that obliges operatives to wearing these items.

12.7 Welfare facilities

A productive workforce should have comfortable welfare facilities to allow them to have meal and rest breaks in good surroundings. Adequate accommodation should include a room in which they can change from clean clothes to work clothes and this room should be heated in winter to allow work clothes to dry out and air before use again the following day. Ideally each person should have their own locker in which to keep personal possessions secure during the work shift or whilst off site.

Washing facilities with hot and cold water should be available with hygienic paper towels sufficient for the number of personnel on the site. WCs and urinals should be provided and maintained with disinfectant to keep the area clean and germ free. A separate room, hut or area should be provided with access to equipment for heating food and it should have tables with laminated tops, and wooden benches. It should be kept clean, free of surplus food which may attract rodents or insects and be of sufficient size to accommodate all the site operatives who will need to use the facility. Again it is a statutory requirement in most industrialized countries to provide adequate welfare accommodation and facilities for construction workers.

Any documents with relevant information should be posted up in welfare rooms for inspection by the workforce and hints on safe working practices should be displayed prominently in welfare accommodation. On larger sites welfare accommodation should be large enough to seat operatives for on-the-job training sessions, or for being addressed by management or trade union officials.

Sub-standard accommodation usually breeds sub-standard work and attitudes while good welfare facilities will produce the opposite. It also distinguishes the poor contractor from the good, and is noticed by the client.

12.8 Training and certification

Staff and operative training should include all who are engaged in construction activities. Training is a necessary part of the job of all engineers, managers and operatives. There are a number of techniques, technical difficulties and practical considerations peculiar only to sprayed concrete which should be learnt by all levels of staff in this specialist operation.

Management training begins with the designer who should be aware of the advantages and disadvantages associated with the application of sprayed concrete. Is sprayed concrete the ideal material and operation for application in areas of difficult access or dangerous conditions? Designers must be aware of the operational limitations and are becoming increasingly responsible for ensuring safe work practices for operatives carrying out their designs in construction. No longer can a designer hide behind the competence of the contractor to ensure work is carried out to meet the design and specification. The designer/specifier should attend appropriate training courses before undertaking clients' commissions. Universities and colleges now run courses for undergraduates and there are many symposia, seminars and commercial courses run for the benefit of engineers and architects involved in design and construction of sprayed concrete.

Staff of contractors responsible for managing sprayed concrete work must also receive training in addition to job experience, so that they have a clear understanding of the mechanics of the operation, the materials being used and the environment created by concrete spraying. Basic training may be started at university or college and extended through in-house training courses, graduate training courses and seminars, symposia organized by academic or commercial organizations. Courses covering material, safety, plant and the environment should be attended in addition to basic construction training.

It is also important to train key operatives of the mixer, gun/pump and nozzle in their various duties so that they understand how good practice will ensure good quality work. They should be trained in basic concrete technology, correct plant maintenance and operation and how to work safely for their own well-being and that of other operatives.

In some countries there are schemes whereby key operatives can be trained to a standard and then assessed practically and by a written or oral test to achieve certification. This enables clients, designers and contractors to recognize that operatives have reached a satisfactory level of competence to produce sustained good quality work. This certification should be the objective of all operatives engaged in sprayed concrete work. Training to reach certification level can be carried out through company training schemes, or courses provided by national bodies (American Concrete Institute, 1991; Construction Industry Training Board, 1994; Sprayed Concrete Association, 1994). Oral or written tests may be used to ensure complete understanding of the process and should be carried out in a formal manner with independent assessors to ensure fairness.

Records of certification of operatives should be maintained both by the employer and the operative and by the promoter of any certification scheme. It is useful for future employers to be able to inpsect the record of any new employee who has previous experience in sprayed concrete, and to have this verified if necessary by the trade association or promoting body. The Sprayed Concrete Association has recently introduced a log book scheme.

Periodic testing may be necessary if certain sprayed concrete applications have not been carried out for some time by the operator. A short refresher course set up by managers will bring operatives up-to-date with new techniques, the use of new plant or new materials.

12.9 Associated operations

There are a number of operations associated with sprayed concrete with which both managers and operatives should be familiar and have a working knowledge before they can be considered fully experienced.

Many sprayed concrete jobs involve the repair of concrete structures which for one reason or another have failed or suffered damage. They may have been subjected to chemical attack, erosion, abrasion, impact or overload. Repair may require breaking out damaged or defective concrete to reach sound reinforcement and concrete. Breaking out concrete by whichever means employed can be dangerous. Whether hand-held tools, mechanized plant, explosives or water jetting are used, there are considerable risks in these operations which must be appreciated by sprayed

concrete operatives who may be working in conjunction with those responsible for the breaking out. Substrate preparation may involve water jetting to clean dirt, chemicals, marine growth, salt water and other deleterious substances from the concrete and exposed steel. The steelwork or reinforcement may need grit blasting to remove rust, corrosion flakes of iron oxides and care must be taken when working in an area close to this type of operation.

The sources of power vary. Electric power is common for hand-held tools (including scabblers and chipping hammers), water for jetters and compressed air for hand-held percussion tools (sometimes mixed with water for washing down and grit for abrading substrates). A knowledge of how to deal safely with all these power sources is essential. Especially important is the use and safe handling of electric power and high pressure water jetting. Care must be taken to inform others in the vicinity of any potential dangers.

Fixing reinforcement in itself is not particularly hazardous but operatives should be aware of how steel bars or mats of fabric should be handled and fixed safely in position. Fixings should be strong enough to carry the weight of the steel and be placed in sufficient number and in the correct place in the substrate. Care should be taken in handling the tools which may be electric powered, air powered or may even be cartridge guns. Specific training should be given for all these tools.

Sprayed concrete requires control points or lines to ensure correct finished placement. Thin guide wires will mark changes of direction or guides to depth. These wires are tightened between fixed points with screw tensioning devices and care must be taken not to over-tighten causing the wire to snap and injure the fixer. Timber or even metal forms may require fixing to give limits of sprayed concrete work and basic training must be given to operatives to understand the mechanics of supporting structures whether permanent or in temporary works. Failure to understand the loading of wet sprayed concrete on a member of a structure could lead to site accidents.

12.10 Accidents

Should an incident occur during any sprayed concrete operation, whether it be a dangerous occurrence in which no one is hurt or an accident leading to personal injury, it should be reported and investigated. Only by investigation and implementation of safeguards will further incidents be avoided. Safety is a continuing learning process and it is every operative's duty to ensure safe working of current and future work. Improvements to plant and equipment may save employees from accidents in the future if action is taken when a defect or incident is first noted.

It is the duty of managers to have a first aid kit on every site and for operatives to know where it is kept and who is qualified to apply first aid. If any injury to an operative is serious enough to require expert medical assistance then telephone numbers of the emergency services should be known so that help can be called swiftly.

12.11 Conclusion

Application of common sense is the most important factor in the safe application of sprayed concrete. The creation of a comfortable working environment and the avoid-

ance of stressful conditions will help to produce good quality work safely. It is the responsibility of managers to ensure these conditions prevail in addition to keeping plant in good order and the site in a clean, tidy and safe condition.

Managers should be experienced and trained in the processes for which they are responsible and they should ensure that operatives are trained adequately for the particular job undertaken at any one time. Current legislation of the country in which the work is being carried out should be understood and complied with, and above all a sense of being proud of the work undertaken will usually ensure that it is of the required standard and that safety conditions have been met.

References

ACI Committee 506 (1982) *Guide to Certification of Shotcrete Nozzlemen*. ACI 506.3R-82, American Concrete Institute, Detroit.

Construction Industry Training Board (1994) *Certification Scheme for Nozzlemen*

European Economic Community, EC Directive (1992*a*) *Framework Directive*, (DGV). Implementation date 31.12.92.

European Economic Community, EC Directive (1992*b*) *Safety and health of workers at the workplace*.

European Economic Community, EC Directive (1992*c*) *Safety and health requirements for the workplace*. Implementation date 31.12.92.

European Economic Community, EC Directive (1992*d*) *Minimum health and safety requirements for the use of work equipment by workers at work*. Implementation date 31.12.92.

European Economic Community, EC Directive (1992*e*) *Minimum health and safety requirements for the use of Personal Protective Equipment*. Implementation date 31.12.92.

European Economic Community, EC Directive (1992*f*) *Concerning minimum health and safety requirements for manual handling of loads*. Implementation date 31.12.92.

European Economic Community, EC Directive (1992*g*) *Minimum health and safety requirements at temporary or mobile construction sites*. Implementation date 31.12.93.

European Economic Community, EC Directive (1988) *Protection of workers from the risks related to the exposure to noise at work*. 86/188/EEC

Health and Safety Executive (COSHH) *Control of Substances Hazardous to Health Regulations*.

National Joint Health and Safety Committee for the Water Service (1979) Safe Working in Sewers and Sewage Works. *Health and Safety Guidelines* No. 2, HMSO, London.

Sprayed Concrete Association (1994), *Guide to Certification of Sprayed Concrete Nozzlemen*. SCA, Aldershot, U.K.

13 New Construction

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13.1 Introduction

Carlton Akeley, the inventor of sprayed concrete, was looking for a method of producing concrete shapes that could not be formed using conventional means. This is still the basic philosophy behind the use of sprayed concrete for new construction. Over the years this process has widened the range of shapes available to architects as well as providing the solutions to engineering problems.

Developments in concrete mixes, such as the inclusion of fibres and rapid-set accelerators, have enhanced the material's capabilities and applications. Whilst some kind of formwork is required, whether it be a blown-up skin, an earth bank or some type of mouldable sheet steel product, conventional two-sided formwork is rarely used and is often a handicap to spraying.

Where reinforcement is required, this can be conventional bars, steel mesh, woven fabric or fibres. The process dictates the limits of bar size and spacing but sprayed concrete would rarely be chosen for new work in which members required particularly heavy reinforcement. Artistry is sometimes required when curved shapes are being produced, to give good finishes of line and texture which are pleasing to the eye. Surface coatings are today very reliable and can be used to enhance the finished appearance.

It is generally cheaper to place concrete between two sides of formwork but this limits structural form and can produce large areas of uninteresting concrete. Spraying opens up the architect's horizons to free-formed shapes – but at a cost. A balance has to be struck between cost and the desired physical interest created by a sprayed concrete structure. It is imperative that sprayed concrete is left to the specialist contractor with the necessary experience, trained personnel and suitable equipment. It is a trade which requires a great understanding of theory and considerable practical experience and one cannot equate the knowledge gained on conventional concrete jobs with the requirements of sprayed concreting.

13.2 Reasons for use

Architects and engineers frequently ask why they should use sprayed concrete, and then proceed to put forward all the arguments against it. Certainly, in many conventional practices there are no advantages to be gained by using sprayed concrete; a multi-storey office block is best cast in formwork, and mass concrete retaining

walls are best poured with a low cement content, large aggregate concrete. However, sprayed concrete is ideal for many other applications, incuding rock tunnels where it would be difficult to use anything else.

The most important property of a sprayed concrete structure is that it can be produced in truly three-dimensional form. It may be a simple dome or a hyperbolic parabaloid roof; and whilst both shapes have been cast using placing and plastering techniques, they are more rapidly and economically produced by spraying.

From the point of view of design, curved shapes offer some strength advantages over conventional design forms, and the thickness of the members can be reduced to offset higher materials costs. To maximize the potential, the curves should be as continuous as possible, avoiding sudden changes in direction. Attention has to be paid to details such as bearing areas and shear resistances to ensure that overstressing does not occur at potentially weak points.

The formwork requirement is generally half that of conventionally placed concrete, even if conventional shapes are to be cast. This formwork needs to be no more strongly constructed. Whilst initial impact forces may be high, much of the energy of subsequent layers is absorbed by the material already in place. Two sided formwork is basically self-supporting so one-sided forms for sprayed concrete need to be braced but this only means a different fixing technique.

For years now it has been common practice to downgrade the strength of sprayed concrete, presumably to allow for defects and imperfections in the material, but with more reliable testing regimes and quality assurance, the true strength of the material is easy to assess and can be used realistically in design calculations. Sprayed concrete contains much more cement than most conventional mixes and hence has a greater strength potential.

The material may be chosen for its surface properties. As shot, the untreated surface has a stippled effect, which an architect might wish to utilise. A flash coat can be worked by trowelling to give a very dense, hard and even surface which can be preferable to the variations found in poured concrete.

Accessibility is a problem which often besets a conventional pour but this may be overcome by conveying the concrete along the hoses as with sprayed concrete. In this instance pumped concrete is the only rival but pump lines are not nearly as flexible or easily moved as hoses. The stop-start capability of the dry mix system can also be exploited where a concrete placement is not completely continuous.

Where a range of construction skills is absent, for example in developing countries, sprayed concrete has been used in the construction of housing, as only two or three skilled men are needed. Concrete is a good insulating material and this property is particularly useful in hot countries.

13.3 Structural form

Sprayed concrete releases the architect from the restrictions of conventionally cast concrete. He should not try to use it as another means of forming the straight up and down structures that abound in our towns, cities and industrial areas. It is a free-form material and is best used as such. That is not to say that it cannot be used in more formal types of construction.

From an engineering point of view, domes have already been mentioned as a



Figure 13.1 *Swimming pool.*

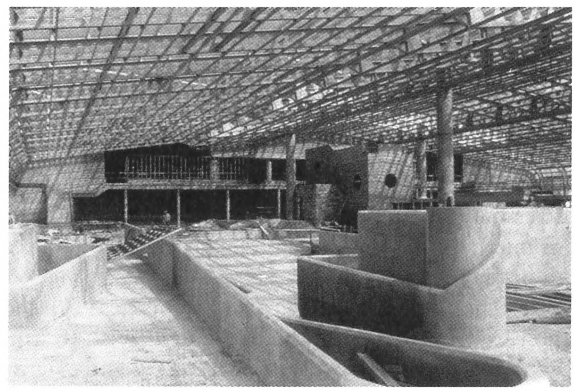

Figure 13.2 *Leisure pool.*

viable form of construction, whether they be hemispherical e.g. St Paul's Cathedral in London or flatter. Add to this the hyperbolic paraboloid and the conoidal shell roof of the Physical Education Centre at Birmingham University and it is evident that there is great scope for sprayed concrete in roof construction. Sprayed concrete is a popular construction material for swimming pools (Figure 13.1) giving unlimited scope in plan shape and using the as-dug hole as the formwork. Of particular note is the increase in leisure pools of complex shapes, in complete contrast to the rectangular ones of yesteryear (Figure13.2). It is also becoming more usual to combine the benefits of sprayed concrete parts of a structure with conventionally cast concrete. This happens to some extent with swimming pools, where the base is often cast, but is more applicable to large civil engineering structures, for example the Rabodanges arch dam in France.

One of the early uses of sprayed concrete was the protection of steel frames, a technique used mainly in America on high rise structures, to give fire protection and protection from the elements (Figure 13.3). This practice has continued, one of the latest examples being the protection of the steel frame of the Hong Kong and

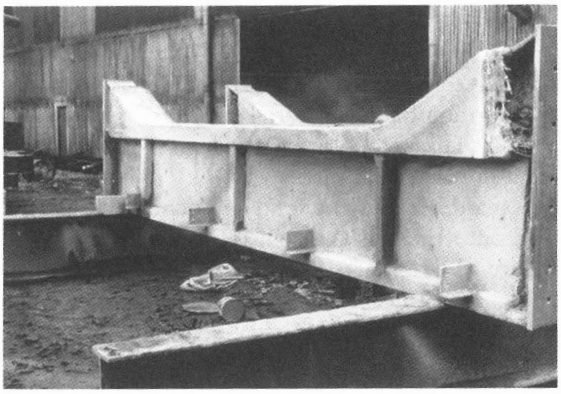

Figure 13.3 *Sprayed concrete used to give fire protection to steel beam.*

Shanghai Bank in Hong Kong. Other forms of protection which have been used are the coating of prestressing cables on circular water tanks, weight coatings on seabed pipelines bringing gas and oil from offshore installations and abrasion-resisting coatings to coal bunkers, other containers, spillways and water channels.

Whilst rock consolidation is dealt with in another chapter it should be borne in mind that similar techniques can also be used above ground where rock weathering needs to be prevented. The variability of colour inherent in sprayed concrete is of benefit here in helping it to blend in with its surroundings. Colouring agents can also be incorporated, if required.

Of historical note, but worthy of mention, are the many sprayed concrete ships and similar structures that were constructed around the times of the two world wars, mainly as a result of shortages of steel plates.

13.4 Special uses

In addition to normal sprayed concrete for structural applications, many special concretes are also available. These include lightweight and refractory materials, and steel-fibre reinforced material.

Lightweight concrete is used for insulation purposes and for reducing the weight of structural elements. It has part of the aggregate fraction replaced with one of the lightweight aggregates available. Those with high water absorption are generally unsuitable as they remove some of the already small amount of water from the cement paste once the material is in place, leading to reduced hydration and consequent micro- and macro-cracking.

Heat resistant refractory mixes are commonplace in the cement and iron and steel industries where they are used in kiln and furnace linings, chimney flues and casting chambers and ladles. In tunnelling work, wet rock faces are sealed using sprayed concrete with even higher cement contents than those normally found, using accelerating admixtures to give a flash set. Normal sprayed concrete is then applied over this layer to form the tunnel lining.

13.5 Substrates

The substrate for sprayed concrete can be any material which is capable of withstanding the impact forces of the material projected onto it. Suitable materials include rock, masonry, concrete, plastic, metal, timber formwork and some types of earth and insulation materials.

Normally these materials must be solid and dense enough not to vibrate as the concrete is sprayed onto them as this will loosen the material already placed and cause adhesion failure. The surface must be in the correct state of wetness to allow a small amount of suction to cause 'grab' but not wet enough to prevent a slight amount of water being drawn into it. However, it is possible to spray an initial coat onto a flexible substrate, allow this to set to give stiffness, then spray as normal.

Whilst a certain amount of mechanical grip is achieved by having the surface roughened, the surface must be clean and free from loose pieces. An old concrete surface should be cleaned by removing the powdery surface using grit or water blasting. The very flat, smooth and unabsorbent surfaces of metal and plastic make it difficult to achieve good adhesion and here it is essential to design for no bond and to give the applied concrete some form of reinforcement. Earth or soil must be well compacted before spraying starts; frequently the nozzleman will stabilize the surface with an initial thin application before starting the work in earnest.

13.6 Formwork

The types of formwork used for conventional concrete work are equally suitable for sprayed concrete. The formwork is not normally designed in the true sense but is detailed from experience. The impact forces of sprayed concrete are small compared to the horizontal force produced by a mass of liquid concrete.

Plywood facing material usually need not be more than 12 mm thick for vertical casting. In some instances hardboard is used or, when the line of the finished product is of little or no concern, hessian tautened by wetting and shrinking onto a frame or stiffened with a quick setting cement grout can be used. Like conventional vertical formwork, that for sprayed concrete needs a system of backing members to resist the forces applied to it. The formwork system has to be self-supporting prior to spraying, and must be braced against collapsing inwards. Should there be a kicker at the base of the wall the form can be tied into or wedged against it but free standing panels need to be tied back to prevent forward movement. The tendency for conventional double forms to lift during concreting does not apply here as there is no lifting force created by the concrete being placed. Sprayed concrete can stand on its own to considerable heights.

The formwork for sprayed roof structures must be exactly the same as that for conventional cast work; thicker plywood (19 mm) and a complete system of backing members and falsework, all designed to carry the given thickness of wet concrete, reinforcement, men and equipment.

When spraying overhead there is very little force applied to the formwork; the only requirements of the formwork are that it should resist any forces placed on it during erection and that it should be held down to resist any upward forces induced by the spraying process.

The action of spraying tends to remove conventional release agents of the emulsion or oil type, by pushing them along the face or into the cellular structure of the plywood. It is therefore recommended that a chemical release agent is used or the formwork is covered with polythene sheeting before spraying commences. A special type of wire mesh interwoven with strong brown paper, a three-dimensional mesh with a core of polyeurethane foam or rib-strengthened expanded metal with small aperture sizes, are sometimes used as formwork. By spraying from both sides the mesh becomes incorporated into the system as part of the reinforcement.

There is also a system for producing domes by spraying onto the inside of a coated woven fabric former which is attached to the foundation ring and inflated.

13.7 Reinforcement

Designers should be aware of the limitations placed on the size and spacing of reinforcing bars by the spraying process. Using a pure sand, cement and water mixture there is a great possibility of creating sand pockets behind reinforcing bars; the larger the bar the greater the possibility. The sand pocket consists mainly of rebounded or undercompacted material due to shadowing by the bar, resulting in a plane of weakness with the possibility of cracking occurring in the cover zone immediately over the bar. Prebagged and other highly cohesive mixes overcome this problem to a large extent as they generally contain additives or admixtures which give the final concrete the ability to flow around and behind the steel. Whilst it is easier to spray around and behind smaller bars (of not more than 12 mm diameter), larger bars (up to 25 mm diameter) have been successfully used in sprayed concrete.

The other limitation with conventional reinforcement is the clear space between bars. The Sprayed Concrete Association recommend that this should be not less than 4 times the bar diameter, nor less than 50 mm. Most designs allow larger spacing than this and seldom is the clear space less than 75 mm. The spacing of links should normally not be less than 100 mm.

The type of reinforcing bar is also important. Round bars allow the concrete to flow around and along them. Any kind of deformation increases the amount of rebound, and any resulting incomplete encasement lowers the bond between the two materials. Expanded metal meshes are frequently too flexible to spray around, unless they are stiffened. Heavy concentrations of chicken wire mesh should be avoided.

Normal practice for conventional concreting is to tie bars together at laps – all at the same location. In sprayed concrete this will give rise to sand pockets, even with small diameters. Lapping bars should always be staggered to give the minimum spacings quoted earlier.

As with many other aspects of sprayed concrete, success lies with the nozzleman and highly experienced ones will cope successfully with the limitations given above. One technique used is to angle the line of shooting to reach behind the bars; another is to move the nozzle in slightly closer and whilst both these actions create more waste, the finished concrete is invariably well compacted to full depth.

For applications such as swimming pools and earth-retaining banks, the reinforcement is present largely to control temperature effects and cracking and as such is usually in the form of mesh or fabric. The reinforcing system requires a great

degree of stiffness to ensure that it remains precisely in place throughout spraying and this precludes the use of synthetic plastic-type mesh materials, which move readily under the blast of air and sprayed concrete. Secure fixing is of paramount importance. The aim must be to ensure that the bars or fabric stay in place until spraying is completed; hence the closeness of bar spacing is determined by the flexibility of the bars and wires. Most types of proprietary spacers are acceptable and it is normal to tie back the reinforcement to prevent it moving forward as concrete is built up behind it.

Prior to encasement the reinforcement must be free from all material that will impair the bond, for example oil, loose rust, mill scale, mud, ice, and overspray. Overspray on adjacent sections is almost inevitable and should be removed whilst it is still soft by brushing and air water blasting – taking care not to damage the newly-shot material. If it has hardened then the overspray will need chipping and gritblasting off before further encasement can take place. The use of fibres for reinforcement of sprayed concrete is dealt with in Chapters 2 and 6.

13.8 Finishes

The most stable finish of sprayed concrete is 'as-shot' and exhibits a stippled effect similar to grout-washed pebble-dashing. As sprayed concrete has such a low water/cement ratio any working of the surface can easily cause tension cracks at a time when the material has a very low tensile strength. Particles which adhere loosely to the surface can be brushed off with a soft brush about an hour after spraying. An experienced finisher can produce a dense, undisturbed surface. To achieve this, the material is slightly overshot and, at the correct time – when the initial hardening of the 'false set' has taken place, usually between 1 and 2 hours – it is sliced back with a sharp trowel. This will still leave the surface slightly rough but takes out surface variations and produces a good tolerance finish. This can be further varied by brushing with a stiff brush or a broom, leaving a brushed texture.

The trowelling technique is akin to that which is used to harden the surface to give a dense floor finish. The action of trowelling with a steel trowel is to tighten up and polish the surface. It is unwise to overtrowel the surface as disturbance will be caused to the concrete below the surface. Wood floats tend to drag small particles along with them and produce a scored surface.

Flash-coating is another surface finishing technique which will not disturb the main thickness of material. This is done with a slightly weaker mix, as in good wall plastering techniques, with a finer sand and more water and need be only 3–6 mm thick. As this tends to fill the undulations on the original surface it can be left as a more even surface, gently brushed as before or it may be lightly worked with a trowel. It must be emphasized that all these techniques are best carried out by skilled men who have full competence in these methods.

The flash coat must not be regarded as a 'curing coat'. It will itself need curing. Whilst undoubtedly it will retain the water required for hydration in the concrete below, it will certainly lose too much water itself and will crack and craze, especially as its area is very large compared to the volume of concrete involved. The popular misconception that sprayed concrete is a self-curing material should be ignored. All concrete containing simply cement, aggregates and water requires time

for the water to combine with the cement before evaporation removes it from the surface. Curing membranes are the most cost effective means but there may be times and occasions when other methods will be more appropriate.

Guidance for attaining the correct line and level on large flat areas is generally given by wires stretched tightly across the surface at, say, 1 m centres. The finisher uses these to obtain the desired profile. Where external corners are incorporated in the structural form a timber batten is fixed securely prior to spraying. Concrete is placed up to this from one side, forming the corner angle. Once this has hardened the batten is removed and the new concrete is used as a guide for the continuation.

13.9 Economics

As the quantity of cement in sprayed concrete is about double that in conventional concrete, the cost of the basic material is higher – in the region of 30%. In addition there is the cost of the gun and nozzle and the provision of compressed air and a pressurized water supply. The placing rate is governed by the thickness of section being cast; straight walls less than 150 mm thick and curved walls less than 250 mm thick are generally cheaper in sprayed concrete (Figure 13.4). This is due mainly to the cost of formwork compared to the volume of concrete involved. It is somewhat erroneous to make a straight comparison in this manner as it is rare for spraying to be chosen as a direct replacement for conventional placing techniques; spraying is more often used in applications where conventional methods are inappropriate.

To be competitive, the contractor must seek ways of minimizing his costs. This involves striking a balance between the number of men and the degree of mechanization. As labour costs increase and machinery becomes more sophisticated and reliable the trend is to reduce the work force. There could be as few as three operatives – a nozzleman, a gunman and one general purpose operative. The contractor should also embark on a high level of pre-planning to ensure that the spraying operation is not held up unnecessarily. He should arrange regular deliveries of materials, movement of plant and ensure that there is always sufficient formwork or support ready for his gang.

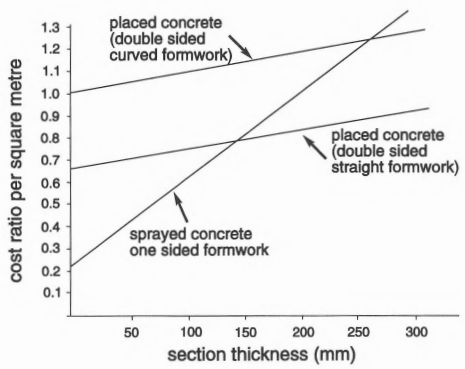

Figure 13.4 *Cost comparison of wall construction.*

13.10 Examples

Tent in Saudi Arabia

The Janadriyah complex near Riyadh in Saudi Arabia is a series of reinforced concrete 'tents'. They provide meeting spaces and were designed along traditional lines. Computer programs were used to assist with the design process.

Construction lasted a mere 120 days and only 87days from starting excavation for the foundations to the completion of the sprayed concrete. The steel skeleton frame was temporarily braced and the tent roof reinforcement of bar and fabric was placed on a layer of Hy-rib. The sequence of spraying different areas was carefully regulated to balance the loading on the steel frame. Curing was effected by draping the completed sprayed concrete tent roofs with hessian and keeping this wet by spraying with water. The underside, being of expanded metal, did not need curing. Ultimately a 25 mm thick sprayed concrete coating was applied to the soffit. The surface finish achieved was deemed good enough to receive a coating of white paint without any further finishing. After about 10 days the temporary struts and guys were removed.

Using sprayed concrete removed the necessity of extensive complex formwork allowing the contractor to minimize his contract period – both advantages when working in a remote location. Figure 13.5 shows an example of 'tent' construction.

Hong Kong & Shanghai Bank, Hong Kong

This structure comprises a steel frame which is protected by 1000 cubic metres of concrete sprayed over an area of 72 000 square metres. The bulk of the spraying was carried out in a compound on the mainland with only sea access. Sprayed sections were transported by barge across Hong Kong harbour and then by lorry to the construction site. The congested site, fast-track programme required and high temperature and humidity combined to produce demanding requirements.

The sprayed concrete had to bond to the steelwork, have sufficient flexural strength to resist stresses and impact loading during transportation and erection, be dense and impervious and be not more than 20 mm thick due to weight considerations. Extensive research and development resulted in a mix incorporating an SBR



Figure 13.5 *'Tent' house in Kuwait.*

and stainless steel fibres which could be sprayed in 14 mm thick layers. The coating was applied in two layers, the second without fibres to reduce possible hazards to personnel. Pre-construction trials were carried out to demonstrate that the use of local materials and labour would produce a coating that met the specification.

Wine storage caves
The Saratoga-Skyline Vineyard in California stores its wine in sprayed concrete caves set in the ground and constructed in a cut-and-cover operation. The construction system consists of interlocking corrugated stamped steel plates, curved and assembled into a framework and then covered with sprayed concrete to form the shell of the structure. Bracing was required until the concrete shell was sufficiently strong to support itself. The thickness of sprayed concrete varies from 350 mm at the base to 225 mm at the crown and the soffit was later coated with a 10 mm sprayed concrete layer to protect the steel plates. Once completed the structure was covered with earth. This system has also been used in a variety of other applications including an underground church, libraries, homes, highway culverts and mines.

Domes (see also Section 7.11)
Domes provide large spans for storage of items such as cement and road salt as well as for sports halls where the intrusion of supporting columns is avoided. They can be produced in a variety of forms: half spheres, three-quarter spheres, with vertical walls or rectangular floor plans. The system of construction is basically very simple with only foundations and ducts being formed conventionally.

The airform, made of pre-coated polyester fabric, is attached to the foundations and is placed over all necessary construction equipment such as crane and scaffolding. It is then inflated to the size and shape of the dome using an airfan. Access to the inside is then through an airlock. Once inflated, a polyurethane foam insulating layer is sprayed onto the inside of the dome; this gives immediate stability and ultimately acts as a protection to the concrete.

Reinforcing bars (supported by hangers) are then placed inside the dome and around any door or window openings. Concrete is sprayed into place and cured. Once the concrete has gained sufficient strength the airblowers are shut down. Dry mix concrete can be used for this application, but wet mix is generally used. It is estimated that dome structures cost around 25% less than conventionally cast ones. Examples of domes can be seen at cement works in France, Germany and Spain.

Liquid storage tanks
Liquid storage tanks are traditionally either made from concrete, either (reinforced or prestressed) or from steel sections bolted or welded together. Sprayed concrete tanks were developed to overcome disadvantages of traditional tanks, such as cost, internal maintenance and leakage. In order to meet the requirements of being internally maintenance free, leak proof, fast to erect, cheaper and of pleasing appearance a form of construction was developed using profiled pressed-steel panels with a sprayed concrete interior. The system is similar to that described for the construction of domes and to date three tanks have been constructed by this method.

Zoological Gardens, Riyadh
One of the largest sprayed concrete projects is the New Zoological Gardens in

Riyadh, Saudi Arabia where over 12 500 m^3 of wet process sprayed concrete was used in structures and finishes.

Concrete was produced at a central batching plant and transported to the required locations in mixer trucks. Up to five spraying teams were working at the height of the work, placing 150 m^3 each shift. Working conditions were onerous with temperatures of around 40°C during the night shift. To counteract these high temperatures, ice was used in the mixing water to keep the concrete batches below 25°C. Many of the above-ground structures formed were curved walls, which were cast against one sided formwork which could be re-used; on below ground structures the back forms were lost.

Shell roof

The storage building of Barclays Bank near Warrington has a double curved roof giving clear spans of 70 m × 35 m. The curved shape of the roof was created by tensioning steel cables between the side walls and a single steel angled arch. Plywood forms were suspended from the grillage of cables and sheets of light steel reinforcing fabric were placed in the top of the roof slab. The whole was then sprayed from above to a thickness of 100 mm using the dry process.

Caisson dome roofs

The storage caisson cells of the Cormorant 'A' oil production platform, fabricated at Ardyne Point in Scotland but now on the bottom of the North Sea, are topped by concrete domes. The permanent formwork for these was created by spraying concrete onto five reusable epoxy resin coated concrete forms. Units were made in a variety of sizes from about 12 m square and weighing between 25 and 40 tonnes. After casting and curing, the units were floated out to the platform which was being constructed in deeper water. More reinforcement was added together with conventional in situ concrete to produce monolithic cells.

Bibliography

ACI Committee 506 (1990) *Guide to Shotcrete*. American Concrete Institute, Detroit.

American Concrete Institute (1981) Shotcrete Applications. *Concrete International* **3**, (1)

Hills, D.L. (1980) A review of sprayed concrete – Part 2. *Concrete*, **14** (3), 20–22.

Hudson, P. and Topping, B.H.V. (1991) The design and construction of reinforced concrete 'tents' in the Middle East. *The Structural Engineer*, **69** (22), 379–390.

Kaneshiro, J. Y. (1989), Shotcrete Wine Storage Caves. *Concrete International*, **11** (7), 42–3

Plum, D.R. (1984) *The Development of Sprayed Concrete Tanks*. Conferences on Design, Construction and Maintenance of Concrete Storage Structures, Newcastle-upon-Tyne, Concrete Society, 37–50.

Ryan, T.F. (1973) *Gunite – A Handbook for Engineers*. Cement and Concrete Association (BCA), Crowthorne, UK.

Shattuck, D.W. (1985) The New Zoological Gardens, Riyadh. *Civil Engineering*, Nov/Dec.

South, D.B. (1990) Economics and the Thin Shell Dome. *Concrete International,* **12** (8), 18–20

Terchert, P. (1981) *Shotcrete*. E Laich SA, Avegno, Switzerland

van Eeden, J.P. (1992) Dome Silos – unique storage systems for the cement industry. *World Cement*, **23**, February, 21–24

Wilson, A. (1990) Very Large Air-Formed Concrete Shells. *Concrete International*, **12** (8), 21–23

14 Repair

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14.1 Introduction

Sprayed concrete is used widely in the repair of deteriorated structures, because of its ease of application in situations where it is virtually impossible to use formwork to recast, and because it can be applied in thin layers whilst ensuring good bond to the existing material (be it concrete, steel, brick or stone).

Spraying is a continuous process, and best use is made of this technique where there is a reasonable amount of continuous work. Spraying is less appropriate for a large number of small areas needing repair and it is not the most appropriate repair method, for example, where the reinforcement to be encased is highly congested or for confined or highly profiled areas. In the UK, nearly all sprayed concrete repair work is carried out using the dry process with aggregate size of less than 10 mm. High volume wet process technology is not normally compatible with the low volumes and frequent stoppages which characterize sprayed concrete repairs.

Prior to repairing, there are many important considerations to be made, including determining the cause of the problem, deciding on the preparation work, designing and detailing the repair, and specifying the material. A successful repair will require a high standard of workmanship, so it is important to select a contractor with a good history of successful work. Sensible supervision by the engineer is also required, with due regard to the fact that this is not conventional concrete. Among the initial design considerations it is particularly important to ensure that the repaired structure acts as it should, by reflecting the original joint pattern together with the movement joints which the structure itself has determined in the form of cracks. Not allowing for these will result in failure of the new sprayed-on part of the structure, in the form of cracking along the lines of the underlying joints.

Repairs have been carried out with sprayed concrete on many different types of structures, including:

- bridges soffits, beams, parapets and abutments;
- steel and reinforced concrete framed buildings;
- cooling tower shells;
- industrial chimneys;
- water-retaining structures including dams;
- tunnels with various linings, and
- jetties, sea walls and other marine structures.

14.2 Diagnosis of defect causes

All causes, even those which appear obvious, should be investigated thoroughly so that the correct diagnosis, and then the appropriate remedial measures, can be determined. Fire damaged concrete is easy to see but its appearance can be deceptive. Soot blackened surfaces often hide perfectly sound material; so the first stage should be to clean the surface. Many concretes conveniently turn pink at the temperature where damage starts to occur but this visual guide should not prevent cores being taken to ascertain the true strength of the concrete. Fire does not usually affect any reinforcing steel except cold worked varieties, so again it is essential to remove a length, or lengths, of reinforcing bar and test them for residual strength. As steel is a good conductor of heat, damaged concrete and steel can be found at some distance away from the areas that are apparently worst affected.

Deterioration of bridges and marine structures is most commonly caused by chloride attack; de-icing salt or saline seawater producing electrochemical attack on the steel. As a result, rust is formed on the steel within the concrete and as this grows it creates a bursting force which ultimately spalls the concrete. Occasionally rust is formed without expansion (oxygen starved corrosion) and as this is not evident on the outside of the structure it is potentially more invidious than that which does cause expansion. The only complete solution to this problem is to remove all chloride contaminated concrete or to remove the chloride from the concrete (a process which is currently gaining in popularity) and replace any deteriorated reinforcement.

The other main cause of reinforcement corrosion is attributable to carbonation of the concrete in the cover zone. This occurs as carbon dioxide from the air is driven into the concrete by rainwater. The weak carbonic acid thus produced reduces the alkalinity of the protective concrete and, once this effect reaches the reinforcement, the steel is open to corrosive attack from air and water. This can also take place if the concrete in the cover zone is poorly compacted, leaving passageways for the ingress of air and water. Where the depth of cover is reduced or the concrete is of low quality, the carbonation front will reach the reinforcement more quickly. It should be stated, however, that dense concrete with a sufficiently high cement content will adequately resist carbonation.

Other forms of chemical attack can usually be determined from the history of the structure, and in most cases will be evidenced by deterioration of the concrete surface. For example, sulphate attack produces expansion which disrupts the surface of the concrete, ultimately exposing the reinforcement.

Physical causes of deterioration are generally more obvious. For example, abrasion on a sea wall wears away the surface, exposing the aggregate; the reinforcement may be exposed or even abraded by the action of beach material. Overloading of a structure produces cracks at points of high stress.

14.3 Preparation

Thorough preparation is essential. Any problems with the reinforcement must be resolved and any contaminated concrete must be removed. At the ends of cut out areas the 'shoulders' must be square to give the repaired area a reasonably even

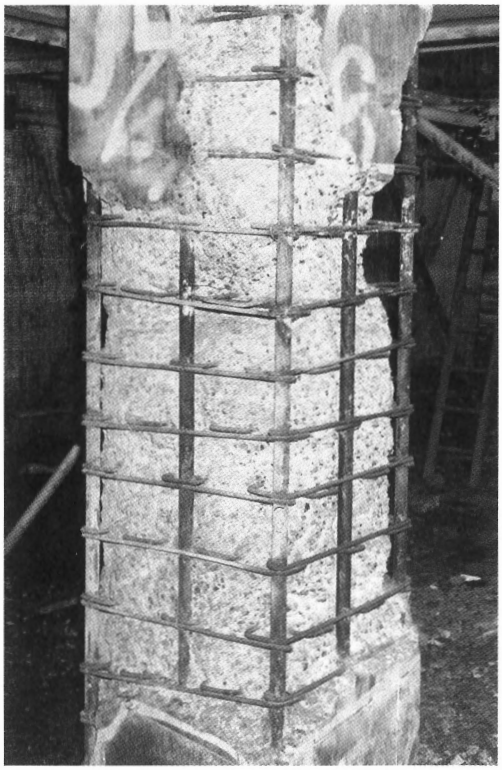

Figure 14.1 *Column partially prepared for repair.*

thickness, preventing feather-edge cracking. The repaired area should never be less than 25 mm thick and when determining the replacement cover thickness it should be borne in mind that sprayed concrete is denser than conventionally placed material. Provided that the rear of the bar is uncorroded and that it is firmly bonded to the rear concrete, chasing out behind steel is to be avoided as the spraying process is prone to producing sand pockets in these areas. Otherwise a clear gap of at least 50 mm should be created behind the bar, so that any corrosion can be removed and the concrete can be sprayed effectively into this region (Figure 14.1)

To ensure good bond with the substrate, all defective or unsound material (including dust and dirt) must be removed and any running water must be stemmed. Porous surfaces should be dampened down to control suction, remaining just-moist. Any surface water will increase the water/cement ratio at the interface and reduce the bond; a good bond is essential for a good repair.

14.4 Reinforcement treatment

Reinforcement corrodes for different reasons and will need different treatments depending on the type of attack. If the reinforcement has been attacked by chlorides from de-icing salts or from a marine environment, then the rust must be com-

pletely removed by power blasting before the protective coating is replaced. Chloride-induced rust can be expansive and cause spalling or it can be oxygen-starved, which may result in corrosion product similar in volume to the steel from which it came thus producing no expansive force. The latter is quite dangerous as the structure can lose its strength without there being any external signs to that effect. To locate these areas the half-cell testing technique should be used. This produces contour line plots of electropotentials, from which areas of high corrosion activity can be judged. The cover concrete is then removed to expose the bars and the corrosion on them.

At the time of testing, dust samples are taken by drilling into the concrete so that the chloride concentrations at given depths can be determined, especially around the reinforcing steel, to help assess the overall condition of the concrete. Maximum tolerable values of chlorides vary, but chloride concentrations as low as 0.2% by mass of cement have been found to permit rusting to take place. Should any rust be left on the bars it is highly likely that rusting will continue in this area after completion of the repair. It is very difficult to remove rust from behind the bars; power blasting is the best option as the abrasive medium will bounce back from the substrate and impinge on the bar. Wire brushing has been found to be almost useless as it tends to polish the rust rather than remove it. When an area of rust has been located the bar must be exposed along its length beyond the rusted area to expose sound reinforcement, say about 50 to 100 mm along the bar. This ensures as far as possible that all the corrosion at this location has been found.

For corrosion found in carbonated concrete the problem and the solution are simpler. Here corrosion is formed by air and water and almost invariably results in spalling of the face. It happens when the cover thickness is not sufficient or the concrete is of poor durability. Again, it is preferable to remove all the rust, though



Figure 14.2 *Wall repair – spraying from the bottom up.*

this not absolutely essential as once it is completely encapsulated in an impervious alkaline or neutral covering it can be considered to be inactive.

Sprayed concrete, which is cement-rich and produces a high concentration of paste around the bars, can be considered an effective repair material for concrete affected by reinforcement corrosion.

14.5 Mixes

The mixes used for sprayed concrete repairs are the same as those used for conventional spraying except that they are also available in pre-bagged form. Prebagged materials are more expensive than combining individual materials at the work-site, but they have enhanced properties. Their main characteristics are improved cohesion, reduced rebound and setting time in the wet state and a more consistent product with enhanced durability in the hardened state. These properties enable thicker build-ups, better adhesion to the substrate and better flow through and around more congested reinforcement. The finished material has better resistance to freeze/thaw attack, diffusion of carbon dioxide and chloride ions and, whilst normal sprayed concrete has low shrinkage, it is even less in these modified materials.

14.6 Procedures

The nozzleman will start by allowing the material to run to waste until he is satisfied that the mix is correct. Starting at the bottom of the vertical section to be repaired he works his way up (Figure 14.2). This is to obviate rebound material being trapped within the repair and also because starting at the top would cause the repair material to hang, causing tension cracks. The thickness of each layer will be determined by the amount which can be built up without it sloughing off; overhead work will be in thinner layers than vertical work. Good operating techniques described elsewhere in this book must be observed, especially those applicable to shooting into corners.

The finished surface is normally best left 'as shot' but repairs usually have to match their surroundings and to this end some form of surface finish is often required. Some materials will tolerate a limited amount of trowelling or slicing off

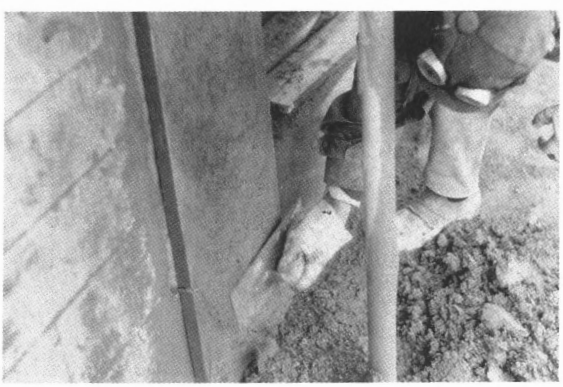

Figure 14.3 *Floating off column repair betweens battens.*

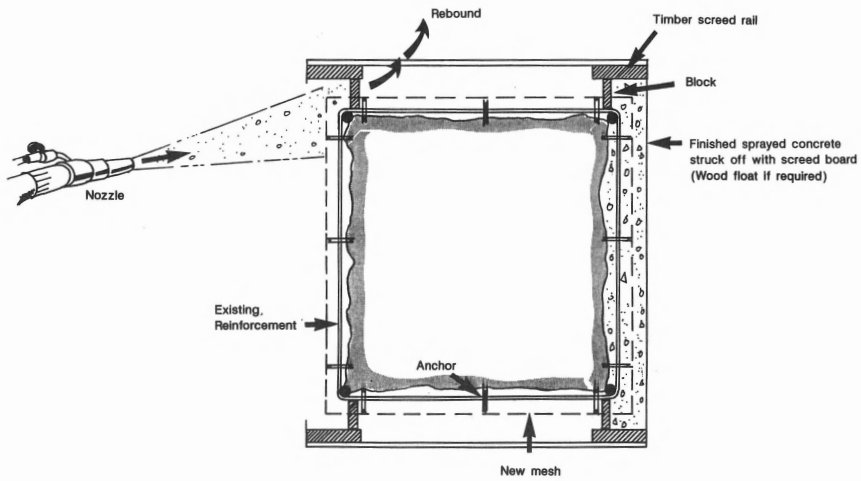

Figure 14.4 *Typical column repair.*

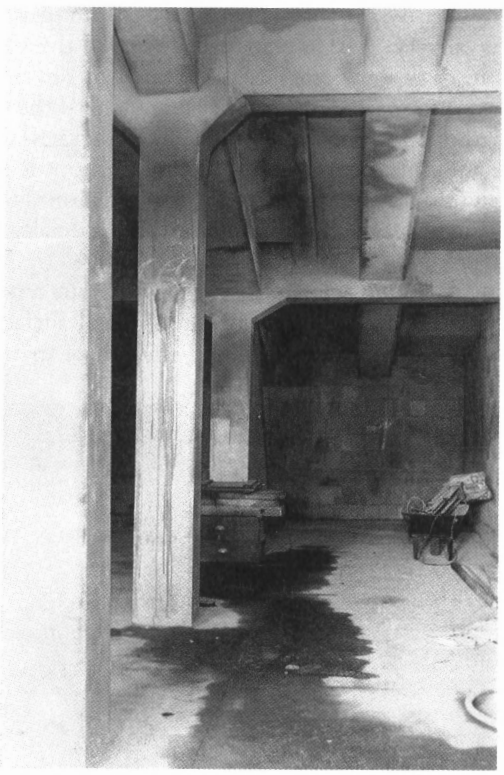

Figure 14.5 *Completed column repair showing the cleanness of arrises achievable.*

provided it is done carefully. Most materials, however, need to be undersprayed by about 5 mm below the final profile and then a final 'flash' coat, containing finer sand and a little more water, is applied to complete the infilling. This coat may then be wetted, floated and trowelled to give a smooth finish (as shown in Figure 14.3). The flash coat must be applied whilst the base coat is still green.

Often, repairs are quite small in area and guidance for the finished line and level can be taken from the surrounding concrete. For column or corner repairs, however, timber guide strips are normally used (*see* Figure 14.4). Two sides are replaced using the guides, which are then removed and the created corners are used to guide completion of the other two sides. An example of the cleanness of arris finish achievable is shown in Figure 14.5.

14.7 Curing

As with any other cement based material, sprayed concrete needs moisture retention to allow full hydration of the cement. Claims that sprayed concrete is self curing are completely erroneous and must be rejected. Some polymers, however, need air to permit setting so the chosen curing regime may be needed for only four days. Because repairs are frequently in remote areas, the most convenient curing method is a sprayed-on curing membrane. Most contain a fugitive dye which initially colours the area of application but this is broken down by ultra violet light and soon disappears. Since they act as debonders care must be taken not to spray the membrane into areas yet to be repaired and, similarly, they should not be used if a surface coating is to be applied subsequently.

14.8 Examples and case studies

Church dome

One of the shrines of Christendom is the Church of the Holy Sepulchre in Jerusalem. The present structure is over 100 years old and has been damaged progressively by fire and earthquakes over the last 70 years. The dome consists of prefabricated wrought iron arches supporting inner and outer shells of mortar and it is the outer shell which was replaced using sprayed concrete in the early 1980s.

It was decided to spray a coating of 115 mm average thickness onto galvanized expanded metal mesh permanent formwork, incorporating a layer of mild steel reinforcing bars. The concrete, with a characteristic strength of 25 N/mm^2 at 28 days, contained 8 mm crushed limestone and natural pit sand. For stability it was decided to spray in two layers of equal thickness, in horizontal circumferential bands approximately 2 m high, starting at the bottom of the dome and working up to the crown. The gradual increase in dead load on the trusses thereby mirrored the reverse of the demounting operation undertaken during demolition. Finishing of the sprayed concrete was achieved using steel trowels, with constant vigilance for smoothness and line. This produced a good dense surface to receive the lead sheeting.

It was found during spraying that the expanded metal initially allowed some material through and its slight lack of stiffness caused high rebound. However, once the initial coat was in place the operation proceeded smoothly. Curing was effected using wet hessian for 7 days.

Sewers

Sprayed concrete is one of the best materials for repairing deteriorated brick sewers. It bonds well to the surface of brickwork, fills all voids that it can reach and can be sprayed in relatively thin yet structurally sound layers. An added benefit is that a distorted crown can be successfully repaired as it will afterwards be stable, obviating the necessity for excavation and rebuilding.

Water running through the sewer must be diverted and leaks temporarily piped before spraying starts. Any material that may interfere with the bond between the two materials must be removed from the surface of the bricks; a low pressure grit blasting is the normal method. A sprayed concrete lining will also permit grouting behind partially collapsed sewers. As far as the hydraulics are concerned, a sewer repaired with sprayed concrete may have a reduced cross-sectional area but friction is less and the end result is normally a flow rate compatible with the original.

Bridge abutment stabilization

Thomas Telford's Cartland Bridge of 1820 is a listed structure and carries the A73 road across a tributary of the river Clyde just north of Lanark. Sprayed concrete was chosen as part of a scheme to stabilize the bridge's abutments which are founded on sandstone. Severe corrosion of the rock was endangering the stability of the bridge although the structure itself was still in excellent condition. After placing nearly 200 rock bolts and anchors in the rock, a 200 mm thick layer of sprayed concrete was applied over the face. Sprayed concrete was chosen because of the difficulty of access for conventional means of concreting and also because its surface could be made to resemble the contours and texture of a natural rock face. Similar work was carried out on the rock below Tintagel Castle in Cornwall.

Lining of river culverts

The river Sheaf runs mostly between walls or in culverts through the city of Sheffield. Repair works to the culvert sections involved the application of a 50 mm thick steel-fibre reinforced coating of sprayed concrete. The coating was applied in two layers with fibres only in the first, 40 mm thick, layer. The second layer was applied whilst the first was still 'green' and was given a trowel finish.

As water was leaking through the original culvert walls, sheets of dimpled high-density polythene sheets with integral woven mesh for lining adhesion were fixed to the channel walls before concrete was sprayed on them. The scheme, comprising realignment and regrading of the channel, has solved the problems of severe flooding in this highly industrialized area.

Prestressed concrete box beam

Latex-modified sprayed concrete has been used to repair places where prestressing strands had rusted on the F G Gardiner Expressway in Toronto. All spalled and delaminated concrete was removed together with areas where the chloride content was unacceptably high. Delamination was detected by hammer testing and concrete was removed using light chipping hammers. Once the strand was exposed the loss of section could be determined and structural adequacy checked. Fortunately all locations of rusting were found to have sufficient residual strength and no additional prestressing or reinforcing steel was needed. Concrete removal extended into

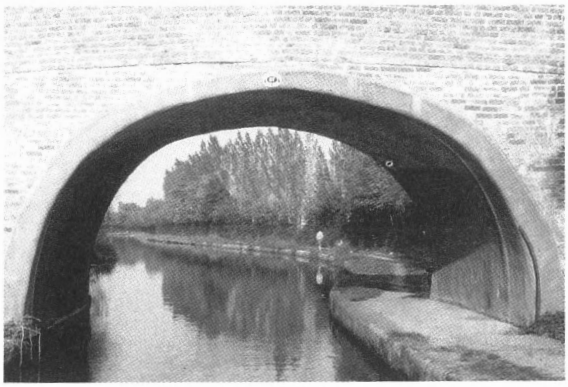

Figure 14.6 *Canal bridge-arch strengthening.*

sound areas until at least 50 mm of clean strand was exposed. The cut out areas extended for a minimum of 20 mm behind rusted steel and all cracks were chased out. The rust was removed by grit blasting, which also prepared the exposed concrete surfaces, and the areas were sprayed with latex-modified concrete. Cover to stirrups was a minimum of 32 mm, even if this meant a thickening of the beam. All repaired areas were hammer tested to prove their soundness; some had to be cut out and resprayed.

Underpass walls

The original concrete for the Tibbet's Corner Underpass on the A3 in London contained chloride carried in on the coarse aggregate; de-icing salts had been sprayed up from the carriageways by passing vehicles. Testing revealed higher than tolerable levels of chlorides at the level of the reinforcement and it was decided to replace all contaminated areas, which occurred near the base of the walls. As all work had to be carried out at night, concrete was removed by high pressure water jetting to minimize noise nuisances in this residential area. Further testing was carried out on site to confirm that chloride levels on exposed surfaces were at acceptable values. Panels were sprayed using pre-bagged polymer-modified concrete and, at an appropriate time, these were treated to match the exposed aggregate finish of the existing faces. The repaired areas were covered in polythene sheeting and taped and then left for seven days to cure. Frost protection was added if there was a prospect of sub-zero temperatures.

Bridge strengthening

Figure 14.6 shows a bridge which had deteriorated and has been strengthened with an arch of sprayed concrete. Many canal bridges have been repaired on Britain's waterways and this example contains a layer of reinforcement.

Sea walls

Erosion from wave action and beach material is common on sea defences and repair is often effected with sprayed concrete. The hardness of the young material is ideal



Figure 14.7 *Repairs to sea wall at Broughty Ferry, Scotland.*

for resisting the effects of a rising tide. As can be seen in Figure 14.7, stainless steel reinforcing mesh fabric can be used to add to the durability of the completed repair.

Bibliography

Allen, R.T.L. and Edwards, S.C. (1987) *Repair of Concrete Structures*. Blackie and Son, Glasgow, 204pp.

Balvac Whitley Moran Ltd (1991) *Underpass Refurbishment, Tibbet's Corner, London*. Technical information leaflet.

The Concrete Society (1978) *Assessment of fire-damaged concrete structures and repair by gunite.* Technical Report No 15.

The Concrete Society (1984) *Repair of concrete damaged by reinforcement corrosion*. Technical Report No. 26.

FIP (1982) Guide to good practice, Repair and strengthening of concrete structures, FIP.

Keith, J.H. (1982) A dome in Jerusalem. *The Structural Engineer*, **60A**, (1).

Morgan, D.R. (1992) New Developments in Shotcrete for Repairs and Rehabilitation. *Proceedings of Advances in Concrete Technology Conference, Athens.*

Scotland Stabilized (1994) *Construction Repair*, **8**, (1).

Torke, A. (1989) Rehabilitation of prestressed concrete box beam deck of an elevated expressway. *Canadian Journal of Civil Engineering*, **16**, (1).

Young, D.R. and Cross, J.G. (1992) Design and Implementation of the River Sheaf Comprehensive Flood-Alleviation Scheme. *IWEM 91 Conference Paper*.

Zurawski, J.F. (1992) Repair and Rehabilitation of Brick Sewers with Shotcrete. *Public Works*.

15 Rock Stabilization and Underground Support

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15.1 Introduction

This chapter is concerned with the stability of rock slopes and undergound openings, and the use of sprayed concrete for the improvement of their stability. The use of sprayed concrete in conjunction with rockbolts and anchors is also discussed, but other stabilization measures such as the use of retaining walls, gabions and reprofiling are not covered. Further information on such measures can be obtained from other publications such as Rock Slope Engineering (Hoek and Bray, 1981).

Rockbolts and sprayed concrete have also been used for the support of tunnels and other underground excavations for many years. The technique is often termed the New Austrian Tunnelling Method (NATM). However, NATM has its own philosophies (see Chapter 8) and is more than merely the use of rockbolts and sprayed concrete.

This chapter covers the general principles of ground stabilization and support by rockbolts and sprayed concrete in the wider context and is not specific to NATM. It is divided into three main sections covering slope stabilization, underground support and rock bolting. The principle objective in the design of underground excavation support is to help the rock mass to support itself. The design of rockbolt and sprayed concrete systems are considered within the overall context of this design philosophy. Although the two systems are considered separately, they act together to limit rock displacement and hence stabilize an excavation.

15.2 Slope stabilization

Failure modes

In order to design an effective rock stabilization system it is necessary to consider the potential modes of failure of the slope. For rock slopes, the principle modes of failure are as follows:

i) plane failure;
ii) wedge failure;
iii) circular failure – weaker rocks only;
iv) toppling failure;
v) failure along weak or shear zones;
vi) surface deterioration leading to failure in the longer term.

Some of these mechanisms are illustrated in Figure 15.1.

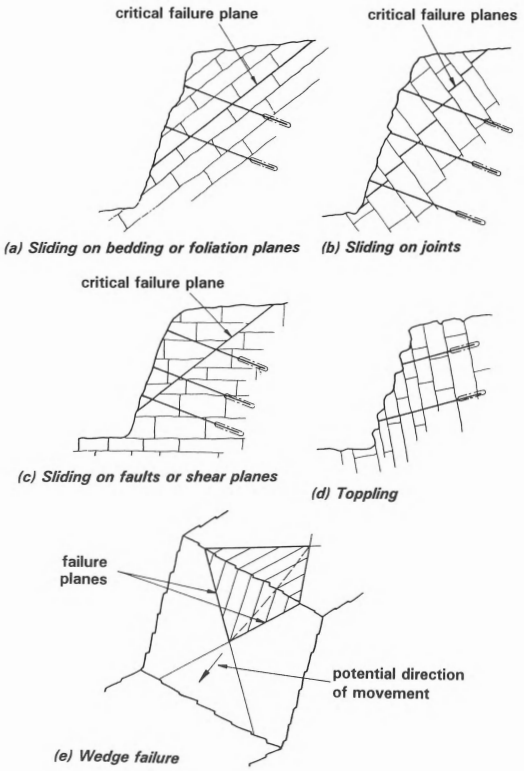


Figure 15.1 *Principal failure modes in rock slopes.*

Analysis of potentially unstable blocks or areas of a slope may be carried out by considering the forces acting on such features. However, overall slope stability will generally depend upon the strength and orientation of discontinuities and therefore it will be necessary to carry out a site investigation programme.

The extent of a site investigation will depend upon the risk associated with a potential slope failure. It is desirable to carry out a risk analysis in order to quantify this. A risk analysis technique for rock slopes was proposed by Daws and Elson (1989) who used the technique for categorizing the work schedule on cliff stabilization works at Dover. The system uses a series of parameters and assigns a numerical value to each one. The parameters are then combined to give a *risk value* which may be used to rank the importance of the work schedule. By the adoption of such a system, the user has to consider each situation in some detail and hence acquire a better feel for each section of slope.

Engineering judgement should not be abandoned in the application of such a scheme. On the contrary, the risk analysis should be used to complement engineering decisions regarding overall slope stability. Table 15.1 gives the parameters used in the risk analysis. The risk value is then given as follows:

$$Risk\ Value = (Hazard + Attachment) + Height + Potential\ Target + Vulnerability$$

Table 15.1 *Parameters for risk analysis*

HAZARD Description		Rating
Pinnacle/Slab /Block/Wedge	$<1\ m^3$	4
	$1–10\ m^3$	8
	$>10\ m^3$	10
Unstable scree	$<50\ m^3$	7
	$>50\ m^3$	10
Broken/ shattered rock	$<10\ m^2$	4
	$>10\ m^2$	6
Undercut walls, etc.	$<5\ m^3$	5
	$>5\ m^3$	7
Trees etc.		4

ATTACHMENT Description	Rating
Overhanging/undercut	+2
Open joints	+1
Closed joints	- 1

HEIGHT Height of Hazard	Rating
<5 m	2
5–20 m	4
20–50 m	8
50–75 m	9
>75 m	10

POTENTIAL TARGET Type of Feature	Rating
Hotel/school	50
Public place–regularly used	45
–infrequently used	30
Listed Building/sites–inhabited	35
–uninhabited	20
Houses	30
Roads	30
Warehouse/storage $< 2000\ ft^2$	10
$> 2000\ ft^2$	15
Garden shed, etc.	2

VULNERABILITY Proximity of Feature to Slope Toe	Rating
0–10 m	10
10–20 m	8
20–50 m	6
50 –100 m	4
100 –200 m	2
>200m	1

Risk Value = (Hazard + Attachment) + Height + Potential Target + Vulnerability

Schedules of work may then be prepared with priority being given to the higher risk values.

Geological data collection and presentation

It is extremely difficult to quantify how much data is required. It is not necessary to collect data on slopes which are stable, but stability can only be truly quantified after an analysis has been carried out. Data collection usually comprises two phases, desk studies and field studies.

Desk studies involve the collection of data from existing geological maps and memoirs. Air photographs, if available, can provide a useful source of data. Field studies involve the examination of outcrops or drill cores and the logging of joint orientations and conditions.

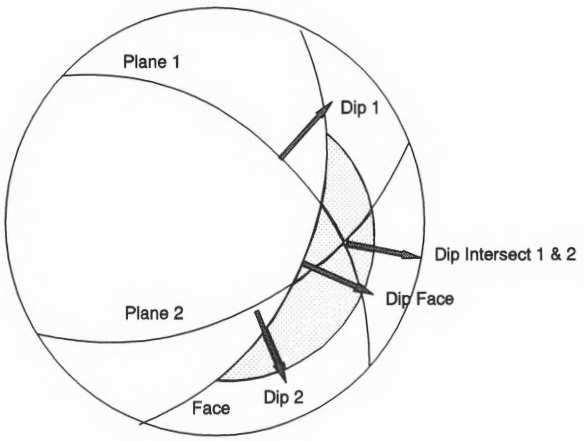


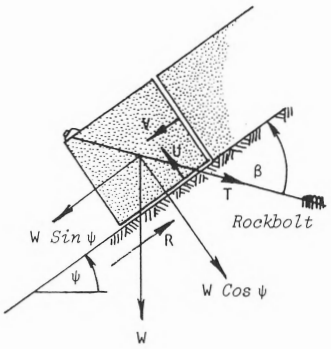
Figure 15.2 *A typical stereoplot, showing wedge failure along the intersect of joints 1 and 2.*

Presentation of the geological data in a form that can readily be understood is then essential. A graphical form known as a stereoplot is a convenient method which permits relatively easy use and interpretation. The equal area system is generally preferred (Hoek and Bray, 1981). In adapting this projection to structural geology, the traces of planes on the surface of a reference sphere are used to define the dips and dip directions of the planes. Imagine a reference sphere which is free to move in space but which is not free to rotate in any direction. Any radial line joining a point in the surface to the centre of the sphere will have a fixed direction in space. If this sphere is now moved so that its centre lies on the plane under consideration, the great circle which is traced out by the intersection of the plane and the sphere will define uniquely the inclination and orientation of the plane in space. Since the same information is given on both upper and lower parts of the sphere, only one of these need be used and in engineering applications, the lower reference hemisphere is used for the interpretation of geological data.

Full details concerning the construction of stereoplots are covered in Rock Slope Engineering (Hoek and Bray, 1981). An example of the use of a stereoplot is given in Figure 15.2. In this case a wedge failure would occur along the intersection of joint planes 1 and 2.

Remedial measures

When the type of failure has been identified, then remedial measures can be designed. The forces involved in stabilizing large blocks and wedges usually preclude the sole use of sprayed concrete for such applications. A simple stability analysis for a rock slope is given in Figure 15.3. This is for a plane failure and considers the effects of water in tension cracks. Drainage of rock slopes is considered essential and often this has to be combined with surface protection systems which prevent surface weathering. If reinforcement of a slope is required then anchor forces may be calculated and the anchoring system designed accordingly. The anchor forces are obtained by calculating the weight of the rock mass above the critical failure plane,



Factor of safety, F, is given by:

$$F = \frac{cA + (W\cos\varphi - U + T\sin\beta)\tan\phi}{W\sin\varphi + V - T\cos\beta}$$

Figure 15.3 *Simplistic plane failure analysis (after Hoek and Bray, 1991).*

multiplying by a suitable factor of safety and dividing by the number of anchors. Further information on rockbolts is given in Section 15.4. For long-term performance, corrosion protection is required. The requirements for corrosion protection of rockbolts and anchors are given in BS 8081 (1989).

The role of sprayed concrete

In rock stabilization, sprayed concrete is used for surface protection, the prevention of weathering and to provide structural support for individual features. In its role of providing surface protection and the prevention of weathering, the sprayed concrete helps to reduce rainwater penetration and prevent erosion of the base material. To achieve these functions, the following aspects of the surfacing material must be considered.

(i) Permeability
The lower the permeability of the surface protection, the greater will be its effect in minimizing infiltration. The effect of rigid surface protection in limiting infiltration can be assessed by measuring the change in degree of saturation before and after rainfall, which is dependent on the permeability of the surfacing material relative to the underlying soil or rock.

(ii) Durability
The effectiveness of the protection can be reduced considerably by cracking and spalling of the surfacing material due to temperature changes, wetting and drying effects or poor bonding of the protection to the underlying material. There is, however, very little information on the design lives of various types of rigid surfacing. Much depends on the thickness of surfacing as well as the type of material and quality of workmanship during construction.

(iii) Strength
The strength of the surfacing material is important in resisting erosion by running water. It also indirectly affects durability and permeability. This property is most commonly adopted in the material specification because it is easy to measure.

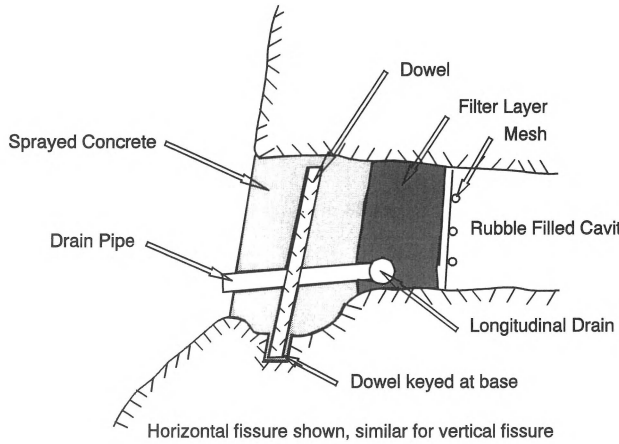


Figure 15.4 *Dentition for a horizontal fissure*

Large areas of rigid surfacing may have an unsightly effect on the surrounding scenery and consequently the use of such areas should be considered carefully. It may be necessary to colour the sprayed concrete to blend in more naturally with the surroundings (Daws and Elson, 1989). If colouring agents are used, then trial mixes should be made up and tested, particularly to assess the effects of the colouring agent on the strength of the sprayed concrete. A compromise in colour may be necessary if strength is significantly affected by a given colouring agent. If quantities are sufficient, it may be possible to obtain pre-coloured, bagged material from a manufacturer.

Often it is necessary to use rockbolts and mesh to stabilize an area before the application of the rigid surfacing. In this case, a wire rope is often tensioned between rockbolts at the top and bottom of a patch area and the mesh anchored securely to these ropes. Intermediate rockbolts secure the mesh across the patch area. Weep holes should be left in the patch at rock joints showing evidence of seepage. Even if the rock appears dry then one weep pipe per 10 m^2 of surface should be considered.

Where defined rock joints are exposed and show signs of weathering and erosion, then dentition should be considered. A typical dentition system is shown in Figure 15.4 which shows dentition for a horizontal fissure. Dentition for a vertical fissure is similar but uses bolts in each wall of the fissure. It is important to provide a drainage system so that water pressure does not build up behind the sprayed concrete protection. This drainage system should be prevented from blocking by the use of a filter layer. Structural support to individual features such as overhanging blocks can readily be achieved by the use of sprayed concrete. It is possible to create buttresses under overhanginging blocks (*see* Figure 15.5) and it may be necessary to provide temporary support to the block whilst work is in progress. This may often be achieved by the use of wire rope slings which are anchored with rockbolts and tensioned by means of a turn buckle. These are sometimes sprayed in as a permanent feature.

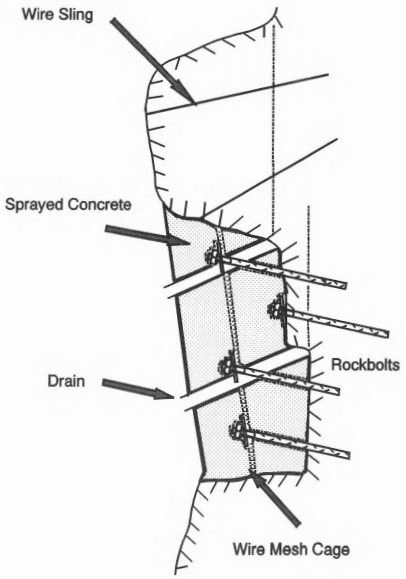


Figure 15.5 *Typical sprayed concrete buttress formed under overhanging block.*

Application of sprayed concrete

It is often necessary to spray small quantities of material over an irregular time span. In such cases the dry process is favoured as it offers the required flexibility. If it is possible to apply large areas at any given time then the wet system may offer sufficient economies and should be considered.

Access to the slope can prove to be the most costly part of a project. If scaffolding is required, this may represent a large proportion of the contract price. Scaffolding can also make spraying extremely difficult. It is recommended that top access methods be considered as a cost effective alternative to scaffolding. Three methods of top access are generally used:

(i) Cradle – supported by lightweight A-frames and powered by small winch motors or Sky Climbers. Hand-operated versions are also available.

(ii) Bosun's Chair – supported individually or in pairs from an A-frame and powered by Sky Climbers.

(iii) Abseil – twin 10 mm ropes used by specialist companies. Usually proves to be the most cost-effective and versatile system.

In these top-access methods, it is necessary to make a coil with the delivery hose at the top of the rock slope in order to reduce surge in the line. Spraying pressures may also have to be increased in order to counteract the effects of gravity in the delivery line.

When using top-access methods, it is often difficult to stand the ideal distance away from the work when spraying. Allowance should be made for this when assessing the possible rebound quantities and choosing spraying pressures. Similarly, it is difficult to return to areas after spraying and consequently any curing should be

achieved by the use of sprayed membranes applied immediately after the final application of sprayed concrete.

Performance monitoring

It is often desirable to monitor the long-term stability of a slope which has been subjected to remedial measures. The type of instrumentation used would be chosen for each individual case but it may be desirable to measure the following parameters:

(i) ground water levels and pore pressures;
(ii) surface movements;
(iii) subsurface movements;
(iv) rock anchor loads, and
(v) ground pressures.

Remote reading instrumentation is often desirable due to the access difficulties associated with rock slopes.

The stability of the sprayed concrete should be determined before application and test panels should be sprayed by the nozzlemen who will work on the contract. Materials testing should follow the recommendations given in Chapters 5 and 6. If cores are taken from applied material then the core holes should be filled with a non-shrink mortar unless the hole is to fulfil the role of a weep hole.

Typical costings

Although guidelines are given here, the application costs will depend very much on individual cases. It is assumed that some form of access is required to the rock slope and that the slope height is 25–50 m. The cost of spraying a 100 mm layer under normal access conditions, i.e. at ground level is assumed to be 100 units per m^2.

Cost of spraying 100 mm on a rock slope: 200–300 units per m^2.
Cost of spraying 200 mm on a rock slope: 250–350 units per m^2.
Cost of dentition – approximately 300 mm wide: 150–250 units per m.

Due to the potential for high rebound losses, the payment for work on rock slopes should be on a measured area at a specified thickness. Variations should be agreed with the Engineer on site at the time of application. It is often necessary to modify the area required to be sprayed as de-scaling reveals the true extent of loose or weathered areas.

15.3 Underground support

When applied to a rock surface, sprayed concrete is forced into fissures and open joints and helps to bond such features together in a similar way to mortar in a wall. It also helps prevent water ingress and this property alone may have a significant advantage in tunnelling. The sprayed concrete layer then protects the rock against deterioration by water and air.

Design of sprayed concrete

A thin layer of sprayed concrete has a considerable capacity to prevent rock movement. Figure 15.6 shows a pyramid of rock in the roof of a tunnel which is isolated

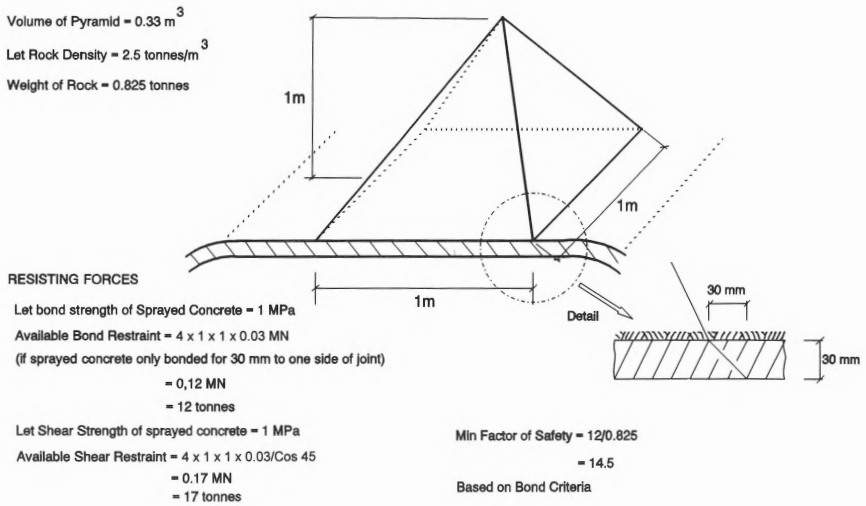


Figure 15.6 *Rock support in a tunnel with sprayed concrete.*

by a jointing system. Without support, the block would fall. Movement of the block is prevented by a combination of bond strength and shear strength of the sprayed concrete in the immediate vicinity of the joints. The block is restrained with a factor of safety of approximately 14 (*see* Figure 15.6).

Usually, the sprayed concrete also acts to form an arch and in this case the theory of thin walled cylinders can be used to determine lining thickness. The following expression is used (Barton *et al.*, 1974).

$$t = PR/\sigma c$$

where t = lining thickness (mm)
P = externally applied pressure (MPa)
R = internal radius of tunnel (mm)
σc = compressive strength of sprayed concrete (MPa)

Extensive work has been carried out at the Norwegian Geotechnical Institute (NGI) on the correlation betwen rock quality and tunnel support systems. This work has led to the publication of design charts which relate tunnelling quality, Q, to a rockbolt and sprayed concrete support system (*see* Chapter 8). The main chart is given in Figure 15.7 (see also Figure 8.7).

Steel fibre reinforcement is used extensively in Scandinavia in conjunction with the wet system of spraying. The choice of system, wet or dry, depends upon many factors and Table 15.2 compares the two systems. Mix design for sprayed concrete is a complex process and due regard must be given to the amount of rebound losses experienced. This will change the proportion of the materials left in situ. The following criteria must be satisfied:

(i) Shootability – the mix must be able to be placed overhead with minimum rebound.

Table 15.2 *Comparison of dry and wet process sprayed concrete*

Factor	Dry mix	Wet mix
machinery	Lower total expenditure. Conveyance by compressed air (low efficiency). Maintenance relatively simple and infrequent.	Less machinery at work site. Diesel or electric power more efficient than compressed air. Less wear rate in pump, hoses and nozzles. 60% less air consumed.
mixing	At work site. Pre-mixed, dry ingredients can be used but cannot be left open in humid or wet environments. Performance impaired by wet sand.	Accurate mixing remote from work site. Multiple handling avoided. Can use bulk ready mix. Wet sand acceptable.
output	Rarely exceeds 5 m^3h^{-1} in place. Can be conveyed over longer distances than wet mixes, maximum 400 m horizontally and 100 m in elevation. 50–100 m normal.	Higher than similar dry mix machines; 2–10 m^3h^{-1} with hand-held nozzle. Up to 18 m^3h^{-1} when boom mounted.
rebound	Can be 15–40% from vertical walls, 20–50% from overhead. Forms rebound pockets. Loss of aggregate makes compliance with mix specification difficult, and excess cement is usually added.	Low rebound with correct mix, can be less than 10%. Little loss of aggregate. Rebound pockets do not occur.
impact velocity	Higher - better adhesion; easier to use overhead.	Generally adequate for tunnel/ mine work.
addition of reagents	Powders in mixer or gun. Liquids at nozzle.	Generally as liquid.
dust	Suppression additives, pre-wetting with 5–15% moisture or 'semi-wet' methods can reduce dust formed.	Very little dust formed: can be one sixth that from dry-mix spraying. Better visibility. No danger of lamination by dust.
versatility	Can be used for sand blasting, guniting, refractory materials, repairs, resurfacing.	Can be used as concrete pump for pouring in place.

(ii) Early strength – the mix must be strong enough to provide support to the ground at ages of a few hours.
(iii) Long term strength – the mix must achieve a specified 28 day strength with the dosage of accelerator needed to achieve the required shootability and early strength.

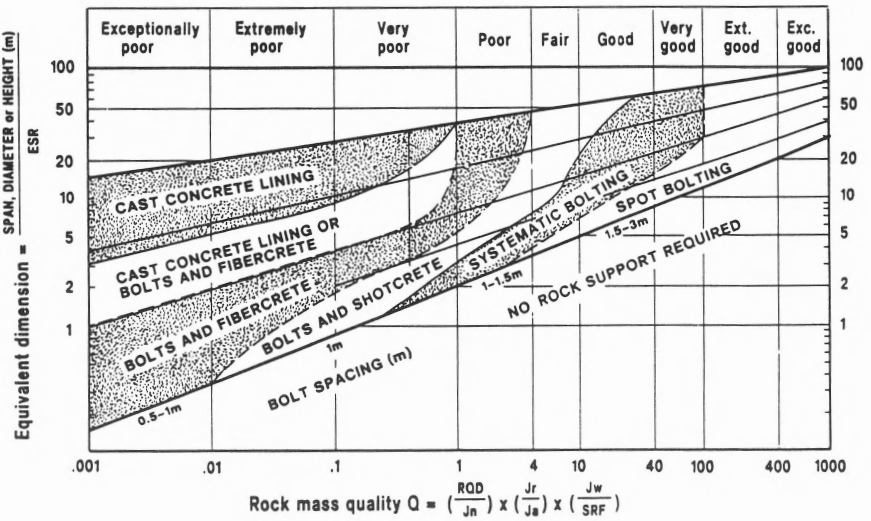


Figure 15.7 *Q-system chart (after Barton et al., 1974).*

(iv) Durability – adequate long-term resistance to the environment must be achieved.

(v) Economy – low cost materials must be used and there must be minimum losses due to rebound.

The quality of placed sprayed concrete depends upon the materials used and the mix design, but it is also heavily dependent upon the method of placement. The skill of the nozzleman in preparing the surface, controlling the delivery rate and thickness and, in the dry process, the water/cement ratio, has a significant influence on the final product.

Application of sprayed concrete

Preparation of the surface to be sprayed is an essential part of the operation. Effective scaling is important for the safety of the operators and also to reduce the chances of ineffective sprayed concrete caused by spraying onto loose rock. If the rock is very poor then scaling may not be possible and the sprayed concrete may have to be applied as quickly as possible to provide some support. In this case, a second sprayed concrete layer should be applied which can be reinforced by weldmesh or preferably fibre-reinforced sprayed concrete should be applied.

Surfaces to be sprayed should be free of all loose material and dust from blasting. This may be achieved by washing the surface with an air/water mixture using the spraying machine, or high pressure water jetting. Once the surfaces have been cleaned then spraying can commence. The optimum distance between the nozzle and the surface being sprayed is approximately 1 metre. The amount of rebound is significantly influenced by this distance and the angle of the nozzle to the surface. Every attempt should be made to keep the nozzle at 90° to the surface being sprayed. (See Chapter 4 on Production and Installation, Section 4.4)

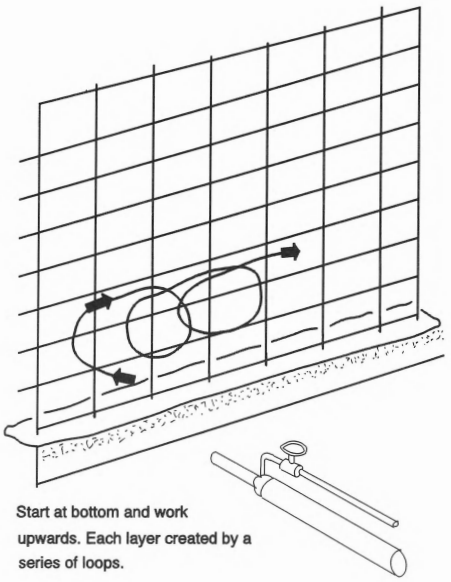


Figure 15.8 *Application technique for sprayed concrete.*

The nozzle must be kept moving in a controlled path whilst delivering the sprayed concrete. Failure to keep the nozzle moving results in sprayed concrete of non-uniform compaction and thickness. When using a hand held nozzle, the sprayed concrete should be applied by moving the nozzle in a continuous series of overlapping circular or elliptical loops (Figure 15.8) which should be approximately 500 mm long and 200 mm high. The advance between loops should be roughly 100 mm. When spraying onto mesh, care should be taken that rebound is not trapped behind the wires. In larger tunnelling applications and particularly when using wet process sprayed concrete, robotic spraying equipment should be used.

The thickness of a sprayed concrete layer is generally estimated from the volume of material placed with an allowance for losses due to rebound. When spraying very irregular surfaces it is almost impossible to achieve a uniform thickness and it is often necessary to apply more sprayed concrete than originally envisaged in order to ensure that the minimum thickness is achieved over the whole rock surface.

15.4 Rockbolting systems

Fully grouted rockbolts are active supports in that they change the ground characteristic line at the point of installation. Figure 15.9 *(upper)* shows the load transfer mechanism from the ground to a fully grouted rockbolt. As bed separation occurs and the surrounding rock dilates then the rockbolt is loaded and the subsequent resisting force is transferred back into the ground via the elastic properties of the resin. An adequate bond stress value is required at the resin/rock interface in order to ensure that the rockbolt does not slip during this process. However, a high value

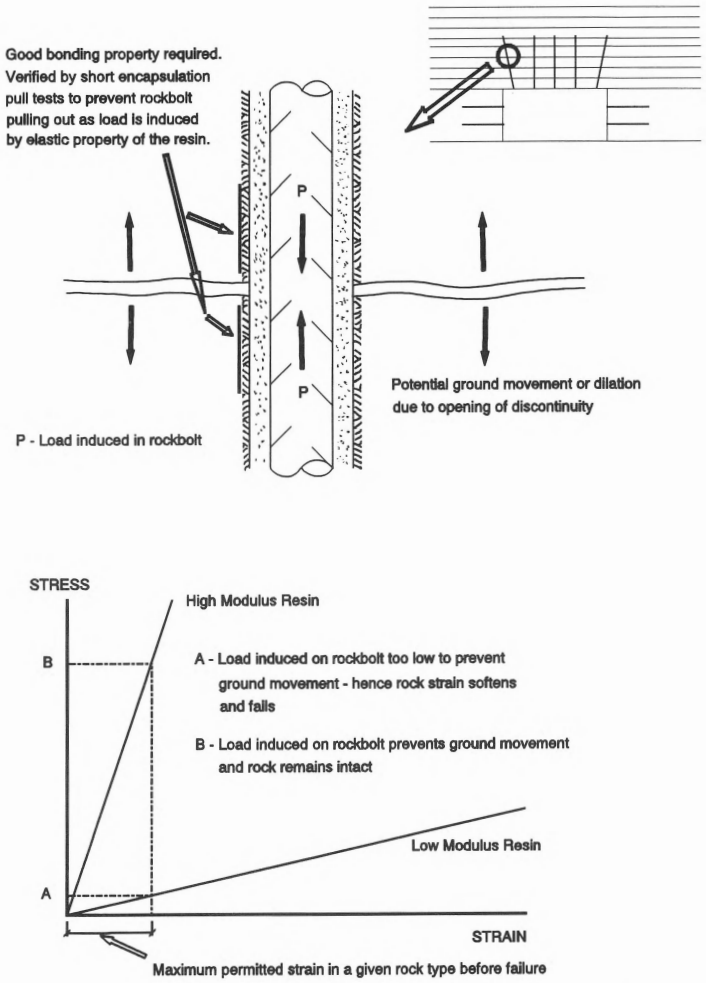


Figure 15.9 *Rockbolt load transfer mechanism: upper-mechanism; lower-influence of resin on elastic modulus.*

for bond stress alone, given by short encapsulation pull testing, does not give an indication of the efficiency of the complete rockbolt installation. Figure 15.9 *(lower)* shows that if the elastic modulus of the resin is low, then it is possible for the ground to exceed its maximum permissible failure strain without inducing sufficient load in the rockbolt to resist this movement. This would then lead to loosening of the rock mass and a reduction in its load-carrying capacity and this must not be permitted to occur.

It is common practice to use non-tensioned bolts in systematic bolting systems used in the tunnelling industry. If active wedges of rock are predicted, then tensioned bolts may be used to give positive restraint as required. Long-term corrosion protection is achieved either by the use of stainless steel or a double corrosion protec-

tion system as specified in BS8081 (1989). Fibreglass rockbolts have recently been used in the Vereina tunnel in Switzerland. Shorter term corrosion protection may be achieved by the use of galvanizing or sherardizing.

When resin anchored rockbolts are used in the mining industry it is common practice to use fast and slow set capsules and apply some tension to the bolt. Although this tension is low (generally about 2 to 3 tonnes) it has the effect of putting a proof load onto the fast set bonded length in order to assess its suitability for further loading.

The effectiveness of a resin anchored rockbolt is governed by the following factors:

(i) the basic parameters e.g., hole/bolt/capsule diameter relationship;
(ii) strength of the bolt;
(iii) properties of the resin – particularly modulus;
(iv) bond stress at rock/resin interface;
(v) mechanical key at rock/resin interface;
(vi) bond stress at bolt/resin interface; and
(vii) mechanical key at bolt/resin interface.

Some of these parameters are discussed further below.

Basic parameters

The basic parameters of the resin rockbolting system must be established at the outset. The important parameters are the borehole diameter and resin capsule diameter in relationship to the bolt diameter. The bolt diameter is chosen when the required load is known. The borehole diameter should then be 7 to 12 mm greater than the nominal bolt diameter in order to limit the annular thickness of resin. It should be noted that the distance across the ribs on a rebar bolt must be considered when choosing the borehole diameter. The above guideline takes this into account.

The resin capsule diameter should be the same as the bolt diameter. The capsule diameter is critical as it governs the available volume of resin for a given length. The capsule diameter is also critical from an installation viewpoint. If the diameter is too small or the borehole is too large for a given bolt diameter then the bolt can force its way past the capsule without fully breaking and mixing it. The capsule then becomes wrapped around the bolt during installation. This is known as cording. If the capsule diameter is considerably larger than the bolt diameter, then the bolt can penetrate the capsule and mix its contents without puncturing the outer skin. This is known as the 'finger in glove' effect.

From the above discussion, it is evident that the basic parameters must be established at the outset of a project and regular checks made to ensure that they are maintained. Attention to detail is important. In particular, hole diameters must be maintained otherwise large inconsistencies will develop in the extent of the bonded length. A constant volume of resin is available with a capsule system and changes in borehole diameter will significantly affect the bonded length.

Bolt/resin interface

The mechanical key and bond stress at this interface can be enhanced by ensuring that the bolt is kept clean and free of deleterious matter before being inserted into

the borehole. The rib size and spacing of the rockbolt will influence the mechanical key. It has been found that limits exist and the ribs should not be too large otherwise other problems are created, the major one being the necessity to increase borehole diameter and hence the creation of a larger annulus of resin between the borehole wall and the core of the rockbolt.

Rock/resin interface

The mechanical key is generally a function of the type of drilling and style of bit employed. It has been found that the degree of flushing also has an effect on the mechanical key. At Asfordby mine in the U.K. holes were drilled using a Fletcher machine equipped with vacuum dust-extraction drilling equipment. It was found that small traces of rock powder left in the rifling of the borehole was sufficient to give a poor value of apparent bond stress at the rock/resin interface. If the hole was flushed with water after drilling then a significant increase in the effective bond stress was obtained. In reality, the mechanical key effect had been improved and the resin was able to bond to the rock surface rather than rock powder.

The effective bond stress at the rock/resin interface is the critical element in the anchorage efficiency of a rockbolt system. This value can be obtained from a series of short encapsulation pull tests. Once a good value has been obtained for this bond stress, the modulus of the resin can be mobilized in order to produce an effective rockbolt system.

Pull testing

The anchorage efficiency of a rockbolt can be assessed by pull testing. In order to gain useful information, it is necessary to carry out tests whereby a failure is induced at the anchorage zone. A test where rupture of the rockbolt steel occurs gives very little information. Consequently, the only tests that give meaningful results and which can be used to assess different resins, different rockbolts, different drilling techniques etc., are short encapsulation pull tests. The procedure for such tests is given in Appendix 1.

In order for the load transfer mechanism (*see* Figure 15.9) to be effective, the rockbolt should not slip in the borehole during this action. Effective bond stress (which may be a combination of actual bond stress and a mechanical key) at the rock/resin interface is therefore of critical interest. From a combination of practical experience in mining and civil engineering applications and laboratory testing, it has been established that a value of 5 MPa is required for the effective bond stress at the rock/resin interface.

Short encapsulation tests should be carried out at intervals along the borehole to ensure that this value is attained along the length of the hole. If the hole is situated within the same geological unit, then a minimum of two locations (in the fast and slow set zones) should be used. Otherwise a test should be carried out in each geological unit encountered.

Design of the resin anchoring system

When the initial design of a rockbolting system is carried out, the rockbolt/borehole/resin capsule configuration is chosen to give the optimum combination with regard

to commercially available equipment. Drilling tests are often carried out in order to measure the actual diameter of a borehole in the given strata conditions. The volume of resin required for full encapsulation is then calculated as follows:

$$V = \pi/4\,(D_2^2 - D_1^2)L$$

where V = required volume (ml)
D_1 = rockbolt effective diameter (cm)
D_2 = measured borehole diameter (cm)
L = required bond length (cm)

The proportion of fast to slow set resin is then determined. In general, the minimum dimension of the fast set bond length is given as follows:

$$L = U/d\,\pi\,\sigma b$$

where L = minimum bond length (mm)
U = yield load of rockbolt (N)
d = measured borehole diameter (mm)
σb = bond stress at rock/resin interface (N/mm^2) usually taken as 5 N/mm^2

A safety factor of approximately 1.5 may be applied to this length if required.

In the tunnelling industry, it is common practice to use a cementitious grout to bond the rockbolts. All the previous performance criteria concerning the use of resin applies to cement grouts. The grout may be site mixed or obtained in prebagged form. The latter eases quality problems on site.

Design of the rockbolting pattern

Two systems of design are generally used and there are empirical systems and theoretical systems. The empirical systems include the rock mass classification systems and the theoretical system uses the rock mass confinement approach. For the final design, it is recommended that the conservative parameters from each of the systems is used and the support system monitored and modified as required.

(a) Rock mass classification system

Two major rock mass classification systems are in use and these are:

(i) The Norwegian Geotechnical Institute (NGI) Q-System
(ii) The Geomechanics System (Bieniawski, 1984)

Of the two systems, the Q-System gives the best guidelines for the determination of rockbolting patterns. The support chart for the Q-System is illustrated in Figure 15.7. From this chart, rockbolt spacing for a given rock quality and span of excavation may be determined. The following expressions are used to determine rockbolt length, L.

$$L = 2 + 0.15\ \text{span/ESR (m)}$$

where L = rockbolt length (m)
ESR = excavation support ratio, which is taken as 1.3 to 1.6 for a permanent mine opening.

This expression does not allow for bolts of less than 2 m to be used.

(b) Other empirical systems

The best known set of empirical design rules are those developed by Lang (1961) for

the Snowy Mountains hydroelectric scheme in Australia. These rules are widely used for determining bolt lengths and spacings for permanent excavations. Lang gives the minimum bolt length, L, as the greatest of :

(i) Twice the bolt spacing, S,

(ii) Three times the width of potentially unstable rock blocks defined by the average discontinuity spacing, b,

(iii) $0.5B$, the tunnel span, for spans < 6 m; $0.25B$ for spans of $B = 18$–30 m.

For excavations higher than 18 m the lengths of the sidewall bolts should be at least one fifth the wall height.

The maximum bolt spacing, S, is given as the least of $0.5L$ and $1.5b$. When mesh is used, a bolt spacing of more than 2 m makes attachment of the mesh difficult, if not impossible.

(c) Theoretical systems

Numerical modelling is now being used to a larger extent to help define the bolting parameters. However, a quick determination of the bolting parameters can be made by the use of the rock mass confinement approach.

In systematic rockbolting, the rockbolts increase the confinement of the rock in the reinforced roof beam and produce a triaxial stress state. Using the confinement approach, it can be shown (Daws, 1991) that

$$P = q\,U\,t/S^2$$

where P = load to be taken by the rockbolts (tonnes/m)
U = yield load of rockbolts (tonnes)
t = thickness of reinforced roof beam (m)
S = rockbolt spacing (m)
$q = \tan^2(45 + \theta/2)$

The angle of friction, θ, is obtained from the output of the geomechanics rock mass classification system. Thickness of the reinforced roof beam, t, is taken either as the length of bolt bonded by the slow set resin capsules, or given by the expression $L - S$ where L is the rockbolt length.

The load, P, to be carried by the rockbolts is taken as either the weight of rock in a potential loosened zone or can be related to the actual geology by using some output from the geomechanics rock mass classification system. If using the latter method the load is given as:

$$P = Ht\,B\,\gamma \text{ (tonnes/m)}$$

where $Ht = (100 - \text{RMR})B/100$
and RMR = rock mass ratio
B = span (m)
γ = rock density (tonnes/m^3)

A factor of safety may be added to this loading as required.

References

Barton, N., Lien, R. and Lune, J. (1974) *Analysis of Rock Mass Quality and Support Practice in Tunnelling and a Guide for Estimating Support Requirements.* Norwegian Geotechnical Institute, Report No. 54206.

Bieniawski, Z.T. (1984) *Rock Mechanics Design in Mining and Tunnelling.* A.A. Balkema, Rotterdam.

British Standards Institution (1989) *Code of Practice for Ground Anchorages*. BS 8081. BSI, London.
Daws, G. and Elson, R.J. (1989) Cliff Stabilisation Works – East Cliff, Dover. *Proceedings International Chalk Symposium, Brighton*. Thomas Telford, London.
Daws, G. (1991) The Use of the Geomechanics Rock Mass Classification System in the Design of Coal Mine Roofbolting Systems. *Nottingham University Mining Magazine*, vol. XLIII.
Hoek, E. and Bray, J.W. (1981) *Rock Slope Engineering*. Institution of Mining and Metallurgy.
Lang, T.A. (1961) Theory and Practice of Rockbolting, *Trans. Soc. Ming. Engrs. Am. Inst. Min. Metall. & Petroleum Engineers*, **220**, 333–348.

Appendix 15.1

TEST PROCEDURE TO INVESTIGATE THE EFFECTIVENESS OF RESIN ANCHORED ROCKBOLTS

1 Introduction

In order to investigate the effectiveness of resin anchored rockbolts, it is necessary to carry out short encapsulation pull tests. These tests are designed to fail the bond between the resin and the rock at the borehole wall. The short encapsulation length is situated in distinct geological zones along a borehole length. If the geology does not vary significantly along a borehole, then tests are carried out in the fast and slow set bonded lengths. At least two tests are required per borehole. The results from the tests allow the limiting bond stress at the resin/rock interface to be calculated. If this bond stress is less than 5 MPa then changes to the rockbolting system will be necessary. These changes may be operational, concern materials usage or involve system design.

2 Test procedure

The same combination of borehole diameter, rockbolt diameter and resin capsule diameter as the production rockbolt system should be used for the tests. However, it will be necessary to produce a capsule of the required length on site as described below. The rockbolt should be cut to such a length to allow a sufficient amount to protrude from the borehole to accommodate the testing jack. Figure 15.A1 shows the general arrangement. The test procedure is be as follows:

(i) Drill the borehole to the required depth and flush it out using the same drilling technique as employed for the production rockbolts.
(ii) Measure the borehole diameter at the bottom of the hole using a borehole micrometer.
(iii) Calculate the volume of resin required to fill the annulus between rockbolt and borehole wall to give a bonded length of 300 mm. Calculate the length of a resin capsule of the production diameter used to give this volume. Section 4 gives the details of this calculation.
(iv) Take a production resin capsule and measure the length calculated in (iii) from one end. Mark this point. Twist the resin capsule at this mark until it is closed off at this point. Tie this node with soft wire or similar to prevent the

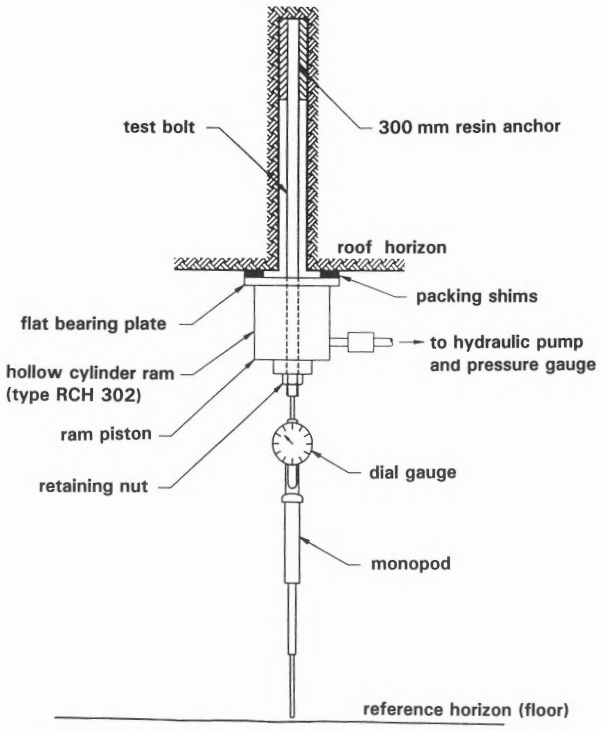


Figure 15A.1 *Short encapsulation pull test set-up.*

capsule returning to its original form. Cut the capsule to form a new capsule of the length required for the test.

(v) Insert the new capsule to the back of the borehole and spin the rockbolt in with the insertion drill. Allow the resin to cure.

(vi) Repeat the above procedure for the number of tests required at a given site.

(vii) Instal the testing jack onto the bolt and increase the load in increments of one tonne. Take extension readings at each load increment. These extension readings should measure the true movement of the rockbolt. Continue loading until failure occurs and the bolt slips. Plot the load/extension curve for the test.

(viii) Calculate the limiting bond stress at failure along the resin/borehole interface. Section 4 gives details of the calculation. If this bond stress is greater than 5 MPa then the system is satisfactory. If not, then a reassessment of the bolting system is required.

3 Common problems

Some of the common problems are listed below. If the remedies fail to enhance the bond stress then a complete reassessment of the bolting system is required.

Hole cleanliness Hole flushing not sufficient. Need to modify flushing procedure.

Insertion technique Rotation speed may not be sufficient to fully mix resin components in the capsule. Rockbolt may be spun for too long resulting in overmixing of the resin.

System design Combination of rockbolt, borehole, capsule diameters incorrect, resulting in annular space being too large for resin. This can result in poor mixing of the resin, or if mixed reasonably well then shrinkage effects influence performance.

4 Calculations

(a) REQUIRED RESIN VOLUME

Let D_1 = nominal diameter of rockbolt (cm)

D_2 = measured borehole diameter (cm)

For a 300 mm bonded length, then the required volume, V, is given as follows:

$$V = \pi (D_2^2 - D_1^2).30/4 \text{ (ml)}$$

(b) REQUIRED RESIN CAPSULE LENGTH

In order to produce a 300 mm bonded length, a volume of resin, V, as above is required. The capsule, length, l, required to obtain this is given as follows:

$$l = 4V/\pi D^2 \text{ (cm)}$$

where D = capsule diameter (cm)

(c) BOND STRESS

After carrying out the test, the bond stress, σb, at the resin/rock interface is given as follows:

$$\sigma b = P/\pi D_2 L \text{ (N/mm}^2\text{)}$$

where P = failure load (N)

and L = bond length (mm), which for this test should be 300 mm.

16 Shotcrete for Rock Support

Tom Melbye, MBT-Holding, Switzerland with Ole Arnfinn Opsahl and John Holtmon, A/S Veidekke

16.1 Introduction

A well-known fact about the construction industry – and underground construction in particular – is that all projects are unique. Projects are highly complex due to the interaction of various parameters and this forces contractors and suppliers to be truly adaptable and flexible.

Shotcrete has become a very important and necessary tool for modern underground construction works due to its enormous advantages as a construction and rock support process. In particular the development of modern wet shotcreting has enlarged the scope of underground construction work. Projects that once were impossible have now become practicable. Subsurface structures can be placed where they are needed, without regard to rock and soil conditions. Shotcrete is not a new invention. Sprayed concrete (mortar) has been used for more than eighty years.The first shotcrete jobs were undertaken as early as 1907 in the United States by the Cement-Gun Company, Allentown. Today there are two shotcreting methods, dry-mix and wet-mix. In the dry-mix procedure, the dry mixture of cement and aggregates is conveyed from the machine through the hoses by compressed air, and the water needed for the hydration is added at the nozzle.

The wet-mix method was first used after the second world-war. Similar to ordinary concrete, the mixes are prepared with all necessary water for hydration before being pumped by suitable machines through the hoses to the nozzle where compressed air is added for spraying. The equipment for dry-mix and wet-mix shotcrete is discussed in Chapters 4 and 9.

Shotcrete solves problems of stability in tunnels and other underground constructions and more than 90% of all shotcrete is used for rock support. It is a key factor for rock support in tunnelling, mining operations, hydropower projects and slope stabilization. The development of equipment and control has led to a rational production and a more uniform product quality. The industry has advanced significantly from when shotcrete was used merely for securing rock.

Dry spraying has been the dominant method, but changes are imminent, especially in the use of shotcrete for rock support. It is likely that wet spraying will become more popular as this method provides a better working environment, consistently higher quality and a much higher rate of production. Future developments within shotcrete technology are likely to be mainly in connection with the wet-mix process. Good examples of recent developments are new generations of additives (Delvocrete, MEYCO TCC, internal curing, silica fume and steel fibres).

Fifty-five per cent of shotcreting worldwide is done by the wet-mix method. In some areas, however, the wet-mix method is almost totally dominant (Scandinavia and Italy where it is almost 100%). Within the next five years the wet-mix method could be used for more than 70-80% of all shotcrete worldwide. Today more than 8 million cubic metres of shotcrete are applied yearly world-wide.

16.2 Dry-mix method

Composition of a dry mix

Cement content

The proportion of the binder in the dry mix is usually between 250 and 450 kg per 1000 litres of aggregate or 320 to 460 kg per m^3 of concrete. In order to judge the actual cement content of the shotcrete applied, the rebound must be considered. In comparison with the initial mix, rebound leads to a loss of the larger aggregate and thus to an increase in the cement content. In a typical standard mix with 350 kg of cement per m^3, a rebound of 20% finally results in approximately 400 kg of cement per m^3 of placed shotcrete.

Admixtures

Various admixtures are available for controlling shotcrete properties. The most important are fast setting admixtures (accelerators). These reduce the setting time. The shotcrete sets more quickly and early strength is increased. This allows subsequent layers of shotcrete to be applied sooner and in greater thicknesses.

On large-scale underground construction projects, accelerators help to increase productivity and are an important prerequesite for many applications. In underground construction works and pit curbing, for instance, the early strength of the shotcrete is decisive and an essential requirement. Accelerating the cement hydration inevitably results in a reduction of the 28-day strengths. In order that the shotcrete quality is consistently high, it is essential to ensure that the lowest possible quantity of accelerator is added. The proportion of accelerator must be determined in each case in relation to the amount of cement used.

Accelerators can be used in powder or liquid form. Powder accelerators are added while feeding the shotcrete machine. Unfortunately it is impossible to guarantee exact proportioning when powder is added manually (still a widespread practice). The usual result is a massive overdose, spread very unevenly. Various studies have demonstrated a reduction of 35% and more in the final strength compared to base concrete, i.e. that without accelerator. Manual dosing can therefore only be accepted in exceptional cases or for shotcrete applications where quality requirements are low.

Greater precision is obtained with feeding devices combined with powder dosing appliances. The best results are achieved with screw feeds equipped with a spindle batcher. Conveyor belt feeders are not recommended. A convenient solution to the problem of proportioning powder accelerators is, of course, to use suitably modified bagged materials. However, these are often out of the question for financial reasons, especially in large projects.

The best way of ensuring the precise dosage of accelerator during application is

to use liquid products. These are measured into the mixing water and thus added to the dry material at the nozzle. To obtain a steady dosage, however, it is essential to use a suitable dosing system even with liquid accelerators. Machines where it is necessary to pre-mix water and accelerator are only suitable up to a point. Since the water/accelerator ratio is fixed, the dosage is altered in relation to the weight of the cement every time the water addition is adjusted by the nozzle man. However, it is both necessary and important to adjust the water quantity, for instance in order to respond to variations in the natural moisture of the aggregate or in the behaviour of the water flow on the surface.

A consistent cement/accelerator ratio can be ensured by using piston pumps, which measure a constant amount of the admixture defined in proportion to the capacity of the shotcrete machine and quite independently of the water flow setting. A further advantage of liquid accelerators over their dry equivalents is that caustic components in the dust are avoided. Dosing at the nozzle prevents flash set and due to the even mix with the spraying material, liquid accelerators can be measured more economically, which also leads to better early strengths. Experience shows that, compared to base concrete, the loss of final strength can be reduced to less than 25%.

The only other admixtures used in the dry spraying process are dust binders, which reduce dust formation. In practice, however, these agents have achieved only limited acceptance.

Additives

Unlike chemical admixtures, the action of additives is mainly physical. Well-known examples are mineral fillers, such as silica fume, which are becoming more important. These fine substances (surface of 20–35 m^2/g) contain 65–97% SiO_2 and depending upon the quality of the product, lead to an important improvement in the quality of the shotcrete, apparent in the increased compressive strength and density. Due to the improved bonding, thicker layers can be sprayed even without accelerators.

Added in the proper way in the dry-mix method, silica fume has the further effect of reducing rebound by up to 50%. With normal (uncompacted or densified) silica fume added in the mixer the rebound reduction is only minimal. Elkem has developed a special technology for adding a 50% slurry at the nozzle (dosed in the water). The slurry system is very efficient but rather complicated. It needs a special dosing pump (MEYCO Mix 100 is possible) and an additional product on site in quite large quantities. The slurry has to be stored correctly and in most cases an agitator is necessary.

Fibres

Steel and synthetic fibres can be used in shotcrete. Their chief virtue lies in the fact that they lead to an improved fracture energy and/or shrinkage behaviour of the shotcrete. The use of steel fibres is still relatively rare in dry-mix compared to wet-mix shotcrete. The main reason is the higher rebound and because of this the cost/performance factor becomes critical. However, the use of steel fibres in the dry-mix method is expected to rise due to the experience gained over the past few years and the present possibilities of reducing rebound.

On-site mixes versus bagged materials

As already mentioned, the dry process allows the use of mixes with earth-dry or kiln-dried aggregates. Earth-dry aggregates are cheap and produce less dust. The natural moisture content is nevertheless sufficient to trigger premature hydration. For this reason, earth-dry mixes have a limited storage life and should be used up within an hour ot two. Storage for a longer time causes an enormous increase in rebound and a large drop in final strength.

The manufacture of the dry mix on site entails the installation of the necessary batching and feeding plants. Such an installation is obviously only worthwhile for large-scale projects. On a smaller scale or for short-term shotcrete projects the dry mix can be obtained from a ready-mix plant. Delivery and placing must be very carefully scheduled in order to avoid delays and interruptions in the work due to inadequate supplies.

Of course, the greatest degree of flexibility is afforded by dry materials that are delivered in bags or silos. These can be stored over a long period of time, thus simplifying planning. Furthermore, they are of consistently high quality. Disadvantages include the increased tendency to dust formation (which can be controlled by pre-wetting) and the considerably higher price.

The development of hydration control systems such as Delvocrete has made it possible to prolong the storage life of earth-dry mixes. By adding the Delvocrete stabilizer during manufacturing, the mix remains fresh and unchanged. The liquid Delvocrete Activator S is added at the moment of application. It simultaneously reactivates the cement hydration and acts as an accelerator. The activator is added like a conventional liquid accelerator, thus technique and equipment need not be changed. With the Delvocrete Hydration Control System dry mixes can be stored for up to three days. This in turn means adequate flexibility in relation to bagged materials, but at considerably lower cost

Problem areas in the dry shotcrete process

Every process naturally has its drawbacks. With the dry shotcrete process, one of these is the relatively high costs due to wear and tear on the rotor machines (Figure 16.1), the rubber gaskets and friction discs being the main culprits. These costs can be kept within reasonable limits through setting up the machines correctly, changing the parts in time and skilled grinding. Another disadvantage is the formation of dust. However, this can be reduced considerably by ensuring a favourable natural moisture content (or adequate pre-wetting) and by using dust binders. Water boosting pumps, which intensify the water pressure during mixing at the nozzle can also help. It is possible to ensure good and steady wetting of the dry material at the nozzle if improved water rings are used. Depending on the system, the hydraulic pressure may rise to about 80 bar. Such appliances are expensive and susceptible to breakdown. In our experience, systems with 10–15 bar are usually fully adequate.

In addition to the formation of dust at the nozzle, it is necessary to control the impact of dust from the feeding system with the machine. In this respect, the traditional double-chamber machines or the modern version of Schürenberg (SBS) are advantageous. Rotor machines can be dust-proofed to a large extent. Complete dust-proofing can be achieved by various means, such as fitting a rotor de-duster or by continuously lubricating the rubber gaskets (intermittent lubrication). Another way

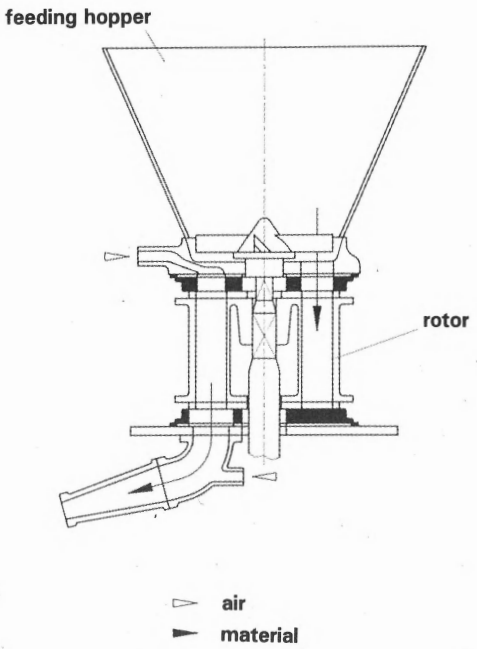


Figure 16.1 *The rotor principle of a typical dry-spraying machine (MEYCO Piccola).*

of completely sealing a rotor machine is to incorporate a hydraulic clamping system (e.g. as in the case of MEYCO Unica). The rotor is sealed by means of a mantle and the clamping pressure is automatically adjusted to the feed pressure. This system guarantees the correct clamping pressure (even in the case of blockages or extreme feeding distances), thus ensuring that the machine remains sealed. This new type of clamping system also results in a significant reduction in costs due to wear and tear and in the amount of compressed air required (a reduction of approximately 25%).

The high degree of rebound is another important problem in the dry spraying process. Depending on the application surface (vertical or overhead), 15 to 35% is lost. The average loss is 20–25%, compared to between 5 and 10% with the wet spraying process. The rebound can be reduced considerably by using the new additives and admixtures mentioned above. Silica fume or hydration control systems like Delvocrete have a positive effect. The average losses can thus be restricted to around 15%, which is comparable to the results obtained with the wet spraying process.

The low performance of the equipment is frequently referred to as a further drawback. However, machines are now available which render application rates of more than 10 m^3/h possible. This is no longer possible by hand, but only by using a manipulator. However outputs in excess of 8 m^3/h become critical from an economical point of view due to the increase in costs due to wear.

Conclusion

It is extremely important to ensure that the materials, equipment and application techniques are selected and matched in the best possible way in order to achieve satisfactory results with regard to quality and economy.

The dry process is the older of the two shotcrete processes. Continuing developments in machine and materials technology have made it possible to extend the field of application. In the future it is to be expected that the dry shotcrete process will continue to play an important role as previous drawbacks are overcome. The main applications will be projects with relatively small volumes and/or high requirements as to flexibility (e.g. repair) or long conveying distances.

16.3 Wet-mix method

This is the dominant method used in Scandinavia, Italy and in a large number of the major underground construction projects around the world. The considerable increase in the use of shotcrete for rock support over the last 10 to15 years has made demands on the method and therefore the technology has undergone intensive development. This development caused a hiatus in Scandinavia between 1971 and 1980, during which time the shotcrete market turned from 100% dry-mix to 100% wet-mix spraying. During these dates a change from manual to robot application took place. This dramatic change is unique to Norway. Since 1976/78, silica fume and steel fibres have been added to wet-mix shotcrete in rapidly increasing volumes. The Norwegians can thus be said to have lead the way into real wet-mix shotcrete and have the longest experience and greatest knowledge about wet spraying.

Today, wet spraying is also used for the construction of new buildings (instead of traditional casting) and repairing of oil platforms in the North Sea. This is proof of the quality of the method as it is well-known that very stringent demands are made on methods and materials used in off-shore construction. The change to the wet method has no parallel, but a description of the reasons pertaining in Norway may provide some explanation.

Economy

The spraying capacity has increased substantially from the dry-mix machines/robots to the later varieties of wet-mix robots. The practical average long-term capacity per 8-hour shift is normally 4 to 5 times higher than that of the dry-mix method.

Investment costs for the new wet-mix robots have increased dramatically, but the cost of applying the shotcrete has decreased significantly. One of the main cost factors, the set-up time per spraying round, has decreased because the use of integrated robot systems permits spraying to start in a matter of minutes after arrival of the equipment on site. Hydraulic bore hammers increased drilling capacity by about 100%. With higher investment, less time is spent per round for drilling and blasting. The time spent on shotcreting had to be as short as possible, and increasing the shotcrete capacity was therefore a key factor. Reduction in rebound of about 25% per m^3 sprayed hasalso proved important economically.

Working environment

Operators of the dry-mix process became accustomed to a lot of dust from the

nozzle and the spraying machine. Levels of dust in the working atmosphere were often more than three times the permitted values. With the wet-mix method the change in the working atmosphere was evident to the satisfaction of the crew.

Spraying under severe rock conditions was one of the features that brought about the development of the wet-mix method. The safety risk often was unacceptable without a robot and the use of steel fibre reinforcement.

Quality

Quality is normally not considered to be an asset of wet spraying nor a reason to change from the dry to the wet method. It is not necessarily the case that the wet-mix method produces bad quality and hence should be avoided. By using water-reducing additives (low w/c ratio) and silica fume, peak compressive strengths of sprayed shotcrete can be as high as 100 MPa. The quality of wet-mix spraying varies little. Dry-mix spraying can produce more variable results.

Application

Ready mixed concrete from a concrete plant is used for the wet method or a pre-bagged mortar is mixed. The concrete is prepared in the same way as for normal concrete, and it is possible to check and control the w/c ratio and thus the quality at any time. It is easier to produce a uniform quality throughout the spraying process. The ready mix is emptied into a pump and carried through the hose by pressure. Mainly mono (worm) pumps were used, but today piston pumps are dominant and this trend will continue.

At the nozzle, air is added to the concrete at a rate of 7–15m^3/min and at a pressure of 7 bar depending on whether the spraying is performed manually or by robot. The air is added to increase the speed of the concrete to achieve good compaction and adherence to the surface. A mistake often made with the wet spraying method is that not enough air is used. Often only 4–8 m^3/min is added, which gives poor compressive strength, adherence and rebound. For robot spraying up to 15 m^3/min is necessary.

In addition to the air, set accelerators are added at the nozzle. Sceptics are wrong to maintain that frost-safe concrete cannot be obtained and that shotcrete with set accelerators gives a poorer bonding. Several well documented tests from public institutes, and practical experience have shown that better frost proofing can be obtained because a tighter and more durable concrete is obtained. Bonding is also improved by the accelerators because trickling is avoided and the concrete bonds immediately to the surface.

Advantages

The advantages of the wet-mix method compared to the dry-mix method can be summarized as follows:

- far less rebound. A loss of 5–10% is normal with use of correct equipment and trained personnel. These figures also apply to the spraying of fibre concrete.
- better working environment; dust problem reduced.
- thicker layers because of effective use of the admixing materials.
- controlled water dosage (constant defined w/c ratio).

- improved bonding
- higher compressive strength and very little variation in results.
- much larger production and consequently improved total economy.
- use of steel fibres and new advanced admixtures.

The disadvantages are:

- limited conveying distance (max. 150 m).
- increased demands on aggregate quality.
- can withstand only limited interruptions.
- cost of cleaning equipment.

Summary of wet method

Average production rates of 60–100 m^3 may be achieved for robot spraying over large areas (with less than 10% rebound) during a production time of 8 hours and with one man. One conclusion from the comparison of wet and dry methods is that the dry-mix method should be used for small volume applications (e.g. repairs) and in cases with very special conditions (long conveying distances, repeated interruptions etc.), whereas the wet-mix method should be used in all rock support works.

16.4 Mix design for wet spraying

Mix consituents for the production of good wet-mix shotcrete include:

- cement
- aggregates
- set accelerators
- after-treatment
- correct execution
- silica fume
- admixtures
- fibres
- correct spraying equipment

The conflict between the properties of fresh and set concrete is particularly strong for shotcrete made by the wet-mix process, and has sometimes led to a reduction in the quality of shotcrete applied by this method. Water-reducing admixtures, silica fume and fibres have, however, altered this.

Silica fume

Silica fume (microsilica) is a very reactive pozzolan, with a high capacity to incorporate foreign ions, particularly alkalis. Silica fume has a filler effect which is believed to distribute the hydration products in a more homogeneous fashion within the available space, leading to a concrete with reduced permeability, increased sulphate resistance and improved resistance to freezing and thawing.

When considering the properties of silica fume concrete, it is important to keep in mind that silica fume can be used in two ways. Firstly, as a cement replacement, to obtain a reduction in the cement content – usually for economic reasons and secondly as an addition to improve concrete properties – both in the fresh and hardened state. In shotcrete, silica fume has to be used as an additive rather than as a substitute for cement, to improve the concrete and spraying properties.

Normal shotcrete qualities, i.e. with compressive strengths of 20–30 MPa, can be produced without silica fume, whereas a practical and economical production of higher strength shotcrete depends on its use. It seems technically favourable to use

5–10% (by weight of cement) of silica fume. The correct use of silica fume can provide the shotcrete with the following properties:

- better pumping ability (lubricates and prevents bleeding and segregation);
- reduced wear on the pumping equipment and hoses;
- increased cohesiveness of the fresh concrete and thus reduced consumption of accelerator which is beneficial for the final compressive strength;
- greater bonding strength to various substrates and between shotcrete layers;
- improved strengths;
- improved resistance against alkali silica reaction;
- improved permeability resistance;
- reduced rebound, and
- improved resistance to sulphate attack.

In fibre shotcrete it also provides:

- easier mixing and distributing of fibres;
- reduced fibre rebound, and
- improved bonding between the cement matrix and fibres.

When silica fume is added to concrete a high rate of plasticizers/superplasticizers is required to disperse it. The dosage of admixtures increases by approximately 20%, compared to shotcrete without silica fume.

Aggregates

As with all special concretes, the aggregate quality is of major importance in the fresh concrete as well as for the hardened product. It is particularly important that the grain size distribution and other characteristics show only small variations. Equally important are the amount and characteristics of fines, i.e. the grain size distribution and grain size analysis. For wet-mix spraying, the following criteria should be observed:

- maximum size: 8–10 mm. This is because of limitations in the pumping equipment and in order to avoid too much loss through rebound. From a technical point of view, a larger maximum diameter would be preferable.
- the aggregate grading is also very important, particularly its lower part. The fine material content in sieve no. 0.125 mm should be not less than 4–5% and not higher than 8–9%. Too little fine material gives segregation, bad lubrication and the risk of clogging. The surplus of fine material is important, both for pumping and compacting but, a high content will give a viscous concrete.

As the margins in the sieve basket are relatively small, it may often be convenient to combine two or more fractions, e.g. 0–2, 2–4 and 4–10 mm, by adjusting the proportion between them, producing a curve that fits within the ideal curve limits. Too little fine material will be compensated by using more cement or silica fume. Too much fine material is compensated primarily by increasing water reducing admixtures. The grain distribution curve for the aggregate should fall within the hatched area of Figure 16.2.

The proportion of particles above 8 mm should preferably not exceed 10% (see Table 16.1). The larger particles will rebound when shotcreting on a hard surface (at the start of shotcreting) or penetrate concrete already placed producing craters that are difficult to fill. During screening, storing, and handling of the aggregates, measures should be taken to prevent the presence of particles in excess of 10 mm. Coarse

Table 16.1 *Aggregate particle sizes*

Sieve	Min.%	Max.%
0.125	4	12
0.25	11	26
0.50	22	50
1.0	37	72
2.0	55	90
4.0	73	100
8.0	90	100
16.0	100	100

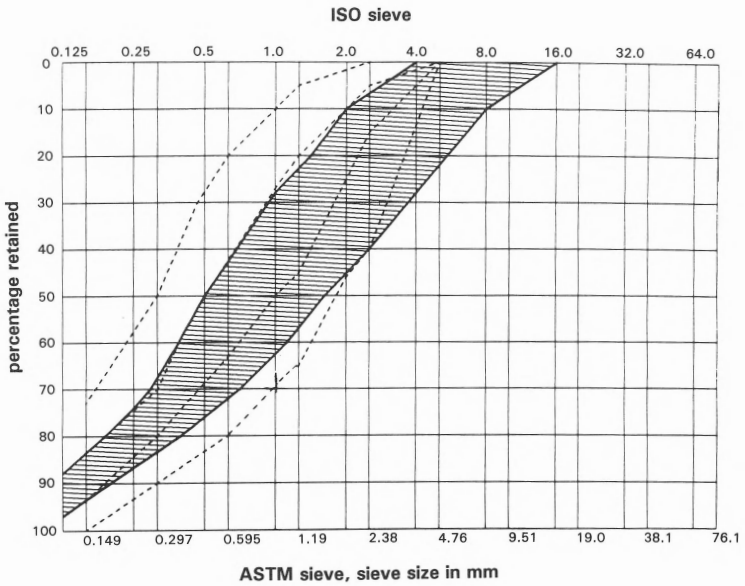


Figure 16.2 *Ideal aggregate grading for wet shotcrete.*

particles may block the nozzle and subsequent cleaning can be very time consuming. The aggregates shall be well graded, and no fraction should constitute more than 30% of the total. The contents of crushed and non-cubical material should not exceed 10%. An improvement of the grain size curve for a natural sand by the use of crushed materials often results in an increased water demand and poorer pumpability and compactibility. Before crushed materials are employed as part of the aggregates, comparative tests should be undertaken to establish whether the addition of crushed material gives an improved result.

Admixtures (plasticizers/superplasticizers)

To obtain specific properties in the fresh and hardened concrete, concrete admixtures should always be used in the wet-mix spraying method. Concrete admixtures are not new inventions. The Romans used different materials, such as goat's blood and pig's fat, in their cement to make it more mouldable. However, only during the last 30 years have the more stringent requirements for higher quality and production speeded up development, research and utilization of admixing materials.

Water reducers

Water reducers are used to improve concrete workability and cohesiveness in the plastic state. The water reducer can give a significant increase in slump with the same water/cement ratio, or the water/cement ratio can be reduced to achieve the same slump as for a mix without the water reducer. A reduction in water/cement ratio relates directly to an increase in strength. The higher slump adds to an increased pumpability.

Combinations of lignosulphonate, naphthalene and melamine are often used to obtain the best concrete for production purposes. Naphthalenes/melamines (superplasticizers) are chemically distinct from lignosulphonates (plasticizers/water reducers). They are better known as high range water reducers since they can be used at high dosages without the problems of set retardation or excessive air entrainment which often occurs with high rates of addition of conventional water reducers. The melamine forms a lubricating film on the particle surfaces, naphthalene charges the cement particles electrically so that they repel each other and lignosulphonate decreases the water surface tension. When well dispersed, the cement particles flow around each other more easily and coat the aggregates more thoroughly. The result is a concrete that is stronger and more workable.

The effect of superplasticizers/plasticizers of dispersing fines makes them perfect admixtures for shotcrete. The shotcrete slump increase achieved by adding conventional superplasticizers is time and temperature dependent. Pumpability can only be maintained for a limited time (20–90 minutes) after mixing and excessive dosages of admixtures can result in a total loss of cohesiveness and in segregation. Normal dosing is from 4–10 kg/m^3 depending on the quality requirements, water/cement ratio, required consistency, as well as cement and aggregate type.

Set accelerators

The wet-mix method needs the addition of fast setting admixtures at the nozzle. The primary effect of the material is to reduce the slump (consistency) at the moment of spraying and while the concrete is still in the open air, so that it will adhere to the surface when the layer thickness is increased. This slump reduction must take place in a matter of seconds.

With the use of set accelerators, spraying on vertical and overhead rock surfaces becomes possible. The setting effect allows the application of shotcrete for initial support – an important function in the New Austrian Tunnelling Method (NATM). Water inrush from the rock behind usually calls for a higher proportion of additives to accelerate the setting of the shotcrete.

Accelerators are added in liquid form via a pressure tank or a special dosage pump (piston or worm pumps). The dosage of accelerator will vary, depending on the ability of the operator, the surface, the water/cement ratio (high water/cement ratios will increase the need for accelerators in order to reduce consistency). A disadvantage of the accelerators is the decrease in final strength. Compared to plain concrete without accelerators the 28-day strength can be reduced significantly, and therefore the accelerator addition rate should be kept at a minimum at all times (for example, use lower addition rates on walls than for the roof).

Different types of accelerators are used in shotcrete. The most common types used in Scandinavia are modified sodium silicates (such as MEYCO SA 430) and, in Europe, different types of aluminates (sodium or potassium aluminates such as MEYCO SA-100 and SA-120). The difference between aluminates and modified sodium silicate/water-glass accelerators is basically that aluminate-based set accelerators take part in the hydration process and contribute to very high early strengths within the first 30 minutes to 2 hours (1–2 MPa).

Normal setting characteristics for aluminate based accelerator (Figure 16.3) are:

initial set: < 60 seconds and end of set: < 3.5 minutes

(tested with manual vicat needle test machine and process.)

Aluminate-based accelerators are used in soft rock with heavy rock deformation and where high early-strength support and large thicknesses (> 15 cm) are required within a short time after the excavation. They start to develop strengths after 5–10 minutes and after 20–30 minutes the strength is normally high enough (> 0.4 MPa) for the shotcrete layer to bear its own weight. Therefore thicker layers can be sprayed with aluminate-based accelerators than with modified sodium silicate or water-glass ones. Typical thicknesses can vary from 20–50 cm overhead.

The normal procedure is to spray a first layer of 6–10 cm over the whole area with each set up. By the time this is completed, strength has developed sufficiently to permit a new 10 cm layer to be sprayed at the start. This process can be repeated until the required thickness is reached.

Aluminate-based accelerators are also suitable for use where there are problems with water. In such circumstances the normal spraying procedure is to put up a

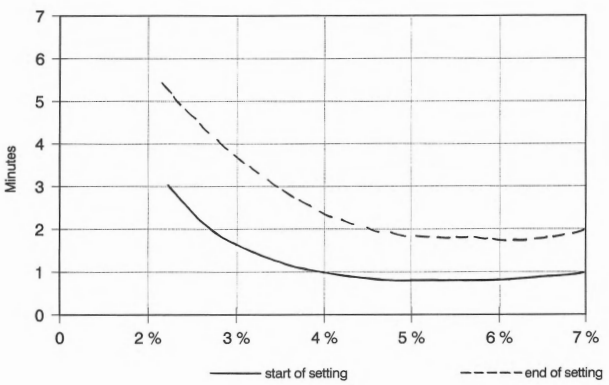


Figure 16.3 *Setting behaviour of MEYCO Gunite F100 high efficiency aluminate-based liquid accelerator.*

very thin layer of shotcrete overdosed with aluminate accelerator (8–10% by weight) and wait for 30 minutes until this layer has sufficient strength to bear the water pressure. Spraying then continues until the required thickness is reached.

The disadvantages of an aluminate-based set accelerator are:

- higher decrease in final strength than with modified sodium silicate (>20–30%)
- high sensitivity to the type of cement. They will not work with every type of cement, and so the reactivity of the cement has to be tested before shotcreting commences.
- very high pH (> 12.5), which renders them aggressive to skin, eyes etc. Special precautions must be observed in handling and using this type of accelerator. Gloves, mask and goggles must be worn and all direct contact with skin must be avoided.

Typical dosages of aluminate based set accelerators are 4–8% of b.w. There are two types of aluminate-based set accelerators:

- sodium aluminate (such as MEYCO SA-100)
- potassium aluminate (such as MEYCO SA-120 / Sika D 20)

The potassium aluminate works with a greater number of different cement types and normally gives faster setting and higher early strength than the sodium aluminate varieties (*see* Table 16.2).

Table 16.2 *Setting test with aluminate-based accelerators*

1. 30–32 g of water
2. 100 g of cement
3. Mix for 2–3 minutes until a homogeneous cement paste is obtained.
4. Add 6 g of the aluminate accelerator to be used.
5. Mix intensively manually for a maximum of 15 seconds so that the accelerator is distributed well into the cement paste.
6. Form a cake out of the accelerated cement paste and put it under the vicat test machine.
7. Use only the *manual* (not automatic) vicat needle machine.
8. Test the initial set and record it. (The needle should stop 1–2 mm from the bottom.)
9. Test the end of set and record it. (The needle may not penetrate into the cement paste.)

Setting criteria

Initial set		End of set	
< 30 seconds	very good	< 3 minutes	very good
< 60 seconds	good	< 4 minutes	good
> 60 seconds	not acceptable	> 4 minutes	not acceptable

Main criteria for aluminate-based accelerator

C_3A	5–10%, preferably 7–9%
Blaine	> 3500, preferably > 4000

Also depending upon the blending of fly sh, slag and gypsum.

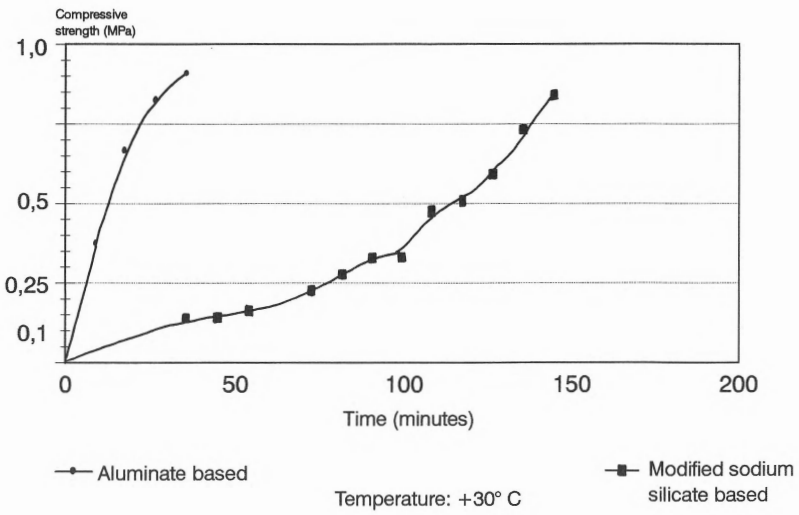


Figure 16.4 *Strength development of aluminate-based versus modified sodium silicate-based set accelerators (penetrometer).*

Modified sodium silicates/water-glass

Modified sodium silicates/water-glass give only a momentary gluing effect (< 10 seconds) and take no part in the hydration process as do aluminate-based accelerators (providing dosages do not exceed > 20% of b.w.). Early age strength development is compared in Figure 16.4.

The modified sodium silicates bind the water in the mix. Dosage therefore depends on the water/cement ratio: the higher the ratio the more modified sodium silicates/water-glass is required in order to glue the water and the mix. Modified sodium silicates/water-glass do not contribute to any strength within the first 2–4 hours. Normally, final setting is from > 60 minutes (depending on cement type and temperature).

The advantages of sodium silicate/water glass are:

- it works with all types of cement;
- less of a decrease in final strengths than with aluminate-based accelerators at normal dosages (4–6%);
- fast initial setting < 10 seconds;
- environmentally friendly, and not so aggressive for skin. The pH is < 12, but direct skin contact must be avoided. Gloves and goggles should always be used, and,
- a lower alkali content than aluminate-based products

Their disadvantages are that they cannot be used at temperatures lower than +5°C, and they allow only limited thicknesses (maximum 8–12 cm) to be sprayed.

Applications of sodium silicate accelerators include:

- permanent support, for durable concrete with high final strengths
- temporary support, where no early strengths are required (hard rock conditions)

- repair work
- places where the maximum thickness of overhead application is limited to 10–12 cm.

Typical dosages

- modified sodium silicates: 3–6% by weight.
- water-glass should normally not be used because the high dosages needed (> 10–12%, normally 20%) decrease strengths producing very bad quality shotcrete (and a false sense of security). To all intents and purposes normal water-glass is banned.

The new draft for European Shotcrete Specification (EFNARC - Specification for Sprayed Concrete - final draft 10.10.1993) allows only the use of liquid accelerators: 8% of cementitious material by weight.

The effect of modified sodium silicates in reducing final strength depends also on the curing conditions. At a dosage of 15% of the cement weight, a 50% strength loss could result; if samples are water cured, the loss is reduced to 30%. Long term curing tests show final strengths equal to zero concrete. In most applications with a reasonable sodium silicate dosage (3–6%) and good quality control, not more than 20% strength loss is acceptable. In practice the loss is usually 10–15%.

It is interesting to note that an 18 year old wet-mix shotcrete tested recently in Norway had the same strength as after 28 days. This contradicts many current claims. The quality of concrete with modified sodium silicate accelerators is now not a problem up to 60 MPa.

New developments

There remains a demand for alternative and improved accelerators to offset the risk of poor quality if the accelerator dosages are not under proper control. Also any new accelerator that did not reduce compressive strength by 10 to 30% would save material costs in cement and additives.

A new generation of set accelerators is under development, to be introduced by MBT and Sika. These set accelerators will be totally alkali-free and non-caustic, environmentally friendly – no protection required, will work with all types of cement, will have setting characteristics and early strengths similar to those with potassium aluminate products, use a dosage of 4–6% by weight, work equally well at low temperatures, and show a lower decrease in final strengths (< 10%).

16.5 Steel-fibre sprayed concrete for rock support

Introduction

The use of fibres in brittle materials is well-known; the Romans used different types of organic fibres such as straw to reinforce buildings and structures. With the introduction of asbestos and fibre reinforced polymers in the 1920s and 1930s, the use of fibres in building materials grew rapidly.

The main reason for using fibres in shotcrete is to increase the fracture toughness. Concrete is a brittle material and the tensile strength is only one tenth of the compressive strength. Furthermore the concrete has a shrinkage of the same magni-

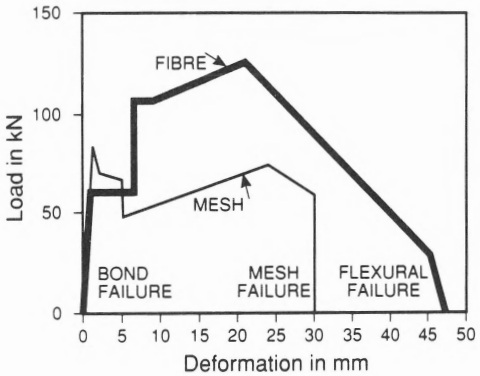


Figure 16.5 *Comparison between mesh and fibre reinforcement.*

tude as the strain capacity of the material, which means that a restrained unreinforced plate tends to crack due to the shrinkage stresses.

From a general point of view fibre reinforcement cannot replace traditional reinforcement in normal concrete structures. In shotcrete linings up to 100–120 mm thickness, however, traditional mesh reinforcement can in most cases be replaced by steel fibers (Figure 16.5). Since the reinforcement is placed during spraying, it is a very cost effective method of providing reinforcement.

Design considerations

Sprayed concrete for rock support is usually applied in thicknesses ranging from 30 to 200 mm. The concrete is often applied on rough surfaces, where local geometric irregularities far exceed the concrete thickness. This, together with complex loads due to interactions between concrete and ground, makes it in most cases impossible to design the sprayed concrete support by structural analysis alone. In addition, durability considerations, water leaks or water pressure may govern the design.

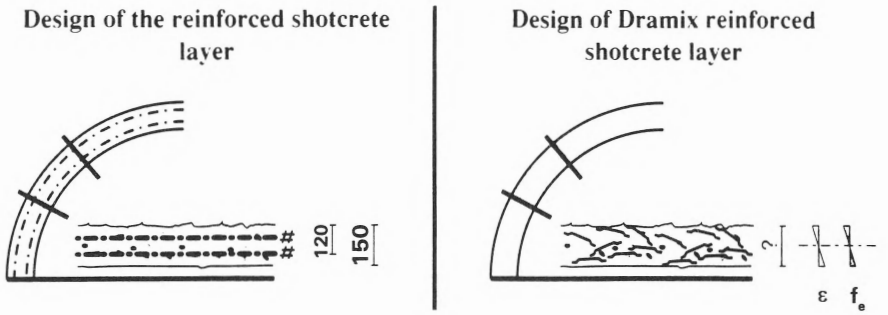
Despite the issues mentioned above, there are several methods for design of tunnel linings with steel fibre reinforcement:

(i) comparative design (fibre vs. mesh, steel-fibre reinforced, bolt-supported sprayed linings vs. cast lining, see Figure 16.6);
(ii) design according to simplified models (falling block, arch/beam models, see Figures 16.7 and 16.8);
(iii) structural design, using real geometry and loading conditions, and
(iv) design according to experience – empirical methods.

When designing sprayed concrete linings it is important to focus on the lining's load-deflection characteristics, rather than on the strength. By increasing the lining's flexibility the self-supporting capability of the ground will increase; this is the main function of a sprayed concrete lining.

1. Comparative design

In comparative design, structural members with steel fibres are analytically compared with support systems/methods where the support capacity is known by experience.



$M_{2m,u} = 0.9hA_s\sigma_{s,u}$
where $M_{2m,u}$ = ultimate bending moment (Nm/m)
H = d - a (mm) d = shotcrete layer thickness (mm)
a = shotcrete cover of wire mesh (mm)
A_s = steel wire mesh cross section (mm^2/m)
$\sigma_{s,u}$ = ultimate tensile strength of steel mesh wires (N/mm^2)
for d = 150mm, a = 30mm, h = 120mm
As = $126mm^2/m$ (#100/4)
$\sigma_{s,u} = 460N/mm^2$
$M_{2m,u} = 0.9 \times 120mm \times 126mm^2/m \times 460Nmm/m$
= 6.259.680
= 6.260Nm/m

$M_{D,2m} = f_e b(d^2/6)$
where $M_{D,2m} = M_{m,u}$ = bending moment (Nm/M)
f_e = equivalent flexural strength of Dramix shotcrete (N/mm^2)
b = width of loaded area (mm)
d = total layer thickness (mm)
for $M_{D,2m}$ = 6.260Nm/m
b = 1.000mm
$f_e = 0.65fu$ for 40kg/m^3 Dramix ZP 30/.50
$f_u = 4N/mm^2$
$f_e = 0.65 \times 4 = 2.6N/mm^2$
$d^2 = \frac{6M_{D,2m}}{f_e b} = \frac{6 \times 2.260.000}{2.6 \times 1.000}$
$= 14.446mm^2$
d = 120mm

Figure 16.6 *Mesh reinforced versus fibre reinforced sprayed concrete*

2. Design according to simplified models
Falling block – In this system the bond between rock and sprayed concrete is the main parameter. Typical for this system is either high capacity and shear fracture without any prior deformations, or low capacity and fracture by debonding between rock and sprayed concrete without any deformations.
Arch/beam-model – This system is independent of the bond between rock and sprayed concrete. Arch/beam theory will give high load-capacity and stiffness.

3. Structural design
Simulation of real conditions requires computer modelling and calculations. Structural design can also be performed combining method 1 and 2 with longhand calculations.

4. Design according to experience
The Q-system is the most commonly used design method in Norway. This is described in Chapter 8.

Specifications

Specifications for sprayed concrete normally include specifications for concrete composition, durability, compressive strength, flexural strength and ductility. The concrete composition is specified through environmental classes with requirements for

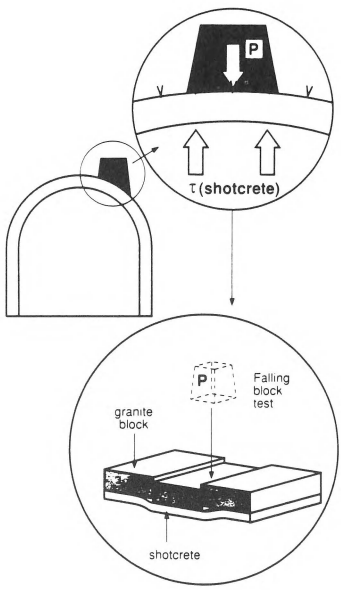


Figure 16.7 *The falling block model*

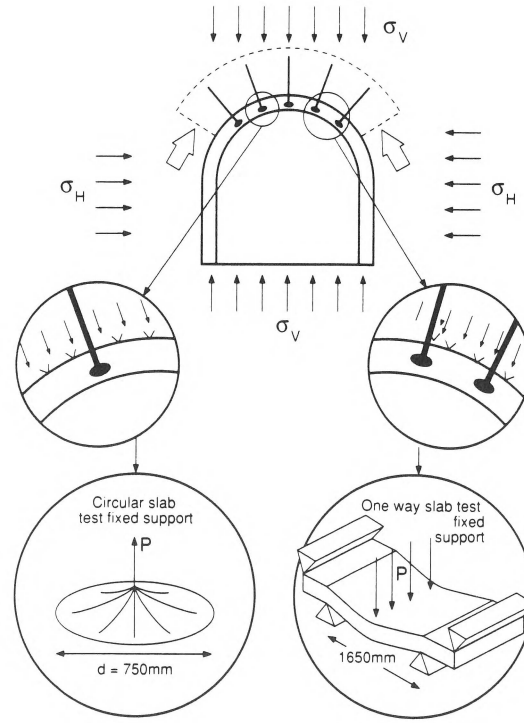


Figure 16.8 *The arch/beam model*

Table 16.3 *Environmental exposure classes (EFNARC, 1993)*

Environmental Class	Maximum $w/(c+a)$	Min. Cement Content, kg/m³
humid, no frost	0.6	360
highly aggressive chemicals	0.45	400
extremely aggressive	0.4	450

maximum w/(c+a)-ratio and minimum cement content as given in Table 16.3. Aggregate grading should ideally be in the shaded area shown in Figure 16.2.

Compressive strength is specified in accordance with strength classes shown in Table 16.4 and sprayed concrete should meet the specifications for in situ strength given in this table. If the flexural strength is specified Table 16.5 can be used.

The sprayed concrete is divided into different classes when specifying ductility or toughness. The ductility is either specified by residual strength factor according to ASTM C 1018, energy absorption capacity or residual strength value (see Tables 16.6 to 16.8). These represent three different ways to specify ductility, and the values should not be compared directly. When specifying it is important to identify where ductility is needed to give the required support.

Table 16.4 *Compressive strength (EFNARC, 1993)*

Strength Class	C30	C35	C40	C45	C50	C55
Characteristic strength, MPa	30	35	40	45	50	55
In-situ strength	19.2	22.4	25.6	28.8	32.0	35.2

Table 16.5 *Flexural strength (EFNARC, 1993)*

	C30	C35	C40	C45	C50	C55
Flexural strength, MPa	3.8	4.2	4.4	4.6	4.8	5.0

Mix design

A typical mix design fulfilling the above described specifications would be:

Portland cement	450–550 kg/m^3	silica fume	2–8% of c.w.
sand, 0–8 mm	1450–1500 kg/m^3	plasticizer	0.4–0.6% of c.w.
superplasticizer	0.4–0.6% by c.w.	water	215–230 kg/m^3
steel fibre	30–50 kg/m^3	w(c+2a)	0.38–0.45

Note that the amount of steel fibres is dependent on fibre type, length and specified ductility.

Application and production

Application

The main application of sprayed concrete, using more than 90% by volume, is rock and ground support. In Norway the rock quality is generally good and the progress in tunnelling is high. An important part of excavation in these conditions is high capacity spraying units for rock support which minimize delay in progress.

However, there are often zones of weakness which require heavy support. Spraying reinforced support ribs in poor rock and soft ground is an application that has been used with success in several projects to replace fully casted linings (Figure 16.9). These ribs are often combined with spiling bolts.

Prior to spraying, loose rock is removed and the rock surface is inspected and mapped and the type of rock support selected. Where the bond between rock and sprayed concrete is of importance, the rock surface must be cleaned with a mixture of water and compressed air using robot equipment and starting at the highest level. An air pressure of at least 7 bars and a water flow of 300 litres/min is used. After cleaning, the water must be allowed to drain off the structure.

The sprayed concrete is most commonly applied in thicknesses of 30–100 mm. The sprayed concrete is usually applied in two passes, starting at the lowest level.

Table 16.6 *Residual strength value requirement (EFNARC, 1993)*

Toughness classification	Deflection 1 mm	3 mm
0	unreinforced	
1	fibre type and amount specified	
2	2.0 MPa	1.5 MPa
3	3.5 MPa	3.0 MPa

Table 16.7 *Energy absorption requirement (EFNARC, 1993)*

Toughness classification	Energy absorption in joules for deflection up to 25 mm
a	500
b	700
c	1000

Table 16.8 *Residual strengh factor (EFNARC, 1993)*

Concrete grade	C25	C35	C45
Flexural strength X $R_{20\text{-}50}$	2.30	2.70	3.00

When spraying, the nozzle must be as near perpendicular as possible to the surface. The distance between nozzle and substrate should be 1–1.5 m and should normally not exceed 2.0 m. If the sprayed concrete is applied correctly, the rebound will be 5–10%.

After spraying, the surface must be protected against drying out. This is achieved by use of a membrane hardener in dosages recommended by the supplier. This is of great importance because sprayed concrete is particularly prone to drying out at an early age because it comprises thin layers, a high content of cement paste and is usually in air of low relative humidity caused by tunnel ventilation.

16.6 New advanced shotcrete admixtures

Traditional shotcrete is a compromise between early and final strength values, flexibility and economic viability. However, the development of new generations of

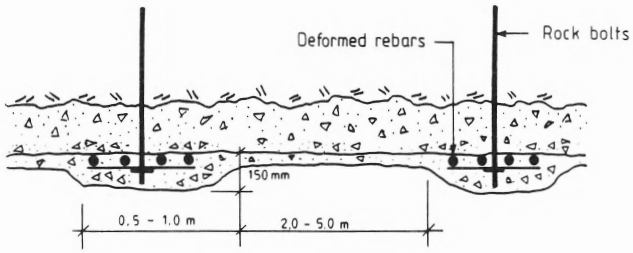


Figure 16.9 *Support with ribs of steel-fibre reinforced sparayed concrete.*

admixtures has led to essential improvements and to new working techniques in the shotcreting procedure.

The following section presents three new technologies which have been developed by MBT:

- The hydration control system Delvocrete which has heralded the way to greater flexibility and higher quality for the utilization of shotcrete and has advanced considerably the wet-mix spraying method. This has contributed to lower costs and better working conditions through reduced dust and rebound.
- A new technology, Total Consistency Control (MEYCO TCC), which overcomes the remaining critical factors in the wet-mix spraying method, namely mix design and aggregate sieve curve.
- A new system to secure efficient and reliable curing of shotcrete.

Delvo®crete

Shotcrete, wet or dry, only has a useful "pot-life" of 1½ to 2 hours and even less at temperatures above 20°C. Material sprayed after this time will exhibit lower strengths and increased rebound, due to the onset of cement hydration.

Long trucking distances from the batching plant to the site, delays in construction sequences as well as plant and equipment breakdowns can mean that much of the shotcrete actually sprayed is beyond its pot-life. In addition, environmental regulations may well impose restrictions upon the working hours of batching plants in urban areas, such that a contractor who requires supply of shotcrete mixes 24 hours per day, may only be able to obtain material for 12 hours each day. Problems such as these create unnecessary additional costs for both the contractor and the client.

A chemical system for the control of cement hydration in both wet and dry shotcrete mixes has recently been developed by MBT, enabling the working life of such mixes to be increased substantially. It also ensures that all shotcrete which is sprayed through the nozzle contains a "fresh" cement that has undergone little or no hydration reactions.

Control of cement hydration

The setting, hardening and strength characteristics of Portland cement are achieved by reaction of the cement with water. The product of this reaction is a rigid material known as calcium silicate hydrate (or CSH) gel. This reaction is known as

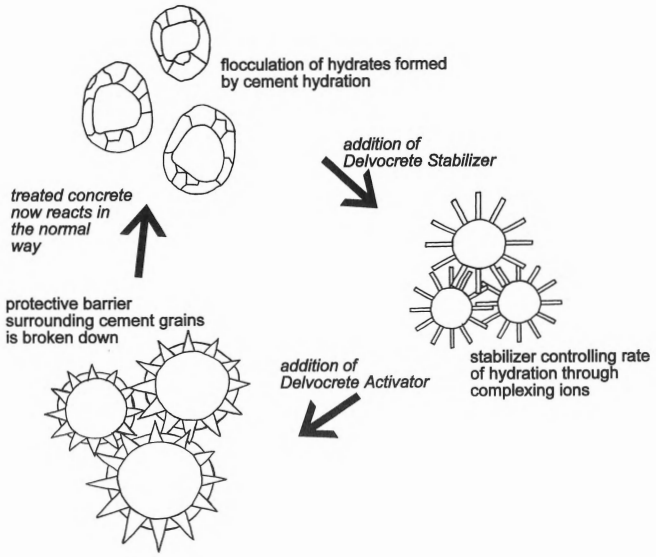


Figure 16.10 *Action of the Delvocrete Stabilizer.*

hydration, which, in simple terms, produces a rapid release of calcium ions into solution and forms a CSH gel shell around the cement grains. As concrete sets, hydrates formed by cement hydration flocculate, and it is this process which turns plastic, workable concrete into a stiff material.

By adding the Delvocrete Stabilizer to a concrete mix, the hydration of cement may be completely controlled for periods of up to 3 days. The stabilizer, when thoroughly dispersed throughout a concrete mix, controls the rate of hydration of the cement by complexing calcium ions on the surface of the cement grains (Figure 16.10). It functions in a dual role by stopping cement hydration through the formation of a protective barrier around cementitious and pozzolanic particles and acting as a dispersant, thus preventing hydrates from flocculating and setting. Concrete may be stabilized and kept in a plastic state for a few minutes, several hours, overnight or even over a weekend. The stabilizer is composed of carboxylic acids and organic acids and salts contaning phosphorus. It is capable of retarding the hydration of all cement minerals and also reduces the rate at which calcium sulphate goes into solution. Its action is different to that of conventional retarding admixtures which, at normal dosages, is complex and can accelerate one mineral component of the cement, whilst retarding others. At higher dosage rates, conventional retarding admixtures may even cause severe concrete stiffening, flash set and low strength. Thus, by using conventional retarding admixtures at dosages high enough to achieve the same degree of retardation as the Delvocrete Stabilizer, detrimental effects to both the plastic and hardened concrete can occur.

The stabilizer may be used to control cement hydration for periods of up to 72 hours. It affects primarily C_3S hydration, but can also delay the initial C_3A reaction with water and sulphate if it is added with the mix water. Normal setting and hardening characteristics of the concrete may be achieved in two ways. One is to allow

the action of the stabilizer to wear off and the other is to add Delvocrete Activator to the concrete to break down the protective barrier surrounding the cement grains (Figure 16.10). As soon as this protective barrier is broken down, the treated concrete will react in the normal way.

Performance

The technical performances of hydration controlled concretes and shotcretes treated with the Delvocrete system exhibit qualities equal or superior to reference concretes manufactured conventionally.

In shotcrete applications, hydration controlled mixes have shown improved compressive, tensile and flexural strengths when compared with reference mixes. Kinney (1989) observed that the Delvocrete Stabilizer appears to slow the formation of CSH nuclei when added with the mix water. It also slows both CSH and CH when added during or after the induction period. It is suggested that this ability to affect nucleation and crystal growth leads to the formation of finer CH and denser silicate hydrates, resulting in beneficial physical paste properties.

Economics

The estimating and costing of the components relating to the final in-place price of shotcrete for a large underground infrastructure project is a difficult and complex task. Many of these costs are overlooked or underestimated by contractors. They may be summarized as follows:

- the cost of the shotcrete mix per m^3;
- the cost of in-place applied shotcrete, allowing for rebound and overspray. (This may be 40% higher than the delivered m^3 cost.);
- the cost of collecting, loading, removing and dumping of rebound from a project to a suitable approved site (environmental legislation);
- the cost of returned shotcrete that has to be rejected because it is too old to use;
- the cost of waste shotcrete that has to be washed out of pumps and hoses at the end of spraying shifts and when breakdowns and delays cause interruption to shotcreting operations, and
- the cost of breaking out, removal and replacement of defective shotcrete resulting from the application of material that may have been too old.

The use of the Delvocrete hydration control system in large volume wet-mix shotcrete projects, permits cost savings to be made in the following:

- reduction in rebound, thus less rebound to be removed and dumped;
- no shotcrete deliveries have to be rejected because they are too old;
- waste shotcrete in pumps and hoses does not have to be washed out and disposed of at the end of a spraying shift or when interruptions occur;
- less defective in-place shotcrete because all applied shotcrete contains cement that has not undergone any pre-hydration and has not exceeded its pot-life;
- the necessity for "trixer" units is eliminated;
- site batching plants may be eliminated (depending upon other concrete requirements on the project), and
- the cost of overtime and down time in plant and personnel may be reduced by ensuring adequate shotcrete deliveries are always available at the excavation face.

Table 16.9 *Cost comparisons of wet-mix shotcrete*

Material	Unit cost (US$)	Conventional mix	Hydration controlled mix
cement	$80.00/T	420 kg – $33.60	420 kg – $33.60
silica fume	$450.00/T	40 kg – $18.00	40 kg – $18.00
aggregate (0–10 mm)	$15.00/T	1680 kg – $25.20	1680 kg – $25.20
water	-	210 kg – -	210 kg – -
plasticizer	$0.70/kg	3 kg – $2.10	3 kg – $2.10
superplasticizer	$1.10/kg	4 kg – $4.40	3 kg – $3.30
stabilizer (0.6%)	$3.50/kg	-	2.76 kg – $9.66
slump	-	200 mm plus	200 mm plus
accelerator	$1.80/kg	21 kg – $37.80	-
activator	$2.00/kg	-	21 kg – $42.00
	TOTAL	$121.10	$133.86

The dosage of the Delvocrete Stabilizer ranges from 0.6–2.0% (b.w.). This will stabilize the cement for between 6 hours and 3 days. The dosage obviously depends upon the requirements of the contractor, but generally 0.6% by weight of cement is used in most works. The dosage of Delvocrete Activators is normally equal to (or slightly less than) the dosage of accelerator that would be required by the same shotcrete mix that contains no Delvocrete Stabilizer.

Table 16.9 shows the cost comparison of conventional and hydration controlled wet-mix shotcretes for rock support. If the conventional mix had 20% rebound, then the in-place cost of the shotcrete would be US$ 121.10/0.8 = US$ 151.38/m^3. In order to make the in-place cost of the hydration controlled shotcrete of the same order, then the rebound of that mix should be (1 – 133.86/151.38) × 100 = 11%. It is not unusual for rebound reductions of this magnitude (9%) to be achieved, as illustrated in the Flurlinger Tunnel project. In addition to the reduction in rebound, the contractor will also make savings by eliminating return and waste shotcrete, reducing down time of shotcrete pumps and related personnel. The consistent quality of the shotcrete is a further beneficial factor.

16.7 The MEYCO TCC system

A new technology for Total Consistency Control (MEYCO TCC) created by MBT now overcomes the remaining critical factors in the wet-mix method, namely mix design and aggregate sieve curve. This system (Figure 16.11) is a two-component admixture system which produces instant loss of slump. Component A is a new advanced superplasticizer (Rheobuild 3520). Its benefits are an extremely good slump retention and improved pumpability (also with fibre concrete). With the Rheobuild 3500 series, good workability and pumpability are achieved even with defective mix designs (coarse aggregates, lack of fines, low cement content).

The addition of component B (MEYCO TCC 765) at the spraying nozzle, while replacing the use of traditional set accelerators/activators, provokes a sharp slump

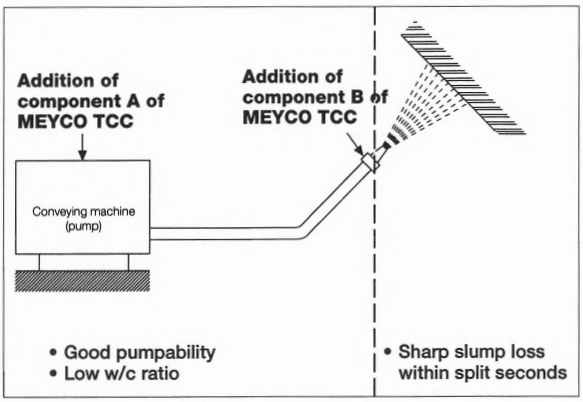


Figure 16.11 *The MEYCO TCC system for slump killing.*

loss of the shotcrete immediately. As the shotcrete hits the substrate, it already has a thixotropic consistency, thus adhering in thick layers without trickling.

Shotcrete is being used increasingly as a permanent support and final lining in underground construction, slope stabilization, repair works to concrete structures and for new constructions. This leads to new demands and requirements for the performance of wet shotcrete. However, the new MEYCO TCC system overcomes all of these problems and ensures an even and problem-free spraying through the provision of the following:

Technical performances:

- Good pumpability
- Low w/c ratio
- Sharp slump loss without simultaneous accelerating effect
- Minimal decrease of final strengths when compared to cast concrete
- Early strengths
- High density
- Homogeneous mix
- Freeze/thaw resistance
- Watertightness
- Substantial reduction of alkali-based admixtures, very low alkali content
- Increased toughness of steel fibre reinforced shotcrete thanks to low fibre rebound and better fibre orientation
- Improved bonding
- Less consumption of activator: $< 5\%$

Application performances:

- Low rebound
- Long open time for surface finishing
- Less dust for an improved working environment

Reduced fibre rebound

Fibre rebound is a typical problem with the use of long fibres (which are being used more frequently), and a large loss of fibres causes a reduction in the toughness values. The thixotropic characteristics of the shotcrete provided by the MEYCO TCC system cause a reduction of rebound and, in particular, a dramatic reduction of fibre rebound because the fibres achieve a better orientation in the plastic concrete.

Practical experience shows that the fibre rebound can be reduced by up to 50%, compared with normal accelerators. In combination with long steel fibres (>40 mm), the system has reduced fibre rebound from more than 20% to below 10%, with a resulting increase of the I_{30} toughness index to >25. It has thus proven possible to produce a shotcrete with an average I_{30} index of >25 with a fibre dosage of 50 kg/m^3 (Dramix 40/50). This opens up new possibilities and sets new standards for the use of steel fibre reinforced shotcrete.

Example

Use of TCC in SFR shotcrete – Hvassum Tunnel

MEYCO TCC has been used in several large tunnelling projects, the final lining of the Hvassum Tunnel in Norway (built in 1991/93 with steel fibre reinforced shotcrete) being an example. With traditional shotcrete mixes, the required toughness could not be achieved due to high fibre rebound. A further problem was the short open time.The MEYCO TCC system enabled a reduction in fibre rebound of 50% and better fibre orientation, with consequent increase in toughness (I_{30} >25), and longer open time.

The system provided the additional benefits for the contractor of improved pumpability and workability, better slump retention and water reduction. In total, 4,000 m^3 of shotcrete with the MEYCO TCC system were sprayed in this job.

Mix design	**old mix**		**MEYCO TCC system**
Portland cement	470 kg		470 kg
Silica fume (densified powder)	8% (c.w.)		8% (c.w.)
Aggregates (0–8 mm)	1670 kg		1670 kg
Superplasticizer (BNS)	5 kg	*Rheobuild 3520*	8 kg
Plasticizer (lignosulphonate)	3.5 kg		
Dramix steel fibres 40/50	50 kg		50 kg
w/c+s	0.4		0.41
Slump	12–16 cm		20–24 cm
Accelerator: A-WG-36 (modified silicate)	5% (b.w.)	*Activator: MEYCO TCC 765*	4% (b.w.)
Rebound	5–6%		4–5%
Fibre rebound	20–25%		10–12%
I_{30} index	13–20		>25 (all tests)
Open time	1 hour		>2 hours
Robot	Robocon		Robocon
		Pumpability	very good

Project description

The Hvassum Road Tunnel near Oslo is 3.3 km long and it was excavated by the drill and blast method. The contractor, Veidekke AS, is the largest in Norway. Rock support was provided by a combination of grouted anchors and steel-fibre reinforced wet shotcrete and shotcrete was also used for the final lining. All shotcrete was applied by robot and the lining thickness varies from 7.5 to 15 cm, depending

on rock conditions. In order to meet the high ductility toughness index of $I_{30} > 22$, the contractor decided to use long steel fibres (Dramix 40/50), which caused higher rebound than shorter fibres.

From the start, it proved difficult to fulfil the requirements for toughness. Due to the high fibre rebound (>20%), the contractor only achieved an I_{30} index of between 13–20. On-site tests were carried out to reduce the rebound by adding more silica fume, changing admixtures and mix design, but all failed. Veidekke therefore tried the new MEYCO TCC system from MBT. The results were noteworthy and the specified requirements were met, even with a safety margin. The fibre rebound was reduced to 10% and the I_{30} index rose to an average of above 25.

Curing

Internal curing

It might be thought that tunnels provide ideal curing conditions with high humidity (water leakage), no wind and no exposure to the sun. However, this is not the case. Tunnels and other underground construction projects have some of the worst curing conditions due to the ventilation that blows dry air (cold or hot) into the tunnel. It can be compared with concrete exposed to windy conditions.

Background

Curing is one of the basic and most important jobs in shotcrete spraying because of the large cement and water content of the mix and the consequent high shrinkage and cracking potential of the applied concrete. Also there is the danger of rapid drying out due to the heavy ventilation found in tunnels, the fast hydration of accelerated shotcrete and application in thin layers. Therefore, shotcrete should always be cured properly by means of an efficient curing agent, but use of curing agents involves several restrictions. They must be solvent-free (to permit use in closed rooms), have no negative influence on the bonding between layers and must be applied immediately after spraying of the shotcrete. Most of the applied shotcrete around the world has limited bonding and many cracks, due to the lack of curing.

The use of shotcrete as permanent final linings, has increased demands for long-term quality and performance. These requirements are: good bonding, high final density and compressive strengths to ensure freeze/thaw and chemical resistances, watertightness and a high degree of safety. When shotcrete is cured with a curing agent, the substrate must be cleaned very carefully before applying a subsequent layer. High pressure air and a lot of water should be used for cleaning.

Another requirement is that the curing agent is applied quickly after spraying is completed. To secure proper curing of shotcrete, the curing agents must be applied within 15 to 20 minutes of spraying. With the use of set accelerators, the hydration of shotcrete takes place rapidly after placing (5 to 15 minutes). The hydration and temperature are most critical during the first minutes and hours after the application of the shotcrete and it is essential that the shotcrete is protected at this stage. Applying curing agents involves two time consuming operations: the application of curing agent and its cleaning/removal from the shotcrete surface when multiple layers are being sprayed. In many countries with experience in wet shotcreting, such as Norway and Sweden, and in big projects world-wide there is an obligation to cure the shotcrete with a curing agent.

Good results have been achieved with a special curing agent for shotcrete, Masterkur 112. This product is solvent-free and easy to apply and remove. It has been used in many large projects and in different countries, everywhere with very good results. The use of specially designed curing agents for shotcrete improves bonding by 10–20% compared to no curing (air curing), reduces shrinkage and cracking and also gives a slightly higher density and compressive strength (at 28 days). These results were confirmed by laboratory tests and field trials. However, in order to achieve these results, proper cleaning is required before subsequent layers of shotcrete can be applied. Even with easy-to-apply products, shotcrete curing remains a time consuming job and is often felt as a hindrance to other tunnelling operations.

Internal curing with MEYCO® TCC 735

MBT has developed a new system for more efficient and secure curing of wet shotcrete, repair mortars as well as concrete. Internal curing means that a special admixture is added to the concrete/mortar during batching. This admixture produces an internal barrier in the shotcrete/concrete which ensures safer hydration and greater chemical resistance than with the application of conventional curing agents.

The benefits resulting from this new technology are:

- the time consuming application and, in the case of multiple shotcrete layers, removal of curing agents is no longer necessary;
- curing is guaranteed from the very beginning of hydration, and
- there is no negative influence on bonding between layers.

As a consequence of this optimum curing effect, all other shotcrete characteristics are improved: density, final strengths, freeze/thaw and chemical resistances, watertightness, reduced cracking and shrinkage. In addition, MEYCO TCC 735 also improves pumpability and workability of shotcrete, even with low-grade aggregates. It particularly improves the pumpability of steel-fibre reinforced shotcrete mixes. In combination with the MEYCO TCC system it also increases the beneficial effects of the slump killing system by further improving fibre orientation, reducing fibre rebound and thus raising toughness values.

The internal curing system – a proven technology

MEYCO TCC 735 has been tested with good results both in laboratories and large field trials. Bond strengths were higher than 2.0 N/mm^2 with failures discovered only in the concrete and not in the bonding area. Density and mechanical strengths at 28 days were more than 10% higher than in conventionally cured reference shotcrete.

In summary:

- increased bonding compared to no curing: $>100\%$ (from 0.5–0.7 to >2.0 MPa);
- increased bonding compared to curing with special curing agent: >30–50% (from 0.7–1.2 to >2.0 MPa);
- all cores of internal curing treated shotcrete show bond >2.0 MPa. Failures were discovered only in the concrete and not in the bonding area;
- increased density ($>15\%$) compared to shotcrete treated with external curing agents;

- increased strength (28 days) compared to air cured shotcrete or treated with external curing agent (> 10%), and
- no signs of cracking.

16.8 Example of wet-mix shotcrete

This section gives an example of typical wet-mix shotcrete mixture proportions. The final strength of the concrete must be higher than the specified strength. Provided materials, mix design and execution of spraying are correct, a rough estimate should aim at obtaining one strength class higher for the final strength than the specified requirement.

Example of C-35

Cement	450kg
Silica fume	20 kg
Fine gravel 0–8 mm	1590kg/m^3
Rheobuild 3520	6–8 kg
Delvocrete Stabilizer	4.5–5 kg
MEYCO TCC 735	5 kg
Steel fibres (Dramix 30/50)	30–60 kg
w/c+s	≤ 0.45
Slump	10–15 cm
Addition at the nozzle:	
MEYCO TCC 765	3–4%

This mix is stabilized for more than 24 hours.

Consequences of using different mix designs

(i) It is vital to obtain soft consistencies (slump > 25 cm). The high dosage of accelerator needed produces a big decrease in final strength, and there is a risk of segregation and clogging.

(ii) Low proportions of cement (< 350 kg) necessitate firm control of the accelerator content and hardening conditions.

(iii) Lower production capacity.

(iv) Overdosing of silica fume (12–15%) gives a very sticky concrete which is very difficult to pump. This must be compensated for with a higher slump.

(v) A high content of coarse aggregates (for instance 20% larger than 4 mm), gives a higher rebound loss.

(vi) Crushed aggregates cause heavy wear on pumps and hoses and large losses through rebound. There is also a risk of dehydration and clogging.

(vii) Large amounts of (long) fibres create pumping and compression problems, including cavities around fibres, poor mechanical properties, poor resistances and inferior adherence to the surface. A reduction of the fibre length helps.

Conclusion

Accelerators are necessary to get good quality wet-mix concrete with fast setting and good adherence to the surface. It is also important to keep the dosages of set accelerators to a minimum.

The following requirements should be observed:

- a nozzle that mixes air and accelerator well into the concrete stream;
- concrete with a low w/c ratio (< 0.45). Addition of admixtures to take care of slump and pumpability;
- sufficient air added at the nozzle (minimum 12–15 m^3 per minute) to get good compaction and high compressive strengths;
- correct viscosity of the accelerator for good and efficient mixing into the concrete jet;
- the temperature of the accelerator must be kept between +10 and +25°C, to maintain the correct viscosity. Therefore, the accelerator tank must be equipped with a heater, and
- curing of the concrete while it is fresh in order to increase final strengths. Alternatively, internal curing may be used.

16.9 Equipment

Parallel to the development in material technology there has been constant innovation in the equipment sector to produce machines suited to the new products. The result is a wide range of systems that cover all shotcreting works, from huge tunnelling jobs with large quantities of shotcrete mixes down to small volume repair works. Common to all developments in equipment is the tendency toward integrated and automated systems which ensures higher production output, consistent and controllable quality and safer working conditions.

Manual system for wet-mix spraying

Wet-mix shotcreting machines (Figure 16.12) normally operate on the double piston pump principle. The pump conveys the shotcrete mix in a continuous flow to the nozzle where compressed air is added to accelerate the mix. This results in lower wear and tear on the equipment and, as a consequence, in lower maintenance costs. It also allows higher output (up to 20 m^3 per hour), thereby increasing the production capacity of shotcreting works. The latest developments in equipment aim to provide pulsation-free conveyance of the wet mix from the pump to the nozzle.

Spraying manipulators or robots are suitable for use wherever large quantities of shotcrete are applied, especially in tunnel and gallery constructions or for protecting building pits and slopes. Mechanization and automation permit even large volumes of shotcrete, dry-mix and wet-mix, to be applied under constant optimum conditions and without fatigue for the nozzleman who also profits from higher safety and improved general working conditions.

The spraying robots typically consist of the following components:

- lance-mounting with nozzle;
- boom;
- controls;
- drive unit, and
- turntable or adapter-console (for different mounting versions).

The lance-mounting allows any movement of the jet that is necessary for spraying. Lance-mountings are available in lengths of 2 or 4 metres. The lance-mounting is attached to the boom, which can be moved in any direction and lengthened by

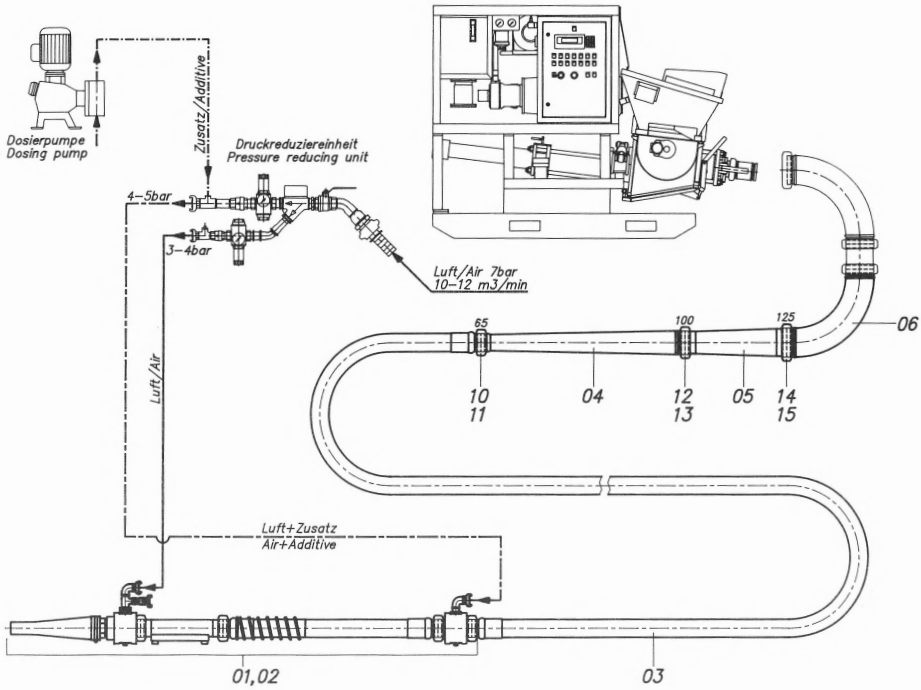


Figure 16.12 *The wet-mix spraying system.*

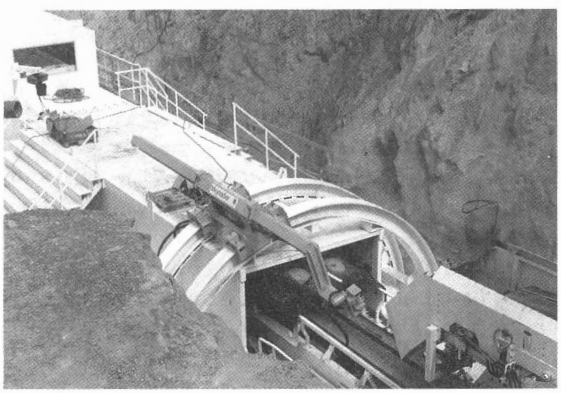


Figure 16.13 *Tailor-made solution from MBT, the MEYCO Robojet sparying manipulator is integrated into a tunnelling and boring machine.*

means of a built-in extension. It is controlled by a portable remote-control.

The MEYCO Robojet (Figure 16.13), for example, has 16 separate individual movement functions that are controlled by means of 4 operating levers. Routine operations, such as horizontal back and forth movements or circular movements of the nozzle, can be automated. The spray-head is powered by three separate inde-



Figure 16.14 *The modular robot system enables spraying systems to be built to answer customers' needs.*

pendent hydraulic drives, thus ensuring that the nozzle is always operated at the ideal angle to the surface. The nozzle can be turned 360°, clockwise or counter-clockwise. The cradle is automatically held parallel to the axis of the tunnel. The remote control is equipped with a 20 m long cable and can thus be operated from a safe position.

Many suppliers also offer complete mobile systems with integrated equipment for the complete shotcreting job. The MEYCO Spraying Mobile from MBT (Figure 16.14), for example, consists of:

- a wet-spraying machine;
- the Robojet described above;
- an accelerator storage tank;
- a proportioning unit for accelerator;
- a cable-reel with hydraulic drive;
- an air compressor, capacity 12 m^3/minute, and
- a central connection and control system for external power.

The benefits of mechanized spraying include:

- reduced shotcreting cycles due to higher output capacity and the elimination of time-consuming installation and removal of the scaffolding, particularly in tunnels with variable profiles;
- cost savings due to reduced rebound and labour savings;
- improved quality of applied shotcrete due to even spraying, and
- improved working conditions for the nozzleman because of the protection from cave-ins, rebound, dust and accelerators.

When using liquid admixtures it is important to ensure that dosing is constant and uniform in relation to the weight of the binder. To achieve this, the use of an appropriate dosing pump (Figure 16.15) is necessary.

16.10 Active mechanisms of shotcrete on rock

There are some important characteristics of the shotcreting process which must be understood:

- concrete is blown against the rock surface at a high velocity of 20 to 100 metres per second, depending on the method and equipment;

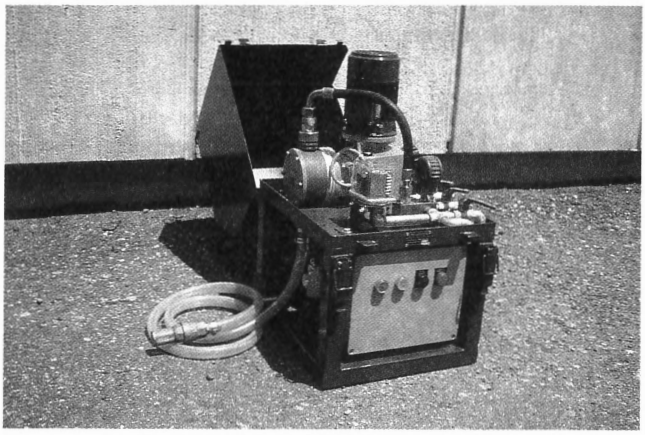


Figure 16.15 *Admixture dosing pump.*

- the rebound consists mainly of coarse particles. The amount of rebound is greatest at the first hit. At a later stage of spraying, when semi-soft shotcrete is on the surface, more will stick. The effect of this is an increase of fines in contact with the rock surface;
- the applied concrete is compacted by later impacts (layers);
- the shotcrete layer will stick to the surface with a bond strength (adhesion) of 0 to 3 MPa;
- the rock surface is completely encapsulated and isolated, and
- fines are squeezed into cracks and joints to some extent.

This application process creates the best possible adhesion by concentration of fine material at the rock surface. At the same time, the fine material has the best properties for entering cracks and joints and repeated impacts of new concrete material squeezes fines into existing openings.

The stabilizing effects identified are thus:

- mortar and fines squeezed into the cracks and joints of the rock produce a wedging effect like mortar between bricks in a wall or arch;
- punching resistance, which means that a loose block is prevented from shearing through the shotcrete layer;
- arch support, sometimes only local arches are effective;
- isolation against changes of moisture, effects of air and temperature, washing effect from running water etc;
- maintenance of the existing stability, at the time of application, and
- simultaneous and combined effect of the above mentioned mechanisms.

For thin shotcrete layers, the mode of operation is more like rock reinforcement than rock support. On the surface there will be a composite action between rock and shotcrete. Practical experience shows that even a 30 mm shotcrete layer is very effective in some situations, supporting the idea of a composite action.

Shotcrete on soft or crushed rock

In many cases it is not possible or correct to think of isolated blocks supported by

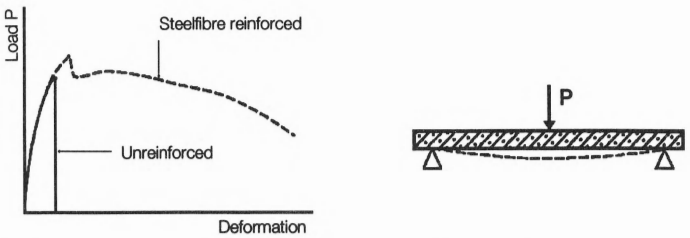


Figure 16.16 *Load-deformation characteristics of a shotcrete layer.*

a layer of shotcrete. When tunnelling takes place in crushed material, experience again shows the effect of the shotcrete even with thin layers. In such situations the large scale tests and block theory are not applicable, and it is harder to explain why it works under such conditions. The most obvious reason is the maintenance of the existing stability. Shotcrete will tie the rock surface together so that differential movement is effectively prevented. An inward deformation of the tunnel contour will take place generally and evenly, not as a local phenomenon, with one side at a time. As the contour moves inward, the length of the contour tends to decrease, which means there are compressive forces in the rock/shotcrete composite. In this way the shotcrete is helping the rock material to carry itself. Again we are looking at a reinforcement effect, rather than a load support. To achieve this in the interface, the concrete shell needs to be of reasonable compressive strength.

Important properties of shotcrete for rock support

The relative importance of different material properties for shotcrete depends on the type of stability problem. Thin layers applied to hard rock to prevent loose stones from falling out depend primarily on adhesion. The compressive strength in such a case is of minor importance. However, compressive strength is the primary factor when a thick closed-ring support of soft ground is considered. In this situation the adhesion is of no interest at all.

Compressive strength should be high enough to ensure that the concrete has a reasonable long term durability in the environment where it is applied. There may be a difference between a road tunnel with heavy traffic and a water tunnel. In most cases this means that the shotcrete should meet a 35 MPa strength class according to a normal national standard test procedure. In Norwegian road tunnels beneath the sea the requirement is now 45 MPa concrete. Generally, the compressive strength itself is not so important, but it is an indirect measure for other properties.

Adhesion to the rock surface is generally an important parameter. However, it is difficult to measure accurately and it varies a lot within short distances. Very often people are reluctant to specify the required adhesion in a contract, because the control results may cause more problems than is worthwhile. In the opinion of the authors the control should be focused on compressive strength, application technique and cleaning of the surface in advance. In this way it is possible to ensure the best possible adhesion that the surface allows.

The *tensile strength* of shotcrete is not so important. In design considerations this strength cannot be used anyway, because there is always a chance of shrinkage

Table 16.10 *The increased efficiency of steel-fibre shotcrete*

Shing Mun tunnels, Hong Kong
(Contractor: Gammon/Dragages/Skanska)

	Wire mesh	Steel fibre
Drilling	2 hrs	2 hrs
Charging and blasting	1½ hrs	1½ hrs
Shotcrete 1st layer	1 hr	-
Mucking out	1½ hrs	-
Fixing wire mesh (50m²)	5 hrs	-
Shotcrete 2nd layer	3 hrs	-
Shotcrete steel fibres single layer	-	1½ hrs
Mucking out	-	1½ hrs
Total	**14hrs**	**6½ hrs**

cracks in critical sections. Across a crack there is naturally no tensile strength. The same applies to the flexural strength of the shotcrete material itself. It is important that the required compressive strength is met by a mix design that gives a minimum *shrinkage*. There are two reasons for this:

- low shrinkage improves adhesion, and
- low shrinkage reduces cracking and improves durability.

To achieve a low shrinkage, the content of fines and cement should be low, as should the w/c ratio (generally less than 0.5) and the application technique must be correct (good compaction and spraying at right angles). Use of a curing compound after application and/or water spraying (or the use of internal curing) should be a routine part of the work.

The *thickness of the shotcrete layer* is subject to the design. The contractor should distribute the necessary concrete volume to meet the requirement as closely as possible. This is a practical problem, especially if the specified thickness is large (200 mm and more) and the full thickness is placed on a limited area during one operation. Under such circumstances the tendency is that the walls get more shotcrete than required and the roof gets less. This is the opposite to what is required for stability.

This leads to one very important parameter in shotcrete application, the *short time strength development*. Safety and economy are improved if the strength gain within the first minutes and hours is high. High early strength is possible when using accelerators. The safety aspect is fairly obvious. Economy is improved to a maximum if it is possible to build the full thickness in one continuous operation, even over a limited area.

Reinforcement (see also Table 16.10)

The traditional reinforcement used in shotcrete is steel wire mesh (normally 3–6 kg/m², with square openings of 100 to 150 mm). It is also named welded wire fabric (WWF). This should not be confused with the kind of nets used in fences

(chain link mesh). Chain link mesh usually has a wire thickness of 2 to 3 mm and openings of 50 mm; it should not be used in shotcrete, due to the small openings which would cause a build-up on the net and leave voids behind it.

It is very difficult to improve efficiency when using WWF because it cannot be automated; it is all manual work. The cost of reinforcement by WWF is thus constantly increasing, because the production capacity is fixed. The erection cost in Norway for WWF is £9–12 per m^2, not including any cost incurred due to the delay in tunnel excavation.

It is important to be aware of the purpose of reinforcement in shotcrete. There is always the possibility of unexpected loads and deformation in shotcrete used for rock support. The best possible safety margin is achieved by the highest possible fracture energy in the shotcrete layer. The fracture energy is represented by the area below the load deformation curve resulting from tests on beams under flexural loading (Figure 16.5).

Modern steel fibre technology improves this parameter by a factor of 50 to 200 over non-reinforced shotcrete (Figure 16.16). In practical terms this means that a shotcrete layer may crack and deform visibly and still have a lot of fracture capacity left. There will normally be plenty of time for observation and strengthening if required.

Reinforcement by WWF may produce similar results if the thickness is about 100 to 150 mm and the steel quality is correct. However, if the net is produced from cold drawn wire, it will break under very small deformations, which might be dangerous. Reinforcing shotcrete with WWF also creates a problem with quality. The shadow effect produces voids behind the bars. This is the case regardless of the shotcrete method. Since the wet-mix method lends itself so well to steel-fibre reinforcement, this problem is solved and at a lower cost. In rock support where deformation always has to allowed for, this is a valuable asset in the quality of the wet-mix method.

Tunnel support methods

It is beneficial to select a temporary support which can act as a permanent support later, or act together with other permanent support methods. The most commonly used support methods are: rock bolts (sometimes combined with steel straps), shotcrete (usually steel-fibre reinforced) and cast concrete using steel shuttering. In recent years it has become increasingly common in very poor rock conditions to replace the traditional cast concrete by steel-fibre reinforced shotcrete combined with rock bolts and steel bar reinforced ribs of shotcrete (*see* Figure 16.9).

16.11 Spraying techniques

Nozzle technique

The sole objective of shotcreting is to obtain a compact, dense and solidly adhering layer with the best possible utilization of the mix, i.e. the lowest possible rebound loss. As explained later, a number of factors affect this, such as the force and impingement angle of the jet. Since the velocity of the material emerging from the nozzle is usually predetermined, the force of impact depends upon the distance

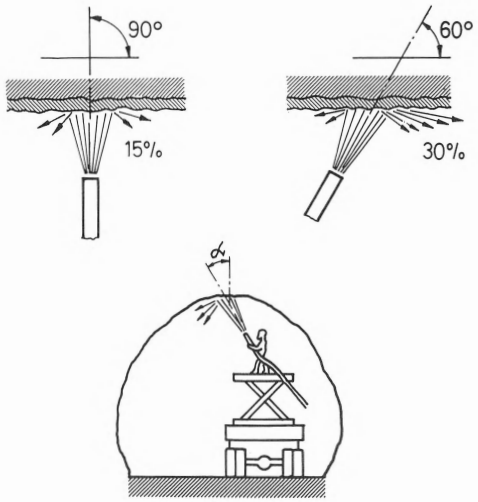


Figure 16.17 *Optimum spraying angles.*

between the nozzle and the substrate surface. If this distance is too short no layer will build up on the surface, because the deposited material will be continuously washed away by the jet. If the distance is too great, the force of impact will be too weak to provide proper adhesion and compaction of the concrete. In either case, the rebound will be excessive, because little material will adhere to the surface. Conversely, the rebound is kept to a minimum when the distance between the nozzle and the substrate surface relates correctly to the exit velocity of the material. It is very important for the nozzleman to maintain this distance exactly.

The angle at which the mix rebounds from the substrate surface is the same as the angle at which it strikes it. The more oblique the angle of impact, the more material will be lost. Hence the nozzle should always be held at right angles to the substrate surface (Figure 16.17).

Strength, compaction and adhesion of the shotcrete are greatly affected by cavities and porosity. Defects of this type occur when rebound collects, for instance, on rock projections or in fillets, or when the encasement of reinforcing bars is inadequate. The occurrence of such defects behind reinforcing bars is referred to as shadowing. It is up to the nozzleman to manipulate the nozzle skillfully to avoid any rebound pockets or accumulation of rebound. Because it is not always possible to spray in the rebound compactly or blow it away with the jet, the hose-dragger often has to assist by removing the rebound with an air blow pipe.

If the fresh shotcrete is to adhere properly to the substrate, its dead weight should not exceed either the internal cohesion or the strength of adhesion to the surface. If the fresh shotcrete layer is too thick, and therefore too heavy, it will break away from the surface under its own weight. This tendency is minimal on vertical or sharply inclined surfaces, because there is pronounced self-support in such cases. Real judgement is required in the case of vertical surfaces. A thick and hence exces-

sively heavy shotcrete layer applied to such a surface will often sag only slightly, without falling off. Serious defects of this type can easily go unnoticed. They are discovered only after the shotcrete has hardened, when the material is checked for cavities with the hammer. Consequently, no more shotcrete should be applied in each layer than will adhere properly. An experienced nozzleman will always stay just below this tolerance limit.

Subsequent layers of shotcrete can be applied only after the previous one has hardened sufficiently. In the absence of compelling reasons to the contrary, such as the rapid application of the thickest possible layers for support in tunnel headings, it is advisable to build up the prescribed concrete thickness from as many thin layers as possible. Each layer should be given sufficient time to shrink before the next is applied. Thus each new shotcrete layer will cover the shrinkage cracks of its predecessor, and the complete section will have a crack pattern similar to the favourable joint pattern in brickwork.

Rebound

Rebound is the phenomenon connected with shotcreting that has the greatest number and variety of causes. It is not easy to say which of the many, mutually dependent factors are the most important but the nature of the aggregates, composition of the starting mix, substrate surface quality, pressure, skill of the nozzleman, layer thickness are all important.

Without a doubt, the gradation of the mix and the structure and hardness of the substrate have a great effect on the rebound material. This is confirmed by close observation of the shotcreting operation. The jet strikes the usually hard and unyielding substrate, say rock or concrete, with great force. During the first moments, the coarser aggregate particles cannot adhere because there is no layer in which they can be embedded. Only after a five to ten millimetre thick layer of aggregate fines, grout and fine sand has built up on the substrate surface can the coarser particles start adhering. Some of them will continue to rebound, however, and a certain proportion of the finer components and cement will also be lost with the coarser particles, because they adhere to them or are carried along by them.

The quantity and composition of the rebound depends on the thickness of the layer. At the start of spraying nearly all the coarse components rebound, but only part of them do so afterwards. Therefore, the rebound is coarser to start with and finer later on; in any case, it contains less cement than the starting mix. After the layer has reached a certain thickness, the quantity and nature of the rebound remain constant unless other factors change.

It is not surprising that the structure of the substrate surface also affects rebound. In the main, the rebound angle is the same as the impingement angle. If the surface is smooth and the nozzle is held at right angles to it, the trajectory of the incoming and outgoing particles will be largely identical. The situation will be quite different in the case of an irregular surface, such as very jagged rock. Each facet will deflect the jet differently, so that a welter of intersecting rebound angles results (Figure 16.17). Rebounding particles again strike projections on the substrate surface, and turbulence occurs in recesses that mix the jet with the rebounding particles. It is not surprising, then, that more mix is lost in the case of uneven surfaces than even ones, and that the more irregular the substrate surface, the greater the

rebound. This knowledge is the basis of the extremely important rule that the nozzle should always be kept as near to perpendicular to the application surface as is possible, though this cannot always be achieved. The nozzle cannot possibly be adapted to the angle of each facet of a very irregular rock surface. In this case, the nozzle should be held to suit the prevailing surface plane.

The specific phenomenon of rebound is exactly the same regardless of whether the application takes place vertically upward, horizontally or vertically downward. The ricochet dynamics are the same in each case, but the amount of material ultimately lost in the form of rebound differs greatly. If one is shotcreting vertically upward to coat the roof of a tunnel, practically every particle of rebound drops to the ground and the rebound loss is at a maximum. If the jet is directed horizontally against a vertical wall, part of the rebounding material will be picked up again by the jet before it drops to the ground. So the amount of rebound loss will be less for a vertical substrate surface. Finally, if the jet is directed straight downward, say on the floor of a basin, the rebound material will fall back to the substrate surface. An experienced nozzleman can gun it continuously back into the layer. So little or no rebound loss is suffered in the case of a nozzle directed vertically downward.

The amount of rebound generally declines slightly if a quick-setting accelerator is added during application. This means that a thicker layer can be applied in each pass. Particularly in the case of vertical substrate surfaces, a properly metered accelerator admixture makes it possible to build up shotcrete layers of virtually unlimited thickness on a continuous basis. This is done by working from bottom to top and taking advantage of the supporting effect of the concrete already placed in addition to the accelerated setting effect. Because rebound has so many different causes, only a rough percentage can be stated as the "normal" amount. For overhead work, 10–15% of the mix may be lost, on vertical surfaces 3–8%.

Substrate

The physical state of the surface is critical for the bond with the shotcrete because the adhesion of the shotcrete depends solely on mechanical meshing with the surface. During the first split second of impact, a thin layer will be formed, consisting of the finest constituents of the jet, namely grout and aggregate fines. This provides a good layer for the following, coarser consistency of the aggregates, and penetrates into the smallest irregularities, pores and cracks of the substrate due to the impact force. Consequently, the shotcrete and its substrate will mesh together intimately after the cement sets on the contact surface. The same applies to the coarse structure of the substrate. The meshing effect will be greater between shotcrete and a jagged rock face than it would be on a smooth granite slab.

Surface structure, strength and cleanliness of the substrate are all equally important for effective adhesion of the shotcrete. The rougher, sounder and cleaner the substrate, the better the adhesion of the shotcrete. This rule makes it possible to generalize about the bond obtainable between shotcrete and various materials. Shotcrete adheres well to rock, provided the rock is freshly broken and solid. This is generally the case at the heading of tunnels and caverns being driven through rock. Adhesion becomes problematical in the case of friable or flaky rocks, such as shale. The same is true of rocks that suffer surface decomposition in contact with air or moisture. Outdoor rock surfaces are generally badly soiled and weathered on

the surface to various depths. Such rock surfaces have to be thoroughly cleared and painstakingly cleaned if the shotcrete is to adhere properly. They must be washed; in certain cases it is even necessary to use high-pressure water, steam or sand-blasting.

16.12 Outlook: The potential for shotcrete applications

Shotcrete is mostly used today in rock support where it has solved many difficult problems and has become a necessary aid. There is a clear trend to the application of greater volumes of shotcrete in international tunnelling and for rock support. The total volume, in Europe alone, is more than three million cubic metres per year. In the author's opinion, this increasing trend will continue for several years to come.

Aknowledgement

The author would like to thank colleagues within MBT's Underground Construction Division for their assistance and support in the preparation of this chapter.

Bibliography

Allen, Ch. (1993) Controlled Hydration Shotcrete Mixes for Infrastructure Projects. *Infrastructure Conference – The Role of Concrete*. Concrete Institute of Australia, Sydney.

Drs J. Internal report: Aluminate based accelerators.

EFNARC (1993) *Specification for sprayed concrete*. Final Draft.

Kinney, F.D. (1989) Reuse of Returned Concrete by Hydration Control: Characterisation of a New Concept. Proceedings Third International Conference, *Superplasticizers and Other Chemical Admixtures in Concrete*. Ottawa, Canada.

Krebs C. MEYCO, Internal report: Equipment for shotcrete.

Master Builders Technologies (1988) *Technical Report 128, Delvo System*. Cleveland, USA.

Master Builders Technologies (1991) *MEYCO Journal No. 1*. Zurich, Switzerland.

Master Builders Technologies (1991) *MEYCO Journal No. 2*. Zurich, Switzerland.

Melbye, T. (1993) Neue Generation von Zusatzmitteln für Spritzbeton. Spritzbeton Technologie 1993, Universität Innsbruck, Austria.

Melbye, T. (1993) New Advanced Shotcrete Admixtures. *Sprayed Concrete Conference* 1993, Brunel University, London, UK.

Norwegian Concrete Association Technical Specification and Guidelines: Sprayed Concrete for Rock Suport. Committee on Sprayed Concrete.

Opsahl, O.A. (1982) *Steel-Fibre Reinforced Shotcrete for Rock Support*. BML-Report 82.205, Division of Building Materials, The Norwegian Institute of Technology, Trondheim.

Opsahl, O.A. (1992) *Konstruktiv anvendelse av sprøytebetong*. NIF kurs Storefjell.

Ramachandran, V.S. (1984) *Concrete Admixtures Handbook*. Noyes Publications, 116–172.

Skurdal, S. and Opsahl, O.A. (1985) *Dramix Shotcrete in Ground Support, Large Scale Testing*. Robocon Shotcreting System, Norway.

Vandewalle, M. (1990) *Tunnelling the World*. N. V. Bekaert S. A.

17 Cathodic Protection of Reinforced Concrete

B.S.Wyatt, Tarmac Structural Repairs, Wolverhampton

17.1 Introduction

It is well recognized that many reinforced concrete structures are at risk of deterioration due to chloride ion contamination of the concrete. Within the alkaline concrete the chloride ions disrupt the passive film which otherwise protects the steel reinforcement from corrosion. The environment within the concrete will determine the form of the corrosion products. These may be primarily hydrated higher oxides of iron which, due to their high volume, can generate early cracking and spalling of the cover concrete for little loss of reinforcement section. If the environment is deficient in oxygen, the corrosion products may be less voluminous but the corrosion may result in deep pitting and serious loss of reinforcement section.

There has been much publicity relating to highway structures and multi-storey car parking facilities suffering chloride contamination and corrosion due to applications of rock salt as a de-icing medium during winter ice and snow. It is estimated that in the USA there are approximately 300 000 bridges which are candidates for cathodic protection. An expenditure of US $23.1 billion would be required to execute the repair and cathodic protection works, a saving of $89 billion compared with replacing the affected bridge decks (Hull, 1985). In the UK, approximately 10% of reinforced concrete bridge stock administered or owned by the Department of Transport will require an expenditure of £755 Million at 1989 prices during the next 10 years to correct the damage caused by corrosion (DoT, 1989). Less well publicized, but probably of equal importance both in terms of impact on the economic and environmental well being of our societies is the corrosion damage to harbour and other coastal civil engineering structures due to chloride contamination from sea water (John *et al.*, 1989; Leppard and John, 1991) and corrosion damage, particularly to buildings, caused by deliberate or inadvertent use of chloride rich concrete during construction.

Many of these structures currently suffering from chloride related corrosion have a sufficiently long useful life and high replacement cost to justify the search for a long term repair and protection strategy. There are various options for long and short term repair of chloride contaminated reinforced concrete. There have been full scale trials on UK highway support structures including surface treatment, concrete repairs, structure replacement and cathodic protection (Boam and Unwin, 1990). International trials are underway to determine whether chloride removal by electro-osmosis is an effective option (Bennett and Schue, 1990).

Cathodic protection of reinforced concrete is emerging as the most viable mid to long term solution for reinforcement corrosion. It offers significant initial capital cost savings compared with extensive removal of contaminated concrete or replacement/reconstruction. It has developed a track record of success and reliability for those systems that have been properly selected, designed and executed. Expenditure in the UK on cathodic protection of reinforced concrete has grown from an estimated £100 000 in 1986 to some £20 million in 1991. Typically the capital cost advantage of repair with cathodic protection over other long term options will be at least a factor of two; for highway structures that require temporary support of live and dead loads during the alternative extensive repairs, the savings can be up to a factor of 10. The Department of Transport estimates that with cathodic protection, approximately £140 milion could be saved on repairs to its highway structures during the next 10 years, which would otherwise result in a final bill of £615 million. As they are responsible for only 10% of all UK reinforced concrete bridges it is easy to predict a requirement (but not the origins of the funding of the expenditure) for a spend of £100 million per annum on concrete repairs with cathodic protection for UK highway support structures alone.

It is critical for the success of cathodic protection of reinforced concrete, that the correct systems are selected for a particular structure and its environment and that they are designed, installed and operated in a proper manner. These activities require expertise in the fields of civil and structural engineering, concrete technology and concrete repair technology to be fully integrated with expertise from the corrosion engineering and cathodic protection fields.

An activated titanum mesh anode within a cementitious overlay is the right choice for environments which are particularly severe, e.g. high chloride contamination, repeated wetting, vulnerability to mechanical wear or vandalism and for those structures which either have a particularly long life or a high cost of access for anode reinstatement. For vertical and soffit surfaces the preferred overlay application method is usually sprayed concrete.

The success of the sprayed concrete will largely be measured by the success of the cathodic protection itself. It is therefore vital that designers and applicators of sprayed concrete used for this purpose have a detailed understanding of the fundamentals of cathodic protection as well as how sprayed concrete fits into this environment. This chapter provides a grounding in both of these areas.

17.2 Anode systems

The historical development of many anode systems including those which have failed to deliver adequate performance and cost effectiveness has been detailed elsewhere (Federal Highway Administration, 1983). This chapter considers those anode systems that continue to offer effective and reliable service and are currently options for the design engineer. The chapter will also deal briefly with less secure systems.

Bridge deck conductive overlay anodes

Early cathodic protection systems for bridge decks, by Stratfull and others, used primary anodes of high-silicon cast iron distributed over the top surface of the

deck, with a nominal 50 mm thick metallurgical or calcined petroleum coke/asphalt conductive overlay. The poor mechanical and water shedding properties of the coke/asphalt conductive overlay dictated a further 50 mm wearing course of asphaltic concrete. Well in excess of 35 such installations were installed in the US during the period 1973 to 1980, and many are reported as still being in satisfactory working order (Stratfull, 1959, 1974, 1985; Federal Highway Administration, 1983; Anderson, 1985).

A variation of the overlay system developed by Stratfull was instigated by Fromm (1981) in which the mechanical and water permeability properties of the conductive overlay were improved by the addition of sand and stone aggregate. This modification allowed a reduction in the thickness of both conductive and wearing course overlays from 50 mm to some 40 mm each, with consequent weight and cost savings. Further variations included inserting the anodes, cables, and monitoring devices in cutouts in the original concrete deck to allow for future resurfacing. Some 50 such systems have been installed, and the system is considered as one of the three routine options for bridge deck rehabilitation in Ontario (Manning and Bye, 1984).

The conductive overlay anode systems are not appropriate for applications of cathodic protection to soffits or vertical surfaces and are, therefore, applicable only to corrosion problems on bridge or car park decks. Weight and height restrictions (particularly in car parks) may limit their application to some decks. Conductive overlays are not proprietory systems, therefore there are no manufacturers promoting their use. Despite this they should be given serious consideration in any bridge or car park deck application which can withstand the weight and dimensional implications of this simple, well proven and low cost anode system.

Slotted anodes

Slotted anode systems were developed initially for bridge decks to overcome the weight, height and possible surface wear disadvantages of the conductive overlays. Initial installations were made in 1977 and used a cementitious mortar to embed a platinum clad niobium wire. The anodic reaction products caused acid attack of the mortar, and development of the slotted anode systems was directed towards improved conductive cementitious and polymer grouts (Nicholson 1981; Federal Highway Administration, 1982; Clear, 1985 and Clemena, 1985).

Even the most prominent of the original proponents of the slotted systems, Clear (1985), indicates that these systems are flawed by the small size of the anode and unavoidable high anode current density. Although some contractors, material manufacturers and patent holders continue to promote these systems in North America it is expected that their poor performance will not result in applications in Europe and elsewhere. It was in the development of these slotted systems using graphite filled polymer grouts that the current North American "standard maximum anode current density" figure of 108 mA/m^2 was empirically derived. It is noted that even slotted systems working at these anode current densities have suffered acid attack or other failure of both the conductive polymer grouts and the surrounding concrete and that the application of the 108 mA/m^2 figure may not be appropriate for other anode materials. Despite the reported problems with these systems over 100 have been installed in North America.

Conductive coating anodes

Requirements to provide cathodic protection for bridge support structures in Florida in 1974 stimulated investigations into the development and testing of both conductive concretes and conductive coatings for cathodic protection (Brown and Kessler, 1983). Early work concentrated on the addition of calcined petroleum coke to concrete to form a conductive secondary anode to be used in conjunction with platinum clad niobium primary anode wires. Limited trials initiated in 1977 with conductive concrete were reported to be successfully operating in late 1984 (Brown, 1985) but, apart from field trials described in the same paper and later in 1987 (Clemena, 1987), conductive concrete does not appear to have become a widely used anode system. It is understood that one European cementitious repair and overlay manufacturer is experimenting with advances to this technology.

Later in the same development programme, Brown and his colleagues in Florida, investigated the effectiveness of six different conductive coatings from three manufacturers. Trials were undertaken for two years on columns, supporting vertical walls and deck soffits in highly aggressive estuarine conditions, including some trials with conductive coatings applied in the splash zone just above high tide. Although, not unexpectedly, some conductive coating failure was reported in the splash zone areas, the conclusion of this study was that conductive coatings were suitable materials for cathodic protection of a variety of concrete structures.

In a detailed study commenced in 1982 and reported in 1985 the most successful of the conductive coatings tested in Florida (Porter XP90895, Redesignated DAC-85), a solvent based, acrylic mastic containing graphite was compared with a water-based acrylic material filled with graphite and a latex based carbon-filled coating. Laboratory tests included freeze-thaw cycles, wetting/drying and heating/cooling cycles, ultra-violet exposure and a range of electrical and bond tests to determine the results of these accelerated environmental conditions. These tests concluded that the DAC-85 coating was much more durable than the other coatings tested and further field trials were instigated with this coating only.

Subsequently conductive coating cathodic protection systems have been successfully applied to bridge structures, car parking facilities and buildings (Lehmann, 1985*a*, *b*). It is understood that in excess of 200 000m^2 of reinforced concrete have been protected with DAC-85 conductive coating in North America and elsewhere.

The significant advantages of the conductive coating system are that, being a coating, it can be applied to complex shapes in any orientation and presents no problems of weight or dimensional limitations. In addition, conductive coating systems can be installed onto suitable structures at approximately half the cost of alternative distributed anode systems which require substantial overlays. Conductive coatings thereby avoid possible cementitious overlay disbondment problems. Other conductive coatings have been developed and some are reported to operate satisfactorily.

These anode systems are currently being specified for the majority of cathodic protection systems in the UK, notably for the protection of highway support structures for the Department of Transport. It is estimated that some 30 000m^2 of such structures have been or are now in the process of being protected using conductive coating anodes. Typical cathodic protection costs for these projects are around

£60–75/m² and combined concrete repair and protection costs £120–150/m² excluding temporary supports. Re-coating with the conductive coating is estimated to cost some £25/m² at 1994 costs.

Flame or arc sprayed zinc

Sprayed zinc is an alternative conductive coating system to the various graphite filled organic coatings. Zinc is applied to the concrete surface by either oxy-propane or plasma arc methods, and is used as an impressed current anode in exactly the same way as the graphite/organic conductive coatings. This system is reported to have been used with some success in North American trials (Apostolos *et al*, 1985, 1987) and has recently become available in the UK. At least one large project has been undertaken in the USA and has been reported along with work to optimize the application techniques (Brousseau, 1992). In addition, sprayed zinc has been used in the very moist, warm, conditions in the Florida Keys as a sacrificial anode without an external power supply. The approach used, with reported success, has been to expose and clean reinforcement in areas of concrete deterioration and then to apply zinc to both the reinforcement and the surrounding concrete (Kessler *et al*, 1990).

It should be noted that the sprayed zinc anode system had a total worldwide application history of 650m² when reported in 1987 (Mudd *et al*, 1988). Even with the recently reported applications sprayed zinc retains a small proportion of conductive coating market.

Activated titanium mesh anodes

These anodes require a cementitious overlay when applied to concrete structures and are therefore of particular relevance to sprayed concrete applications. Expanded titanium mesh coated with mixed metal oxides or precious metal compounds are proving to be one of the most widely used and successful anode types. They are related to anode materials which are widely used in electrochemical applications such as chlorine generation and electrowinning. Proprietory coated titanium mesh anodes specifically designed for cathodic protection of reinforced concrete are the Eltech Elgard, DeNora Permalec Lida-Mesh and a product similar to Elgard from Eltech's one time affiliate company Heraeus Elektroden. A similar protection from ICI was withdrawn from the market due to commercial and patent factors.

Dimensionally the various manufacturer's activated titanium mesh anodes are similar. They are formed from titanium sheet 1 mm thick, cut and expanded into a diamond shaped mesh, dimensions 100 × 50 mm. The particular cutting, expansion and resultant mesh dimensions are tailored to provide meshes of different anode surface area per unit area of mesh, enabling the selection of different grades of mesh to suit differing steel/concrete current density requirements and differing steel densities within the concrete.

The individual manufacturers are notably reticent regarding their proprietory coatings applied to the expanded titanium. It is clear from published information that some of the manufacturers utilize conductive formulations including oxides of Ti, Ta, Ir, Ru (Hock *et al*, 1988). It is believed that others may include oxides of Pt or Pd or consist of spinel materials containing cobalt. It is widely accepted that

activated titanium mesh anodes have an anticipated service life in the range of 20 to in excess of 100 years (Hock *et al*, 1988; Mudd *et al*, 1988; Warne, 1988). ICI reported accelerated life test data producing theoretical life for their now withdrawn Tectrode material in excess of 400 years and acid resistance significantly in excess of even their own enhanced acid resistance MA grade platinized titanium (Hock *et al*, 1988; Mudd *et al*, 1988; Hayfield and Warne, 1988).

There is an emerging ASTM/NACE accelerated test procedure for this type of anode (Schell, 1987) and one manufacturer implies that the coating compositions and thickness are tailored to give a minimum 40 year life at a uniform anode current density equivalent to a constant cathode demand of 20 mA/m². Some might consider this requirement too lenient in view of probable non-uniform current density demands and a lack of test data for other possibly important parameters such as acid resistance.

The various activated titanium mesh anodes are similar in that they are manufactured in rolls approximately one metre wide. All the manufactures have commercially available spot welding systems proven for use with their anode materials. These systems can be rapid, convenient and of low cost for use on bridge or car park deck applications. However, the weight and electrical safety aspects of the spot welding equipment may be disadvantageous in particular applications such as soffit work immediately above sea water. All systems utilize proprietory plastic fixings to attach the mesh to the concrete surface. Some applications have used anode mesh installed by fixing to reinforcement in both new construction and reconstruction. Particular design and application care is required to ensure that there are no short circuits established between anode and reinforcement during concrete placement and compaction.

The titanium mesh anode systems are flexible in that the different grades of material available provide concrete surface area current densities of approximately 15 mA/m², 20 mA/m² and 30 mA/m². Therefore the design can be tailored to reflect the reinforcing steel density and steel/concrete current density requirement variations over a structure by selecting different grades of anode or even combinations of grades in multiple layers for parts of the structure with high local current demands.

The Eltech Elgard material has the most extensive track record of the activated titanium mesh anodes with over 400 000m² of projects being listed to November 1991. This probably reflects their "home base" in the USA where the market to date has been largest. However, all the manufacturers have objective claims to extensive track records of similar anode materials in related electrochemical applications and it is not yet possible to infer that any one system will be either technically or commercially superior to the others.

Although product literature from some of the anode manufacturers indicates that the maximum anode current density is 108 mA/m² (10 mA/ft²), this figure is understood to be based upon the maximum derived for carbon-based conductive polymer mastic in slotted anode systems and merely reflects the emerging standards based on these figures from the USA. Data from the manufacturers of titanium based anodes indicate that these anode materials can be operated at 200 mA/m² without significant deterioration to either anode or surrounding concrete and, for the short term, at up to 400 mA/m² without deterioration of the anode coating

(Mudd *et al*, 1988; Warne, 1988).

Activated titanium anode materials have been developed in different physical forms to suit particular applications. Notably one manufacturer is promoting anode in strip or ribbon form for applications in new construction and relatively localized protection and another offers a high surface area grid anode that can be cut and assembled into anode forms that enable current density to be tailored precisely to cathode current density requirements. Typically cathodic protection costs for projects utilizing titanium mesh anode with sprayed concrete overlays are around £100-125/m² compared with the £60-75/m² for the shorter life conductive coatings.

Internal discrete anodes

The use of discrete anodes for cathodic protection of reinforced concrete has been established in trials using surface mounted conductive ceramic discrete anodes (Lewis and Boam, 1987) and using surface mounted anodes of precast conductive resin (Schell, 1987).

Since 1986 the Danish consulting engineering firm Birch and Krogboe have been experimenting with and subsequently (in conjunction with the system manufacturer Cathodic Protection International Aps) installing commercial cathodic protection systems using internal discrete anodes. The anodes used are in the form of platinized titanium solid rod, of 3 mm diameter and typically 50 to 200 mm long. The anodes are inserted into drilled holes 12 mm diameter and are backfilled into the centre of the hole with a graphite paste. Twenty five projects had been completed by 1991 (Nielsen-Dharmanratne, 1991; Groenvold, 1991) including one in Denmark for the protection of 3100 beams and columns which required 40 000 individual anodes over a concrete surface area of some 8200m².

This anode system is offered by its manufacturer as part of a fully integrated cathodic protection system comprising not only the anode system but also power supplies, monitoring and distribution cabling and junction boxes. The developers of the system report total repair and cathodic protection costs of less than £50/m² for one car park project and calculations for the Danish project appear to show a cost of £150/m² (Schell, 1987).

This anode system is in many ways more closely related to "conventional" buried structure cathodic protection than any of the other anode systems described earlier. It has potential for the types of structures which have to date received cathodic protection and for those critical parts of structures such as joints or under bearings which may not be susceptible to full cathodic protection with surface mounted anodes.

Other anode systems

Sacrificial anodes have been used for trial bridge deck applications, but have been proven to have insufficient driving voltage to achieve adequate protection (Stratfull, 1974). Some projects have been undertaken in North America using co-extruded platinum-clad copper-cored niobium anode wire directly in cementitious overlays.

Raychem Corporation played an active role in the 1980s promoting cathodic protection of reinforced concrete using their Ferex polymeric wire anodes. Raychem were also involved in the development of flat strip conductive polymer anodes for

mounting directly on the surface of concrete. It is unclear what, if any, progress can be expected from this or related quarters using polymeric anode materials or adaptations of the surface mounted concept using activated titanium mesh anodes.

It is likely that there are other developments underway in ceramic, coated metal and conductive coating anodes which may widen the choice of anodes for reinforced concrete cathodic protection. As it will not be easy for system designers to effectively balance proven track record of the presently available anode systems against the possible merits of new but unproven anode materials, it appears most likely that the vast majority of cathodic protection systems for reinforced concrete will incorporate the proven anode technology represented by conductive overlays of coke/asphalt, conductive coatings, activated titanium mesh and internal discrete anodes.

17.3 Overlays for anodes

It is not appropriate to consider anode materials in isolation from the overlays which often form an integral part of the anode system. One of the commercial/contractual problems that has delayed the growth of cathodic protection of reinforced concrete has been the difficulty encountered by purchasers in obtaining a clear source of performance responsibility for an anode system that incorporates anode materials and overlay materials from different manufacturers each with a limited understanding of the other companies' products.

Sprayed concrete overlays

Sprayed concrete has been used, sometimes with controversial results, in a number of trial and full scale applications as an overlay to both polymer wire anodes and titanium mesh anodes. Well publicized trials by highly respected workers in Ontario (Wyatt and Lothian, 1988) have been reported to show delamination of sprayed concrete which might be related to the transmission of cathodic protection current. Other instances of delamination appear to be related directly to insufficient surface preparation and to be quite unrelated to cathodic protection current or even the presence of anode at the overlay/substrate interface.

Well executed trials and commercial projects, notably the Mina Zayed undertaken in 1988/90 and reported in 1991 (Wyatt *et al*, 1991) point clearly to the importance of:

(i) surface preparation;
(ii) substrate pre-wetting;
(iii) applicator technique; and
(iv) curing methods,

in the achievement of good overlay/substrate adhesion, irrespective of the presence or operation of cathodic protection anodes. It is concluded that the success of these trials and commercial projects will define the requirements of items (i) to (iv) above and prove conclusively that properly executed sprayed concrete is a suitable and economic overlay for titanium mesh anodes.

It is normal for sprayed concrete to provide 25–30 mm of cover to the anode system, i.e. a sprayed concrete total thickness over the substrate of 30 mm. There is some indication that localized lack of cover to anode material can result in local

high current discharge with resultant damage to anode or overlay, particularly if the area of low cover happens to be wetted frequently.

Sprayed concrete used as a cathodic protection anode overlay is, perhaps, the most critical application of the sprayed concrete technology. There is no secondary steel provided to give a supplementary key between the substrate and the overlay; the sprayed concrete integrity is determined by the cohesive bond between it and the substrate. Further, the anode mesh, its conductor strips and associated cables may all provide points at which the access to the substrate may be less than perfect and, if inadequately fixed, may vibrate in the sprayed concrete stream and cause voids. In addition, because cathodic protection is still relatively unusual and it requires regular (typically annual) measurement and control, the sprayed concrete overlays are subject to more regular and critical review than a more conventional strengthening or repair overlay.

The forthcoming European Standard for Cathodic Protection is anticipated to define a minimum bond strength of 1 N/mm^2 for sprayed concrete overlays to cathodic protection anodes and to allow both site batched and pre-bagged materials both with and without polymer and cement replacement additions. The reader should refer to other chapters of this book with regard to materials (Chapters 2 and 3) and mix design (Chapters 6 and 7).

Any specification for sprayed concrete overlays associated with cathodic protection anodes should require trials of the proposed surface preparation technique. A rigorous abrasive grit blast to expose aggregate, producing a 2–3mm profile and a clean non-friable surface is the preferred surface preparation. For some substrates, mechanical scabbling or hydro-demolition techniques may be acceptable but they introduce risks of damage to the surface aggregate and uneven preparation, respectively. This may in turn limit the overlay/substrate bond strength. Measurement of the cohesive (tensile) strength of the prepared surface by pull-off techniques is a valuable procedure in selecting the specific preparation method for a particular substrate (see Chapter 5, section 5.7).

Pre-wetting of the substrate is critical in the achievement of good overlay/substrate bond. Sufficient saturation of the substrate to prevent suction of moisture from the overlay is necessary; this may require pre-wetting for 24 hours prior to overlay application. To maintain the highest levels of cohesive bond between the overlay and substrate, it is recommended that the sprayed concrete is finished by cutting to dimension and flashing; finishing by steel float increases the risk of disturbing the interface, resulting in an inadequate bond.

Immediate placement of a curing compound is highly beneficial as the anode system within the overlay will have none of the crack restraint properties of even a light secondary steel reinforcement. In this respect also, cathodic protection anode overlays of sprayed concrete are more vulnerable to imperfect workmanship than almost any other application. It should be emphasized that sprayed concrete is sensitive to applicator skill. Standards for sprayed concrete are available and should be used. Individual operators should be tested and approved for the type of work envisaged and the specifications and selection of contractors should take into account the challenging nature of installing as an anode overlay compared with spraying steel reinforced repair overlays or new construction such as swimming pools. The UK Sprayed Concrete Association operates a training scheme in conjunction

with the CITB and administers the *Certification of Training Achievement for Sprayed Concrete Operators* scheme.

With the appropriate attention to overlay/substrate adhesion the Mina Zayed project used sprayed concrete as an overlay to titanium mesh anode applied to 11 000m² of beam sides and soffits. A total of less than 10 m² of delamination were located and repaired at a full inspection 3 months after placement. Further full inspections 12–18 months after placement confirmed no new delaminations and no growth of those which had been repaired.

Relatively thin cementitious renders containing only fine aggregates and placed by low pressure spraying or by hand trowelling (both techniques similar to those used for domestic plastering) have been used with mixed success as an overlay for titanium mesh anodes. The ability to place well adhering, thin layers of render either by spray or by hand, over the thin titanium mesh anode presents significant advantages over poured or sprayed concrete for structures where weight or dimension are critical or in environments where sprayed concrete is not appropriate due to aggregate rebound and dust problems. However, caution should be exercised and extensive field trials undertaken with such a setup before they are used in commrcial projects.

Poured concrete overlays

Titanium mesh anodes have been used widely for bridge deck applications in North America for which conventional and air entrained concrete have been used as a combined anode overlay and wearing surface. As with any such paving application it is necessary to abrade the substrate concrete surface mechanically to present a clean, laitence free, exposed aggregate surface to ensure good bonding with the overlay. It is equally important to wet the substrate thoroughly to avoid suction effects, extraction of water from the overlay and reduction in bond strength between the substrate and the overlay. These procedures are normal for any paving concrete contractor, which is probably why there have been no published reports of poor bonding of such concrete overlays.

It is normal for such running surface overlay concrete to have a minimum thickness of 40–50mm. This provides an ideal, if somewhat excessive cover for the titanium mesh anodes which have an installed thickness of only 1–2mm. Variations on this technique which are understood to have been used with at least two of the titanium anode mesh materials are:

(i) to place the mesh into the surface of green, recently placed concrete and to pour the overlay immediately, achieving the smallest of construction joints at the interface.

(ii) to use mounds or strips of concrete to fix the mesh in place (rather than drilled plastic fixings) prior to placing the overlay concrete.

The author has been associated with a project in which 13 500m² of titanium mesh anodes have been successfully laid onto wet concrete and then, within 30 minutes of placing the first concrete, incorporated into an overlay of 25 mm of placed and vibrated cover concrete.

A significant modification and recent development in the use of conventional concrete as an anode overlay has been the relatively small scale use of shrinkage-compensated enhanced-flow concrete repair materials. These proprietory repair

materials have been specifically developed for the repair of bridge and road reinforced concrete structures. The geometry of such structures and associated reinforcing steel concentration has dictated the use of extremely fluid materials which can be pumped or poured into complex formwork around columns, beams or panel walls. The material must fill all interstices behind exposed reinforcing steel and yet not shrink and crack away from the substrate concrete. These materials have been used with some success as combined concrete repair and anode overlay materials in combination with titanium mesh anode in various trials in Europe.

Other overlays

The conductive overlay system for bridge decks incorporates its own overlay system as described earlier, although even conductive coatings have been used with overlays. The simplest of these is a decorative overcoat, often of white or light grey paint, to improve the otherwise black finish of the carbon loaded conductive coating and, possibly of greater importance, to provide UV protection and to limit heat gain in the structure.

There are limited reports from North America of some successful trials of conductive coatings under both sprayed polyurethane coatings and sprayed acrylic modified mortars, enabling conductive coatings to be used on the running surfaces of car park decks. The results of these trials are, as yet, unpublished and some caution should be exercised in extending these trials before the results of the earlier works are known.

Sprayed zinc anode systems may be developed with phosphate or chromate based overcoats to limit the atmospheric corrosion of the external zinc surface. The activated titanium mesh anode types require overlays in all applications except when incorporated into some forms of new construction.

17.4 Selection and design of anode systems

Over the past thirty years of development of these systems, four generic anode systems have been developed in whose performance the system designer can have reasonable confidence if properly applied and operated. These systems are:

(i) activated titanium mesh anodes within cementitious overlay (e.g. sprayed concrete);
(ii) conductive overlay anodes;
(iii) conductive coating anodes; and
(iv) discrete internal anodes.

The selection process of the optimum anode and overlay system for any given project, and consequently the potential use of a sprayed concrete overlay, should include the following considerations.

Structure geometry and service

Activated titanium anodes with cementitious overlays such as sprayed concrete are suitable for application to concrete surfaces of any orientation. However the substantial weight of the overlay may render this method unsuitable for some structures. In addition, the difficulties or high costs of reproducing particular architec-

tural features or the simple addition of 30 mm thickness to parts of some buildings may be unacceptable.

Conductive overlays are suitable only for top of deck applications. Due to the methods of placement of hot rolled asphalt they are not suitable for applications such as tops of crossbeams. Their weight and thickness will preclude certain otherwise suitable applications.

Conductive coatings cannot be recommended for use on bridge deck or car park running surfaces despite limited trials with abrasion resistant overcoats. However many such decks are amenable to soffit applications of conductive coatings although continued water transmission through the deck, and extremes of local chloride contamination and moisture content may be strong indicators to avoid this anode type. Conductive coatings will have a limited life on structures which are regularly wetted and are not recommended for structures or parts of structures which are immersed, are splashed with sea water or which are subjected to ponding of water contaminated with chlorides.

Discrete internal anodes can be used for all orientations of surface. The requirement to supply each anode with cables within even very well designed surface cable trays may limit the use on some structures and buildings if there should be five anodes per square metre.

Reinforcement density/Current density requirement

Activated titanium mesh anodes are extremely flexible in providing a range of concrete current density figures. Products typically cover the range 15–30 mA/m² concrete current density, covered by anode mesh at an anode current density of 100 mA/m² (measured relative to the actual anode mesh surface area). For applications requiring higher current densities, two or even three layers of mesh can be applied or the DeNora Permalec anode grid system whose anode element can be rated at 70–220 mA/m² of concrete current density can be used. Discrete internal anodes can be distributed according to reinforcement density and different lengths of anode are available rated at different current outputs.

In North America, conductive overlays have been used only for relatively lightly reinforced bridge decks. It is not considered appropriate to use them for structures with a high density of steel reinforcement. Many bridge and car park decks have steel/concrete surface area ratios in the region of 0.5 to 1 (i.e. less steel surface area than concrete surface area on the top deck). This enables the conductive overlay anode to provide sufficient current to the reinforcement to meet the common design requirement of 20 mA/m² cathode current density but not to exceed the notional anode current density limit of 20 mA/m² .

Conductive coatings are similarly limited to a long term anode current density maximum of 20 mA/m² and are not generally suitable for structures or parts of structures with a steel/concrete surface area ratio in excess of one if a 20 mA/m² cathode current density design figure is required.

Vandalism and mechanical damage

It is unfortunate that many structures and buildings which are candidates for cathodic protection appear to be afflicted by vandals as well as chloride ions.

Activated titanium mesh within a sprayed concrete or other cementitious overlay can be designed with all positive and negative power cables and monitoring cables within the cementitious overlay. These systems are intrinsically vandal proof but care is required in siting and protecting power supplies and the cable routes between the supply and the structure. These systems have been employed successfully beneath wharves which are subject to storms and wash from vessels .

Conductive overlay anodes are also vandal proof but particular care is required in siting and protecting the off-bridge or under-bridge cables and power supplies. Conductive coating anodes are vulnerable to vandalism, whether it be graffiti or mechanical damage. However it is certainly possible, albeit at a higher cost, to recess all cables into the concrete surface prior to conductive coating application or to provide rigid metallic trunking (insulated from the conductive coating) which may prove vandal resistant in most areas.

Discrete internal anodes, at least in their present form, also appear particularly vulnerable to vandalism due to their surface mounted cables and anode elements (which minimise cost and aid maintenance). However, these features are not fundamental to discrete internal anodes and recessing cables and anode entries in mortar is a feasible option in areas of high vandal activity.

Anode current distribution and anode zones

It should be self evident that the primary requirement of an anode system is to deliver the appropriate magnitude of current to all reinforcement within its area of influence. The value of the "appropriate magnitude of current" will often be determined at the design stage by taking a conservative overall figure based upon previous success in similar structures with similar chloride and moisture levels and in similar atmospheric conditions.

Most designers presently use an overall design figure of 20 mA/m^2 cathode current density but there is clearly scope for reduced figures in relatively dry structures with limited chloride contamination and higher figures (at least for the early months/ years of operation) in wet structures highly contaminated with chlorides, particularly those in warm climates. Perhaps there is a requirement to learn from the offshore industry and to set levels of cathode current density provision that more accurately reflect the likely variation throughout life, e.g:

(i) *Initial.* The peak demand for polarization within a reasonable time period of, say, 3 months. This figure would determine power supply and circuit capacities and the short term maximum anode current densities would be applied. In a wet heavily contaminated structure this might be 30 mA/m^2.

(ii) *Average.* The current provision over the system design life of, say, 25 years. This figure would determine the electrochemical capacity of the anode in ampere years. In a wet, heavily contaminated structure this cathode current density might be 15 mA/m^2.

(iii) *Final.* The current provision during the final year of operation at 25 years. This figure would determine the extent to which evenly distributed anode failure could be permitted at the end of life whilst still adequately controlling corrosion. In the same context as the above figures this might be 10 mA/m^2.

Following offshore practice, variable cathode current densities can be applied to reinforcement in different areas of a structure. Highest current demand can be

expected in the outer layers of reinforcement in the wettest/most contaminated areas. Whatever current density figure is used at the time of design it is critical that this is applied to reinforcement surface areas which are properly sub-divided and related to those areas of anode which are closest to them and which will provide them with current.

Optimum cathodic protection will only be achieved if the anode system is designed correctly to provide current to the concrete surfaces which properly matches the current demand of the local reinforcement. This is calculated as the product of local reinforcement surface area and local reinforcement current density. This requirement will dictate both the provision of separately controlled zones within the anode system and, for those anode types which allow it, the provision of various levels of current output within each zone to match the local reinforcement current demand.

In practice these requirements result in anode zones being in the range 25–250m² rated at 0.5 to 5 amperes (the *average* definition above). Zones can be effective at the higher end of this scale, or even above 250m², *only* if anodes such as activated titanium mesh or discrete internal anodes have been distributed within the zone to reflect the reinforcement density and any known variations in local current density requirement. It follows that anode zones in conductive overlays or conductive coatings which will provide a current distribution affected only by localized anode/cathode resistances (i.e. high current at wet, low resistance areas), not by reinforcement quantity or its current demand, should be relatively small and limited to approximately 100m² or 2 amperes.

These generalizations are obviously subject to variations determined by the structure. If, for example, a uniformly reinforced and uniformly contaminated bridge deck were being provided with cathodic protection a designer might consider increasing the zone size to 500m² rated at 10 amperes. However, this would probably be appropriate only after detailed trials using potential and potential decay survey techniques on such a structure under cathodic protection with this zone size.

It is emphasized that in any impressed current anode system the weakest point is the anode/cable connection. Any failure of electrical insulation at this point will be vulnerable to enforced corrosion and rapid failure if there is continuity of electrolyte between its surroundings and the concrete of the structure. There is adequate engineering technology available for conventional buried and submerged cathodic protection; it is critical that this technology is properly applied to reinforced concrete cathodic protection. Most specifications call for 100% redundancy in positive supply cables and anode/cable connections. This is normally achieved by ring main circuits and a multiplicity of anode/cable connections in each zone.

Power supply and other considerations

The previous sections have addressed developments, selection and design of anode systems. It should be emphasized that the anode system, albeit a critical component in the overall cathodic protection system, is only one part and that all parts require correct design, installation and operation to ensure optimum performance.

Electrical continuity of reinforcement is a pre-requisite for full cathodic protection although there are indications (Wyatt, *unpublished data*) that in certain cases, short discontinuous reinforcement components at suitable geometric locations within

structures may not be affected by stray currents and may even have their corrosion risk reduced, presumably by chloride migration and/or oxygen depletion. Generally, however, detailed testing of reinforcement electrical continuity is required at the concrete repair stage. Depending upon the extent of any discontinuities located, testing and bonding may have to be extended to all reinforcement in a structure by way of cutting chases in the cover concrete to expose both main bars and links.

Such work is the exception, rather than the rule, in cathodic protection projects and reflects either poor steel fixing initially or relatively severe corrosion which has caused deterioration of the electrical continuity. This work can be the subject of considerable contractual dispute if proper provisions are not made in both the specification and the bills of quantity.

Negative power connections should be provided in duplicate to each anode zone and are typically provided with cable redundancy by the use of a ring main system. Electrical power supplies may be considered by some to be items of such standard form and high reliability that little attention is required to achieve optimum performance and reliability. It is relevant that in one country the greatest source of failure in cathodic protection systems is breakdown of poorly specified and constructed power supplies. For applications in reinforced concrete, particular attention should be paid to the extent of stability and fine adjustment of output current at low levels, the requirement for constant current output and the proper interfacing with monitoring equipment. Power supplies with individual zone transformer-rectifiers rated at between 0.5 and 5 amperes at 0–12 volts are better served for reliability and accuracy with interrogation sockets for portable digital multimeters rather than fixed panel instruments. Current output interruption facilities are required to switch the output DC open circuit on a cyclical basis, driven either by a timer or by a more intelligent external source, to facilitate instant-off potential measurements.

Permanently installed reference electrodes, pseudo-electrodes, macro-cells or coupons and corrosion rate monitoring equipment are all potentially important parts of a cathodic protection system and some are essential. It is an important part of the cathodic protection design to determine the requirement for monitoring devices and their positioning. It is normal for most of these devices to be terminated in the power supply enclosure to facilitate relatively easy interrogation of the overall system performance from a single location.

Many sytems rely on manual monitoring of cathodic protection performance. The use of permanently installed or portable data logging equipment, the former possibly interlinked by modem to a remote office location, is a further factor in the cathodic protection system design.

Expertise in both concrete technology and cathodic protection technology is required when dealing with anodes and other important components in system design. Almost all failures of cathodic protection systems for reinforced concrete can be traced back to a lack of sufficient input of established technology from one of these sectors.

17.5 Conclusions

Much excellent development has been undertaken in cathodic protection of reinforced concrete structures and buildings over the past thirty years. The proven cost

advantages of cathodic protection over other repair and protection options for chloride-contaminated reinforced concrete structures will dictate significant growth. The single most damaging influence to the rational growth of this technique is the high risk of failed cathodic protection systems arising from contractors inexperienced in the dual requirements of concrete repair and cathodic protection. Sprayed concrete has a vital part to play as a durable overlay of mesh anode systems, but must be designed and installed to the highest standard if it is to increase its share of this substantial construction market.

Cathodic protection of chloride-contaminated reinforced concrete structures and buildings is proven to offer a two to ten-fold cost saving over other long term repair and protection options. The development of cathodic protection systems for above ground reinforced concrete has been largely a matter of anode system development plus the use of well developed power supply and monitoring equipment and procedures from the "conventional" buried and submerged cathodic protection fields.

The success of cathodic protection of reinforced concrete measured by both its effectiveness in extending the life of chloride-contaminated structures and buildings and by the growth of its application is dependent upon the close integration of concrete repair and cathodic protection technologies by designers and contractors.

Anodes and cathodic protection systems

The anode system is only a part of the overall cathodic protection system; even the full and proper design of the distribution of an anode system does not constitute a full cathodic protection system. Effective design, installation and operation of all components of the cathodic protection system are required for best performance.

Coated titanium mesh anodes with sprayed concrete or other cementitious overlays may prove to be the best available compromise of cost, performance and longevity. Test procedures or more explicit manufacturers' data are required to enable designers to properly judge the life expectancy and other performance variations of the different products. The present limit of 108 mA/m^2 anode current density may prove to be unduly low for some or all of these materials. The quality of overlay application may be the life determining factor in the use of this anode system.

Conductive overlay systems for bridge decks are proven and cost effective for those applications which can withstand the weight and dimensional limitations of the system. Conductive coating systems, using proven coatings and the most rigorous application procedures, are viable anode systems for dry structures and have extensive track records.

Discrete embedded anodes are developing an effective track record for cathodic protection of reinforced concrete. They may be particularly advantageous in areas such as joints and under bearings where surface mounted anodes may not be ideal to achieve full protection.

Sprayed concrete overlays

Sprayed concrete is a potential overlay material for titanium mesh anode systems where shape or access makes a cast cementitious overlay impractical or uneconomic. This anode type is well proven and therefore the growth of this area of application for sprayed concrete is largely dependent on the establishment of a successful track

record for this approach to cathodic protection.

Experience has shown that proper surface preparation, pre-wetting, spraying technique, surface finishing and curing are vital to obtain satisfactory bond between the substrate and overlay. Cathodic protection represents one of the most demanding applications of sprayed concrete because of the lack of other reinforcement or key. Any flaws are likely to be identified during routine measurement and control activity.

Acknowledgements

The views expressed in this paper are those of the author and not necessarily of Tarmac Global or its principals Tarmac Structural Repairs and Tarmac Construction Ltd. The author places on record his thanks to these principals and to his colleagues for their continued support and wise counsel.

References

ACI Committee 506 (1990) *Guide to Shotcrete* ACI 506R-85 506.3R and 506.2. Detroit Michegan.

Anderson, G.H. (1985) *Proc. Conf. C P of Reinforced Concrete Bridge Decks*, NACE, Houston, Texas, p82.

Apostolos, J.A., Carello, R.A., and Howell, K.M. (1985) *AASHTO/FHWA/NACE Seminar*, Paper No. 16, San Antonio.

Apostolos, J.A., Parks, D.M., and Carello, R.A., (1987) *Corrosion '87*, Paper 137, NACE, Houston, Texas.

Bennett, J. and Schue, T.J. (1990) *Corrosion '90*, paper 316, NACE, Las Vegas.

Boam, K.J. and Unwin, J. (1990) *IHT Leamington Spa Workshop.*

Brousseau, M. (1992) *CEEC Conference*, Paris.

Brown, R. P., and Kessler, R.J. (1983) *Corrosion '83*, Paper No. 179, NACE, Houston, Texas.

Brown, R.P. (1985) *AASHTO/FHWA/NACE Seminar*, Paper No. 22 San Antonio.

Clear, K.G. (1985) *Proc. Conf. C P of Reinforced Concrete Bridge Decks*, NACE, Houston, Texas, p55.

Clemena, G.G. (1985) *Proc. Conf. C P of Reinforced Concrete Bridge Decks*, NACE, Houston, Texas, p89.

Clemena, G. G. (1987) *Corrosion '87*, Paper 122, NACE, Houston, Texas.

Department of Transport (1989) *The Performance of Concrete Bridges.* HMSO.

Federal Highway Administration, (1982) *FHWA Demonstration Project No. 34 Interim Report.* FHWA DP-34-2.

Federal Highway Administration (1983) *FHWA Report* FHWA/RD-83/048.

Fromm, H. S. (1981) *Corrosion '81*, Paper No. 50, NACE, Houston, Texas.

Groenvold, F., and Nielsen-Dharmaratne, K. (1991) *Corrosion '91*, Paper 551, NACE, Cincinnati.

Hayfield, P.C.S. and Warne M.A. (1988) *UK Corrosion '88*, CEA, Brighton.

Hock, V.F., *et al.* (1988) *Corrosion '88*, Paper 230, NACE, Houston, Texas.

Hull, T.J. (1985) *Cathodic Protection of Reinforced Concrete Bridge Decks.* NACE.

John, D.G. *et al.* (1989) *Corrosion '89*, paper 387.

Kessler, R. J., and Powers, R.G. (1990) *Corrosion '90*, Paper 324, NACE, Las Vegas.

Lehmann, J.A. (1985*a*)*AASHTO/FHWA/NACE Seminar*, Paper No. 21, San Antonio.

Lehmann, J.A. (1985*b*) ACI, Denver.

Leppard, N.W., and John, D.G. (1991) *UK Corrosion '91.* CEA, Brighton.

Lewis, D.A. and Boam, K.J. (1987) *2nd International Conference, Deterioration and Repair of Reinforced Concrete in the Arabian Gulf.*

Manning, D.G., and Bye, D.H. (1984) *Bridge Deck Rehabilitation Manual*, Ontario, Ministry of Transportation and Communications, Part 1, November 1983 and Part 2 April 1984.
Mudd, C.J., Mussinelli, G.L., *et al.* (1988) *Corrosion '88*, Paper 229, NACE, Houston, Texas.
Nielsen-Dharmanratne, K. and Groenvold, F. (1991) *Construction Maintenace & Repair,* **5** (1).
Nicholson, P. (1981) *Corrosion '81*, Paper No. 42, NACE, Houston, Texas.
Schell, H. (1987) UK *Corrosion '87 CCEJV*, Brighton.
Sprayed Concrete Association (1986) *Design and Specification for Dry Process Sprayed Concrete*. London.
Stratfull, R. F. (1959) *Corrosion*, 14 (6), p65.
Stratfull, R. F.(1974) *Transportation Research Record*, 500.
Stratfull, R. F. (1985) *Proc. Conf. C P of Reinforced Concrete Bridge Decks*, NACE, Houston, Texas, p66.
Warne, M.A. (1988) *BAC Concrete Cathodic Protection Seminar*, Copenhagen.
Wyatt, B.S. and Irvine, D.J. (1987) *Materials Performance*, 26 (12), 12–21.
Wyatt, B.S. and Lothian, A. (1988) *UK Corrosion '88*, CEA, Brighton.
Wyatt, B.S., Schols, A.J.H., Leppard, N.W. and John, D.G. (1991) *UK Corrosion '91*, Inst. Corr, Manchester, October.

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