Ultrafine Cement in Pressure Grouting

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Preface

This book was written with the goal of introducing the reader to some of the more general concepts and terms associated with ultrafine cements and grouts made from them. The reader is thought to be a person who is relatively new to working with ultrafine cements, but because of project-specific conditions is required to utilize ultrafine cement in one or more of the project's grouting operations.

Another term widely used throughout the engineering and construction industry to describe cement products with the same or very similar properties to ultrafine cement is "microfine cement." These two terms, ultrafine and microfine, should be considered synonymous and are often used interchangeably in the technical literature. Additionally, other terms are also used for products having similar properties to ultrafine cement, such as "superfine," "very fine," and "micro-cement"; however, their use is not as widespread.

A very simplified definition of ultrafine cement is a cementitious product made from portland cement or portland cement blended with blast furnace slag or pumice, which is ground finer than portland type III cement or to approximately 10 microns.

The purpose for creating this fined-grained cementitious material is for use in making grouts able to penetrate finer-grained soils and very small cracks in rock masses and concrete structures which cannot be penetrated with grouts made from standard portland cements (types I through V). Grouts made from ultrafine cement offer an alternative to chemical grout.

The worldwide wide use of ultrafine cement-based grouts has grown substantially over the past decade. With the current expanding global economy and the increased need for the heavy civil engineered infrastructures and mine developments to sustain this growth, the use of cement-based grouts can only be expected to follow these global growth patterns. However, many future worldwide heavy civil engineering projects will necessarily be forced to be located in less than ideal (and in some cases, poor) geologic settings. Factors including nearby population centers; access to river and rail transport systems; access to ports and harbors; availability of electric infrastructure; locations of natural resources; political boundaries; topographical conditions; climates; and security issues will all need to be considered for future project site selections. These factors could easily outweigh site selection based primarily on more favorable geologic conditions.

Likewise, future heavy civil engineering infrastructure developments, upgrades, and expansions in existing well-established urban areas may experience similar problems of finding "good ground" for their projects, since most of the good ground may already be taken. The need for vast amounts of new and upgraded infrastructure to be located in increasingly less favorable geologic and groundwater conditions will require vast amounts of effective and innovative construction methodologies, technologies, equipment, and materials. One of these materials, ultrafine cement, is already leading the way to the future. More engineers, contractors, and owners are discovering that an effective grouting program, especially one performed pre-excavation, can reduce a project's overall construction costs and time, as well as in many cases making the construction site a safer place to work.

In the nineteenth and twentieth centuries, grouting was considered more an "art" than a science. On underground projects, it was often performed during construction, usually only after encountering water inflows that were so large as to impede construction progress. On the other hand, dam construction projects usually employed fairly extensive grouting programs which were anticipated during the design engineering phase, often relying on injecting large quantities of grout over large areas to be considered successful.

The current state of the practice in grouting is to pre-plan and engineer grouting programs that best meet project-specific needs and objectives as the primary goal. This goal can be accomplished most efficiently by bringing together the most appropriate components available, such as construction methodologies, technologies, equipment, and materials. Quite often this means selecting the individual components that are the most cost- and time-effective to the overall grouting program.

Ultrafine cement is often one of these key components of modern grouting programs. While the initial cost of ultrafine cement can be several times greater than ordinary portland cement, the overall quantity of ultrafine cement used to achieve the same (and in many cases, superior) grouting results will very often be less. The fact that more and more contractors and owners are choosing to utilize ultrafine cement-based grouts rather than ordinary portland cement-based grouts for their project grouting programs makes a good case for the overall cost and technical effectiveness of ultrafine cement-based grouts. For these reasons, we believe that the use of ultrafine cement-based grouts will continue to expand throughout the world in the coming years.

It is therefore important for engineers, both experienced and new to the field, to understand what ultrafine cement is and for what it can be used. This book provides some basic facts, definitions, engineering properties, mixing and equipment information, quality control and testing references, and examples from actual projects related to utilizing ultrafine cement in a grouting program.

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CHAPTER 1

Introduction

This book provides background and practical information to professionals involved with projects which could benefit from the use of grouts made with ultrafine cements. It provides an overview that explains what ultrafine cement is, its uses, its history, and how it is manufactured. It describes its engineering properties and the applications in which it has typically been employed.

This book is not intended as an introduction to grouting. However, to help the reader better understand the role of ultrafine cement in the modern grouting industry, some basic concepts such as engineering properties and mixing and pumping of grouts are touched upon. This book is not based on new author research but, rather, attempts to pull together various existing information about ultrafine cements to aid the professional whose expertise is in other areas of engineering and construction.

Chapter 8, Recommendations for Contract Specifications, is intended for use by engineers and designers who wish to specify the use of ultrafine cement in a grouting program. Language and wording suggestions are offered that can be added or used to modify a typical project grouting specification to incorporate the use of ultrafine cement-based grouts. Also, Appendix B provides information from specific projects where ultrafine cement was used.

Uses for Ultrafine Cement-Based Grouts

Ultrafine cement-based grouts are utilized primarily for permeation grouting in soil formations and for fissure grouting in rock masses. Ultrafine grouts are also employed to repair concrete structures. The two reasons for performing grouting with ultrafine cement are to reduce the permeability of the geologic material or concrete structure, and to strengthen the geologic material or concrete structure. The grouting program can have as its goal one or both of these desired effects. Grouts made with ultrafine cements have gained usage in underground excavations both for heavy civil construction, such as in shaft, tunnel, and chamber construction, and for mine development and operations. Ultrafine cement-based grouts are also being used to grout soil and rock in association with foundations and for ground improvement on various types of construction projects. Cracks and other defects in concrete structures such as dams, water control structures, tanks, pipelines, and other elements of infrastructure have also been repaired using ultrafine cement-based grouts. Other industries that have utilized ultrafine cement for grout are oil and gas as well as environmental remediation.

Although this book touches on grout properties and grouting operations, briefly describing grout mixers, agitators, and types of pumps, these subjects are not the focus of the work. Listed below are five publications that deal with these subjects in much greater detail for both aboveground and underground applications.

Construction and Design of Cement Grouting, by A. C. Houlsby (1990, John Wiley & Sons, Inc., Hoboken, N.J.)
Practical Guide to Grouting of Underground Structures, by R. W. Henn (1996, ASCE Press, Reston, Va.)
AUA Guidelines for Backfilling and Contact Grouting of Tunnels and Shafts, edited by R. W. Henn (2003, ASCE Press, Reston, Va.)
Practical Handbook of Grouting; Soil, Rock, and Structures, by J. Warner (2004, John Wiley & Sons, Inc., Hoboken, N.J.)
Dam Foundation Grouting, Revised and Expanded Edition, by K. D. Weaver and D. A. Bruce (2007, ASCE Press, Reston, Va.)

History of Ultrafine Cement

Prior to the late 1960s and early 1970s, permeation grouting of fine-grained soils was accomplished using chemical solution grouts such as silicates, lignins, and acrylamides. Each of these materials had a potential for extreme toxicity and/or environmental damage if improperly applied. Increased international interest in ultrafine cement-based grouts over the past several years has been largely due to continued concerns and research regarding the environmental effects and long-term stability of chemical solution grouts (Getzlaf 2006). An incident occurred in Sweden with the use of chemical solution grout where the water inflows into a tunnel during construction resulted in contamination of surface streams. This contamination of surface water killed fish and caused paralysis of numerous cows (Risk and Policy Analysts Limited 2000). As a result of these and other incidents, the use of acrylamide grouts appears to have declined sharply starting in approximately 1992.

Originally developed in Japan in the 1970s, ultrafine cement was intended to be an alternative to chemical solution grouts to fissure-grout small fractures in rock and permeate the pore spaces of fine-grained soils. Ultrafine cement is commonly an extremely fine-ground portland cement that is often mixed with varying amounts of blast furnace slag or pumice. Ultrafine cement was introduced to the United States in 1984 (Clarke 1984; Clarke et al. 1992). The first major use of ultrafine cement in the United States was for groundwater control grouting associated with the Helms Pumped Storage Project outside Fresno, California (Clarke et al. 1992). Ultrafine cement products are now widely available in the United States and around the world.

Although the cost of ultrafine cement is typically five to ten times higher than ordinary portland cement (OPC), this higher cost is often more than offset by the advantages and overall superior performance of ultrafine cement-based grouts. Appendix A shows 2009 prices of OPC versus ultrafine cement for 19 major cities in the Unites States. Several underground construction projects have actually reported significant cost savings in their overall grouting programs by using ultrafine cement in the formulation of their grout as opposed to "traditional" cement-based formulations. Some key reasons for these ultimate cost savings are:

1. Because of their greater penetration potential, grouting with ultrafine cements may allow an overall reduction in the number of grout holes required to achieve the same results as with a greater number of holes when utilizing grouts made with type I, II, or III portland cements.
2. Reduced grout injection times and improved groutability, which results in reduced overall grouting cycle time and related costs.
3. More effective grouting campaigns for reducing groundwater inflow and improving ground conditions, resulting in helping reduce the time and cost for excavation and construction activities.
4. Significantly higher water to cement (w:c) ratios (6:1 to 8:1 by weight) have been reported being used to grout soil formation with ultrafine cement-based grout mixes (Warner 2004). Use of mixes with these higher w:c ratios will increase yield while reducing the overall

> quantity of cement product used. However, our research for this book indicates that the maximum w:c ratio most commonly used on projects in the United States appears to be 2:1.

The inclusion of requirements for the use of ultrafine cements in more specifications, greater acceptance of ultrafine cement by the engineering and construction communities, and the increased use of ultrafine cement-based grouts has fostered the need for a reference document on the subject. It is the goal of this book to provide the reader with a basic general understanding of the ultrafine cement product and its uses in the heavy and underground construction industries.

CHAPTER 2

Definition of Ultrafine Cements

Currently, no standard definition of ultrafine cement has been adopted by any domestic or international standardizing agencies or the U.S. construction industry. The terms ultrafine, superfine, microfine, and microcement are used interchangeably throughout the literature and in practice. There are also numerous definitions of these cements:

- The International Society for Rock Mechanics (ISRM 1995) gives the following definition: "Superfine cement is made of the same materials as ordinary cement. It is characterized by a greater fineness ($d_{95} <$ 16 microns) and an even, steep particle size distribution."
- The American Concrete Institute (ACI) Committee 552 has unofficially adopted a definition that states that 100% of the particles must be less than 15 microns (Henn 1996).
- The Portland Cement Association provides this definition in Kosmatka et al. (2002): "The cement particles are less than 10 micrometer in diameter with 50% of particles less than 5 micrometers."

To help the reader better visualize the order of scale of the term "micron," which is one millionth of a meter (10,000 Angstrom units), Fig. 2-1 shows the relative particle size of ultrafine cement when compared to various other material particle sizes.

There are three primary suppliers of ultrafine products in the United States: Surecrete Inc./Nittetsu Cement Company, De Neef Construction Chemicals, Inc., and US Grout. Other potential international suppliers include Spinor Ciments D'Origny, BASF, and Minova International. Nittetsu Super Fine cement is represented to have a d_{95} particle size of 9.5 microns. Reportedly, De Neef has three ultrafine products: MC-800 $d_{95} =$ 16 microns, MC-500 $d_{95} =$ 9.5 microns, and MC-300, $d_{95} =$ 6 microns. US

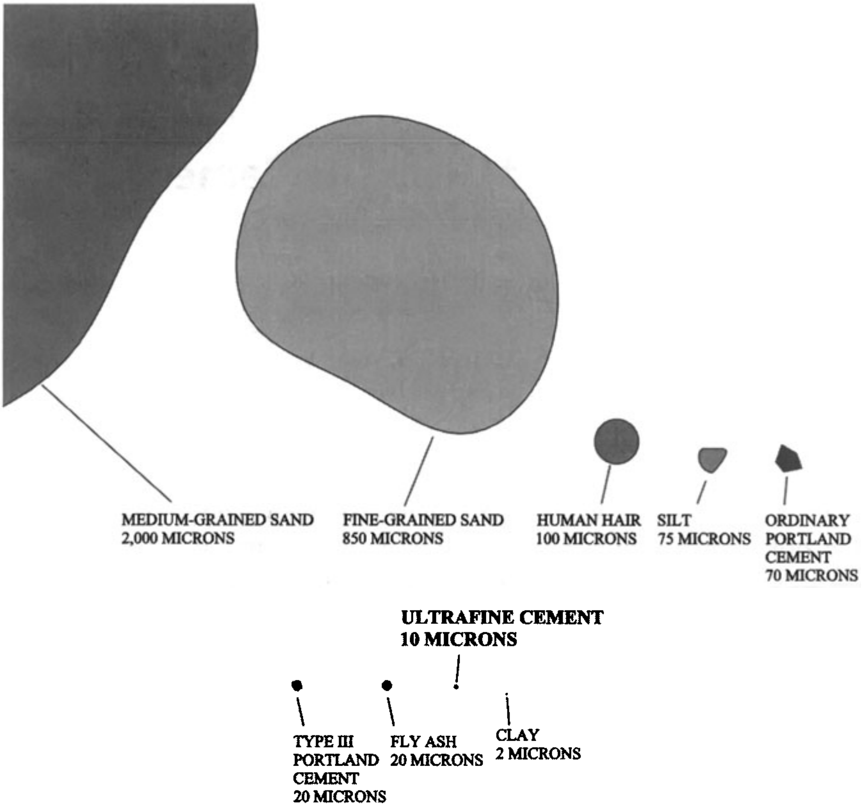

Figure 2-1. Approximate relative sizes of various particles and substances in relation to ultrafine cement.

Grout supplies two products: Standard Ultrafine, represented as d_{90} = 8 microns, and Premium Ultrafine, represented as d_{90} = 5 microns. Figure 2-2 shows a typical gradation curve for ultrafine cement in comparison to types I and III portland cement.

Another method commonly used by the cement industry to quantify fineness of grain sizes is the Blaine Fineness Test (ASTM C 204-05; ASTM 2007). Blaine Fineness provides an average surface area for the sample being analyzed using an air permeability apparatus. Grain size is not taken into consideration and therefore is not a reliable test for determining grout penetration capabilities or overall grout performance. When specifying ultrafine cements, a maximum grain size should always accompany a Blaine Fineness value. For example, consider the two images in Fig. 2-3. Both have the same Blaine Fineness but have significantly different maximum grain sizes and would behave much differently upon injection.

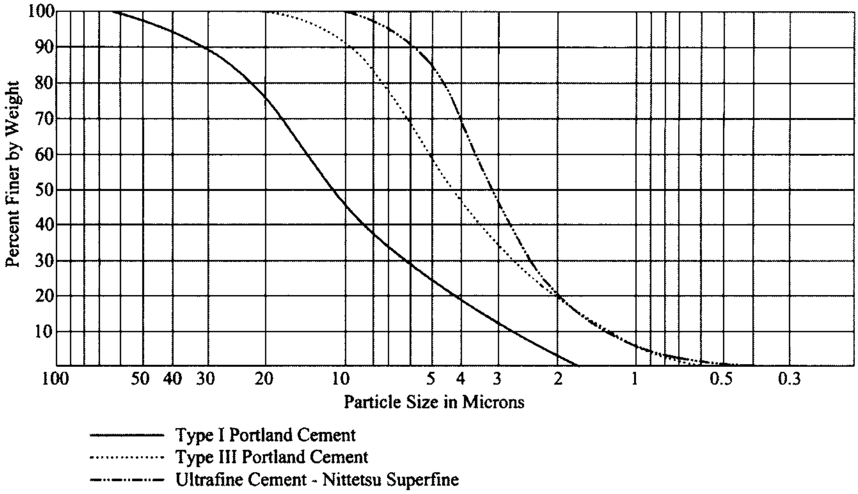

Figure 2-2. Gradation curves comparing typical ultrafine cement to typical portland types I and III cement.

Source: Warner 2004, with permission from John Wiley & Sons.

Despite its limitations, the Blaine Fineness Test values are almost always provided by manufacturers for ultrafine cement products. Nittetsu Super Fine cement reports a fineness between 950 and 980 m^2/kg. De Neef lists finenesses between 1,200 to 1,900 m^2/kg for their three products. US Grout lists finenesses of 1,511 and 1,710 m^2/kg for their Standard and

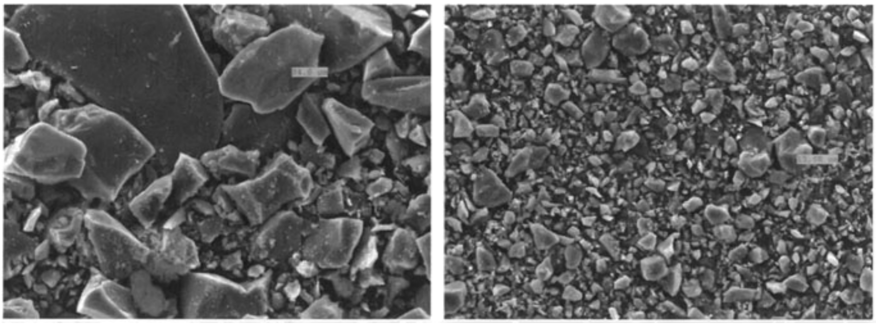

Figure 2-3. Image results for the Blaine Fineness test. Both images are at the same scale and the Blaine Fineness for each is 1,200 m^2/kg. However, the material shown in the left photograph has a much larger maximum grain size than the material in the photo on the right. Clearly the penetration capabilities of these two materials would be quite different.

Source: Courtesy De Neef Construction Chemicals Inc., Houston, TX.

Premium grouts, respectively. Various authors and researchers have proposed classifications based on Blaine Fineness values for ultrafine cement as well. For example, Sarkar and Wheeler (2001a) required their ultrafine cement to have a Blaine Fineness of at least 700 m^2/kg. Schwarz and Krizek (2000) conducted research of various mixes and found them to have a Blaine Fineness between 900 and 1,200 m^2/kg.

We recommend that the term "ultrafine" be reserved for cements with a $d_{95} < 10$ microns and a Blaine Fineness of at least 900 m^2/kg. However, some in the grouting construction industry say the relative comparison of Blaine Fineness values does not actually reflect performance of grouts (Powers et al. 2007).

Another important consideration when selecting from the available ultrafine cement products listed above is the proportion of portland cement, blast furnace slag, and/or pumice used to produce the final "as shipped" ultrafine cement. Figure 2-4 shows scanning electron microscope images of portland cement and Nittetsu Super Fine cement. The images show the actual differences in grain sizes. The finer that portland cement is ground (which increases its surface area or Blaine Fineness), the faster it reacts with water (hydrates) and the faster it begins to set. An example of this is the high early strength of type III portland cement (~20 microns in size) compared to type I portland cement (~70 microns). To mitigate the potential for these sometimes undesired fast set times associated with portland cement, gypsum ($CaSO_4 \cdot 2H_2O$) is added at the end of the manufacturing process. The addition of gypsum, a source of sulfate, helps control setting,

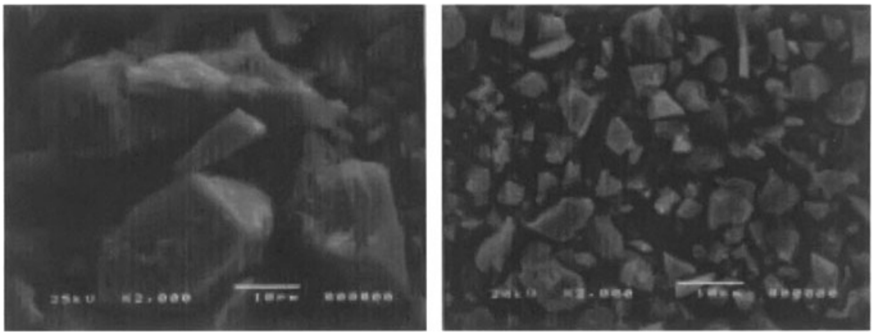

Figure 2-4. Scanning electron microscope (SEM) images of portland cement (*left*) and Nittetsu Super Fine Cement (*right*) at the same magnification.

Source: Courtesy of Surecrete Inc./Nittetsu, Seattle, WA.

drying/shrinkage properties, and strength development. The gypsum only reacts with the portland cement and not with the blast furnace slag or pumice component of ultrafine cement, which contains these in addition to portland cement.

Slag, a byproduct of iron production, develops in a molten condition simultaneously with iron in a blast furnace and is often rapidly quenched in water, which causes it to form into glassy beads (Kosmatka et al. 2002). As a result of the way the slag is quenched, the particles typically have a semispherical shape. The size of slag particles as they are formed varies considerably, but typically ranges from coarse to fine sand size (4.75 to 0.75 mm) (FHWA 2006). However, when the slag is ground to ultrafine cement-sized particles, angular-shaped particles typically result. The ground slag is a hydraulic cement consisting essentially of silicates and aluminosilicates of calcium developed in a molten condition simultaneously with iron in a blast furnace. The rough and angular-shaped ground slag in the presence of water and an activator, NaOH or $Ca(OH)_2$, both supplied by the portland cement, hydrates and sets in a manner similar to portland cement. However, the chemical reaction (hydration) of the slag is much slower than with portland cement and water. Typically, slag is mixed with portland cement where the presence of calcium hydroxide from the hydration of the portland cement accelerates the reaction of the slag (ACI 233R-95; ACI 2003). In general, a higher percentage of slag for a given amount of portland cement will slow the hydration. Figure 2-5 shows a scanning electron microscope image of blast furnace slag.

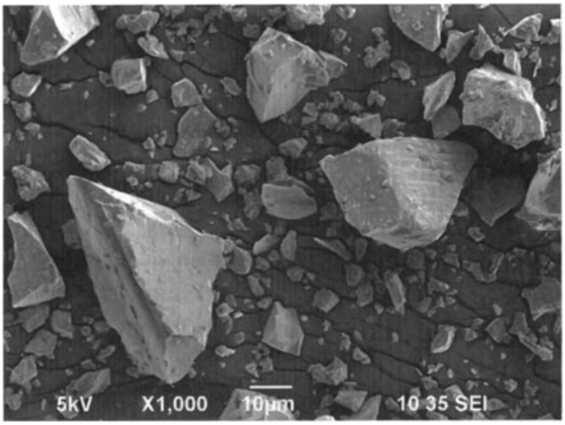

Figure 2-5. SEM image of blast furnace slag.

Source: Courtesy of Surecrete Inc./Nittetsu, Seattle, WA.

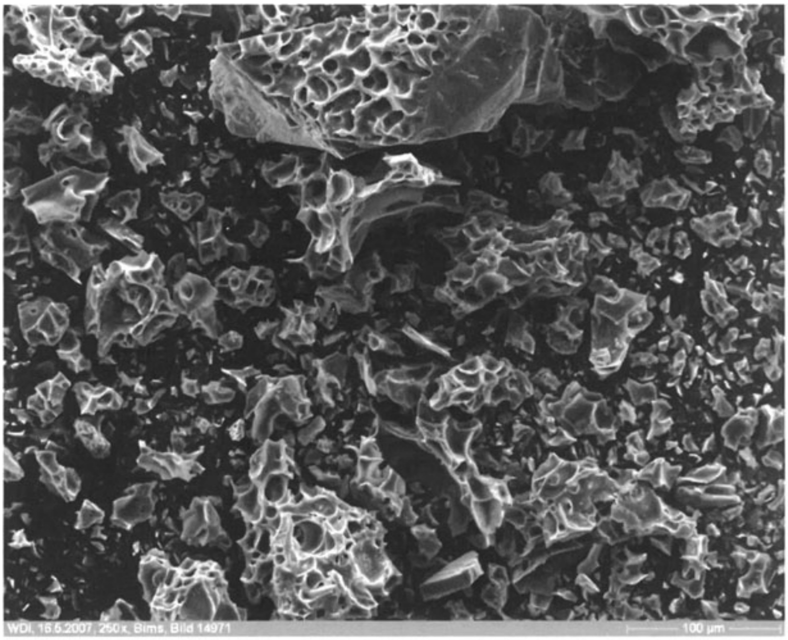

Figure 2-6. SEM image of pumice particles showing their irregular shape and relatively large surface area.

Source: Courtesy of De Neef Construction Chemicals Inc., Houston, TX.

US Grout manufactures an ultrafine cement product that uses pumice in the formulation of ultrafine cement. The use of pumice as a replacement for slag also reportedly achieves the desired control of set time. Pumice, which is naturally occurring, is a pozzolanic material that in the presence of hydrating portland cement will develop cementitious properties. Figure 2-6 shows a scanning electron microscope image of typical particles of pumice. Note the highly irregular surface of the pumice grains, which tends to produce extremely high surface areas. Table 2-1 shows the

Table 2-1. Mix Components of Various Ultrafine Cements and Their Suppliers

	Component (%)			
Supplier	*Portland*	*Slag*	*Limestone*	*Pumice*
Nittetsu	35	65	0	0
De Neef	20	60	20	0
US Grout	45	0	0	55

Table 2-2. Approximate Primary Chemical Composition of Various Ultrafine Cements

	Oxide (%)			
Product	*Silicon Dioxide* (SiO_2)	*Aluminum Oxide* (Al_2O_3)	*Calcium Oxide* (CaO)	*Sulfur Trioxide* (SO_3)
OPC	21	5	64	3
Super Fine (Nittetsu)	29	11	50	1
Microfine (De Neef)	31	12	48	0.8
US Grout	71	14	1	0

proportions of portland cement to slag or pumice for ultrafine cements widely available in the United States.

The chemical composition of ultrafine cement is not the same as that of ordinary portland cement (OPC). The major chemical components of the ultrafine cements from the major U.S. suppliers compared to OPC are shown in Table 2-2. Note the relatively high sulfur trioxide and low aluminum oxide contents of the OPC as compared to the ultrafine cements. This results from ultrafine cement blends typically having as little as 20% to 35% portland cement.

CHAPTER 3

Engineering Properties

When ultrafine cement is to be used, it is necessary to know its specific engineering properties and how these properties relate to the material to be grouted. Material properties such as soil gradation, chemistry, pH, groundwater conditions, porosity, and permeability of the target soil; fracture roughness and aperture in rock; and surface roughness and crack apertures in concrete structures must be considered. The common parameters of the grout that are specified include the minimum compressive strengths required and the age of the hardened grout at which the strength is required, set times, percent bleed, pressure filtration coefficient, and viscosity.

Porosity

The porosity of a soil material is defined as the ratio of the volume of the voids to the total volume of the material. The pore space is the void volume between the solid particles that can potentially be filled with grout. The term "porosity" is most commonly applied to soil because rock typically has very low or zero porosity. When grouting rock, grout fills fractures, joints, and discontinuities in the rock rather than permeating the rock mass itself, as discussed in the Permeability section below. However, some rocks such as vesicular basalt and some sandstones can have porosities similar to soil, as shown in Table 3-1.

Porosity is dependent on the gradation, particle shape, and density of the soil. Uniformly graded sand will have a higher porosity than a well-graded soil because the finer particles fill in the gaps between the larger particles in the well-graded soil. Likewise, loosely packed uniform sand may have a porosity of up to 40%, whereas if it were densified the porosity may decrease to around 25%.

Table 3-1. Porosity of Common Soils and Rocks

Soil	*Loose*	*Dense*
Clay[a]	55	45
Silt[a]	50	35
Uniform coarse sand	50	32
Uniform fine to medium sand	50	29
Well-graded sand	49	17
Well-graded silty sand and gravel	46	12
Glacial till[a]	25	10
Rock[b]	*High*	*Low*
Vesicular basalt	50	10
Sandstone	30	5
Limestone/Dolomite	20	1
Shale	10	0
Fractured crystalline rock	10	0
Unfractured crystalline rock	<1	

[a] Clay, silt, and glacial till are typically considered ungroutable, even with ultrafine cement.

[b] Values are for the porosity of the rock mass. Typically, fissures in the rock control the flow of fluids, especially in very low permeability rocks such as shale and crystalline rocks.

Sources: Warner 2004 and Sutch & Dirth 2006.

Knowledge of the porosity of the soil material to be grouted allows the user to estimate the volume of grout the material will accept. To estimate this volume of grout, the designer must take into account the total volume of soil to be grouted, the size of the pore spaces, and the interconnectedness of the pore spaces. For instance, because of its platy shape, clay has one of the highest porosities of any soil, between 45% and 55%. Some soil/geotechnical engineering texts give the porosity of loose clay as high as 71% (Powers et al. 2007). However, the size of the pore spaces in clay is too small for even an ultrafine cement grout to permeate. Also, if the pore spaces of a soil are not interconnected, the grout will not infiltrate the void areas well. A measure of the interconnectedness of the pore spaces can be estimated by measuring the effective porosity of a soil. The effective porosity is the volume of interconnected voids that water, air, or grout can effectively move through. As a general rule of thumb when estimating "grout take" volumes of a sandy soil, it can be assumed that only

50% to 80%+ of the porosity will be groutable. When this volume is reached, it should be assumed that the soil mass is fully grouted. To some extent, increasing the pressure and adjusting the flow rate with which the grout is injected may allow more voids to be filled, but a practical limitation is reached when the grout injection rate exceeds the soil's acceptance rate. When this occurs, hydrofracturing of the soil mass or rock, or heaving of the soil, can result.

Permeability

Common practice in the rock grouting industry is to assume that the smallest groutable crack or fracture is three times larger than the maximum particle size of the grout, including flocculates (Garshol 2007). Therefore, ultrafine cement-based grouts are potentially capable of penetrating much smaller cracks or fractures than OPC due to their relatively small grain size, as graphically demonstrated in Fig. 3-1.

Penetration in fractured rock masses is a function of the fracture aperture and surface roughness as well as the cohesion of the grout. The higher the cohesion of the grout, the shorter the distance it will penetrate for a given pressure. This is due to the fact that suspension grouts are non-Newtonian fluids. That is, they exhibit both cohesion and viscosity as opposed to Newtonian fluids such as water, oil, or chemical solution grouts which do not have cohesion. Lombardi (1985) found that the grout take in a rock mass is inversely proportional to the square of the grout

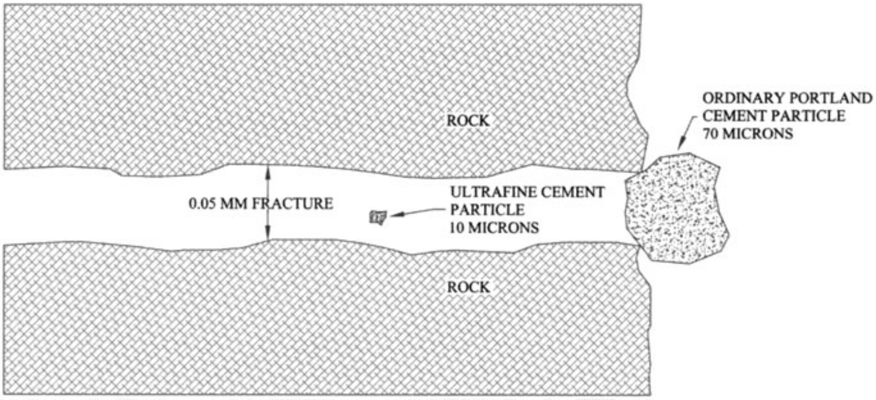

Figure 3-1. Relative size of portland cement versus ultrafine cement in the context of permeating fractures.

cohesion. He summarized his findings into the following three formulae (Eqs. 3-1 through 3-3):

$$R_{\max} = p_{\max} t/c \tag{3-1}$$

$$V_{\max} = (2\pi p^2_{\max} t^3)/c^2 \tag{3-2}$$

$$F_{\max} = (\pi p^3_{\max} t^2)/c^3 \tag{3-3}$$

where

$R_{\max}$ = maximum radius of grout penetration from the source
$V_{\max}$ = maximum volume of injected grout
$F_{\max}$ = maximum total uplift force
$p_{\max}$ = final applied pressure
t = the half-thickness of the joint
c = cohesion of the grout

and all units should be consistent.

In soil, groutability ratios are another common way to estimate what cement particle sizes will penetrate soil pore spaces, and are provided as a numerical value. Gallagher (2000) and De Paoli et al. (1992) give two formulae for determining the groutability ratio, shown in Eqs. 3-4 and 3-5, respectively.

$$N = (D_{15})_{\text{soil}}/(D_{85})_{\text{grout}} \tag{3-4}$$

where

N = groutability ratio
D_{15} = grain size of soil for which 15% by weight is finer
D_{85} = grain size of cement for which 85% by weight is finer

If N is greater than 24, grouting should be possible. If N is less than 11, grouting will not likely be effective. If N is between 11 and 24, grouting may be possible, but field and laboratory tests should be performed to assess groutability.

$$N_c = (D_{10})_{\text{soil}}/(D_{95})_{\text{grout}} \tag{3-5}$$

where

N_c = groutability ratio
D_{10} = grain size of soil for which 10% by weight is finer
D_{95} = grain size of cement for which 95% by weight is finer

If N_c is greater than 11, grouting should be possible. If N_c is less than 6, grouting is not likely to be effective. If N_c is between 6 and 11, grouting may be possible, but field tests should be performed to determine groutability. Table 3-2 shows a generalized chart of the penetration capabilities of ultrafine versus OPC.

Grout permeability in No. 40 clean sand was demonstrated at the University of Florida "Fundamentals of Grouting" short course held in Denver, Colorado in 2003. Demonstrators tested grouts made with OPC, OPC with superplasticizer, ultrafine cement-based grout without superplasticizer, and ultrafine cement-based grout with superplasticizer. All four grout mixes were injected under the same uniform, constant pressure into sand columns. Figure 3-2 shows the results (the vertical distance of penetration) after completing the injections. As can be seen in the photograph, the ultrafine cement-based grout surpassed the OPC grout by approximately twice the injection height, and the ultrafine cement-based grout with superplasticizer penetrated the full 60-in. length of the column.

Table 3-3 provides the reader some sense of the as-mixed properties of several grouts made with a portland cement and several different ultrafine cements.

Compressive Strength

The compressive strength of the grout is usually not of significant importance and therefore is generally not made a specification requirement when grouting is being performed solely to reduce the permeability of the soil or rock mass. However, the compressive strength of a grout is important whenever the purpose of the grouting is to strengthen the ground or an existing concrete structure. The ratio of water to cement is the most

Table 3-2. Penetration Capabilities of Ultrafine Cement-Based Grouts versus Ordinary Portland Cement for Different Soil Types

	Gravel	*Large Sand*	*Fine Sand*	*Silt*	*Clay*
Particle size (mm)	>2.0	0.42–2.0	0.074–0.42	0.005–0.074	<0.005
Coefficient of permeability (cm/sec)		10^{-1}	10^{-2}	10^{-3}	10^{-5}
Penetration					
Ultrafine cement	Yes	Yes	Yes	Yes	No
Ordinary portland cement	Yes	No	No	No	No

Figure 3-2. Grouts injected into sand columns. OPC grout is far left, OPC with superplasticizer is middle left, ultrafine cement-based grout is middle right, and ultrafine cement-based grout with superplasticizer is far right.

Source: Henn & Davenport 2005 reproduced with permission from RETC/SME, http://www.smenet.org.

significant factor affecting the strength of the grout. Table 3-4 shows a range of compressive strengths that have been obtained with ultrafine cement-based grout mixes, some of which utilized superplasticizer admixtures. Figure 3-3 shows compressive strength test results of 2-in. grout cubes from a project the authors worked on in 2008.

There appears to be little documentation on actual field results of the compressive strength of soils or rock post-grouting with ultrafine cement-

Table 3-3. Selected Properties of Different Grouts

	Test 1	*Test 2*	*Test 3*	*Test 4*	*Test 5*
Supplier	Holnam Cement	Holnam Cement	US Grout	Surecrete Inc./Nittetsu	De Neef
Name of product	Type I-II portland cement	Type I-II portland cement with plasticizer	Ultrafine	Super Fine	MC-500
Water [kg (lb.)]	43 (94)	43 (94)	43 (94)	43 (94)	43 (94)
Product [kg (lb.)]	64 (142)	64 (142)	64 (142)	64 (142)	64 (142)
Admixture [kg (lb.)]	0 (0)	0.6 (1.4)	0.6 (1.4)	0.6 (1.4)	0.6 (1.4)
Admixture	None	Rheobuild 2000	Rheobuild 2000	KAO Mighty 150	MC 200 Helper
Ambient air temperature [°C (°F)]	29 (84)	30 (86)	NA	35 (95)	36 (97)
Duration in mixer (sec)	315	204	210	120	180
Duration in mixer prior to adding admixture (sec)	NA	60	NA	50	60
Duration in agitator prior to circulation (sec)	15	100	NA	110	90
Grout temperature [°C (°F)]	27 (81.0)	29 (84.0)	NA	30 (86.0)	34 (92.5)
Mixer type	ChemGrout	ChemGrout	ChemGrout	ChemGrout	ChemGrout
Specific gravity	1.57	1.64	NA	1.61	1.61
Unit weight [kg/m^3 (pcf)]	1569.9 (98.0)	1642.0 (102.5)	NA	1610.0 (100.5)	1610.0 (100.5)
Grout cohesion (mm)	0.079	0.054	0.081	0.250	0.048
API 13 B-2 Marsh Funnel Viscosity (sec/946 cc)	58	56	NA	59	70

(continued)

Table 3-3. Selected Properties of Different Grouts *(continued)*

	Test 1	*Test 2*	*Test 3*	*Test 4*	*Test 5*
ASTM C-939 CRD Funnel Test (sec/946 cc)	9	10	NA	10	10
Duration injecting into column (min.)	20	20	NA	19	20
Injection pressure [bars (psi)]	0.3 (5)	0.3 (5)	NA	0.3 (5)	0.7 (10)
Final grout injection height in column [mm (in.)]	83 (3.25)	241 (9.5)	NA	1524 (60)	482.6 (19)
Final bleed water height in column [mm (in.)]	178 (7)	NA	NA	None	None
Comments	Test was unsuccessful in the first two sand columns due to suspected faulty pressure gauge readings. Successful test occurred on the third column.	Bleed water/ grout line not clear.	Test was abandoned because grout was too thick to mix within 3 min of adding cement.	1 min to reach an injection pressure of 5 psi. No bleed water. Grout leaking out at bottom of sand column. Reached top of cylinder at 19 min and test was stopped.	Clump of product in mixer resulted in a longer mixing time. Grout was circulated back into the mixer to help mix product.

Source: Henn et al. 2001, with permission from SME, http://www.smenet.org.

Table 3-4. Unconfined Compressive Strengths of Various Ultrafine Cement-Based Grout Mixes

Strength [psi (MPa)]				*W:C*	*Admixture*	
3 days	*7 days*	*14 days*	*28 days*	*Ratio*	*(Superplasticizer)*	*Source/Reference*
347 (2.39)	1094 (7.54)	1497 (10.32)	1829 (12.61)	1:1	1% Mighty 150 R	Nittetsu
263 (1.81)	457 (3.15)	744 (5.13)	975 (6.72)	2:1	0.5% Mighty 150 R	Nittetsu
110 (0.76)	142 (0.98)	155 (1.07)	181 (1.25)	3:1	0.3% Mighty 150 R	Nittetsu
222 (1.53)	864 (5.96)	1295 (8.93)	1575 (10.86)	1:1	1% Mighty 150 R	Nittetsu
115 (0.79)	442 (3.05)	587 (4.05)	666 (4.59)	2:1	0.5% Mighty 150 R	Nittetsu
33 (0.23)	165 (1.14)	265 (1.83)	325 (2.24)	3:1	0.3% Mighty 150 R	Nittetsu
508 (3.50)	725 (5.00)	870 (6.00)	870 (6.00)	2:1	2% NS-200	De Neef (MC-300)
435 (3.00)	580 (4.00)	653 (4.50)	653 (4.50)	2:1	2% NS-200	De Neef (MC-500)
363 (2.50)	435 (3.00)	508 (3.50)	580 (4.00)	2:1	2% NS-200	De Neef (MC-800)
—	2063 (14.2)	4531 (31.2)	6023 (41.5)	0.6:1	0.8 polycarboxylate	US Grout
—	—	2102 (14.5)	3309 (22.8)	0.8:1	0.65 polycarboxylate	US Grout

Sources: Data provided by listed supplier.

based grout. Henn et al. (2005) recorded compressive strength test results from the University of Florida "Fundamentals of Grouting" short course held in Denver, Colorado in 2003. In addition to the 60-in.-tall sand columns, standard concrete cylinder molds fitted with an injection valve at the bottom were filled with the same sand as the columns and the ultrafine cement-based grout was injected into the molds, as shown in Fig. 3-4. The molds were allowed to cure and were then tested per ASTM C 31-06 to determine the compressive strength, as shown in Fig. 3-5. The results of the compressive strength tests are shown in Fig. 3-6. Krizek et al. (1992) and Liao et al. (1992) performed experimental research using a grout with a mixture of ultrafine cement and sodium silicate. They recorded, among other parameters, unconfined compressive strengths in grouted loose, medium, and dense sands that were injected with this hybrid grout mix. Table 3-5 shows the test results.

LIVE GRAPH
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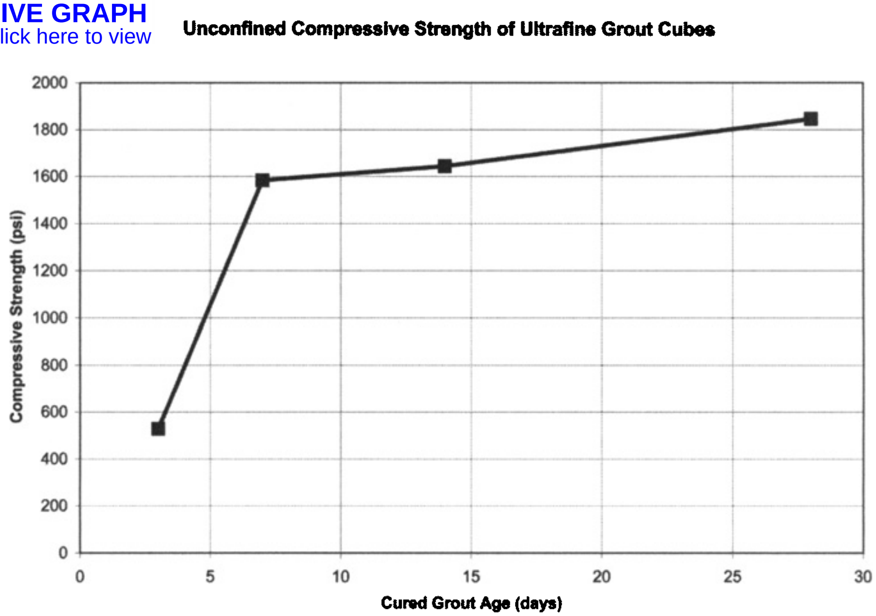

Figure 3-3. Unconfined compressive strength results of 2-in. grout cubes made from ultrafine cement. This grout was made from Nittetsu Super Fine with a 1 : 1 water : cement ratio and no sand in the mix.

Table 3-5. Unconfined Compressive Strengths of Grout with Ultrafine Cement Mixed with Sodium Silicate Injected into Ottawa 20-30 Sand

	Strength [psi (MPa)]		
Initial Sand Density	*7 days*	*14 days*	*28 days*
Loose	—	458 (3.16)	—
Medium	419 (2.89)	489 (3.37)	564 (3.89)
Dense	—	502 (3.46)	—
Grout Only	538 (3.71)	526 (3.63)	566 (3.90)

Note: 2:1 w:c ratio by weight ultrafine cement grout was mixed with 20% sodium silicate by volume.

Source: Krizek et al. 1992, ASCE.

Figure 3-4. A concrete cylinder mold fitted with an injection valve.

Source: Henn et al. 2005; reproduced with permission from RETC/SME, http://www.smenet.org.

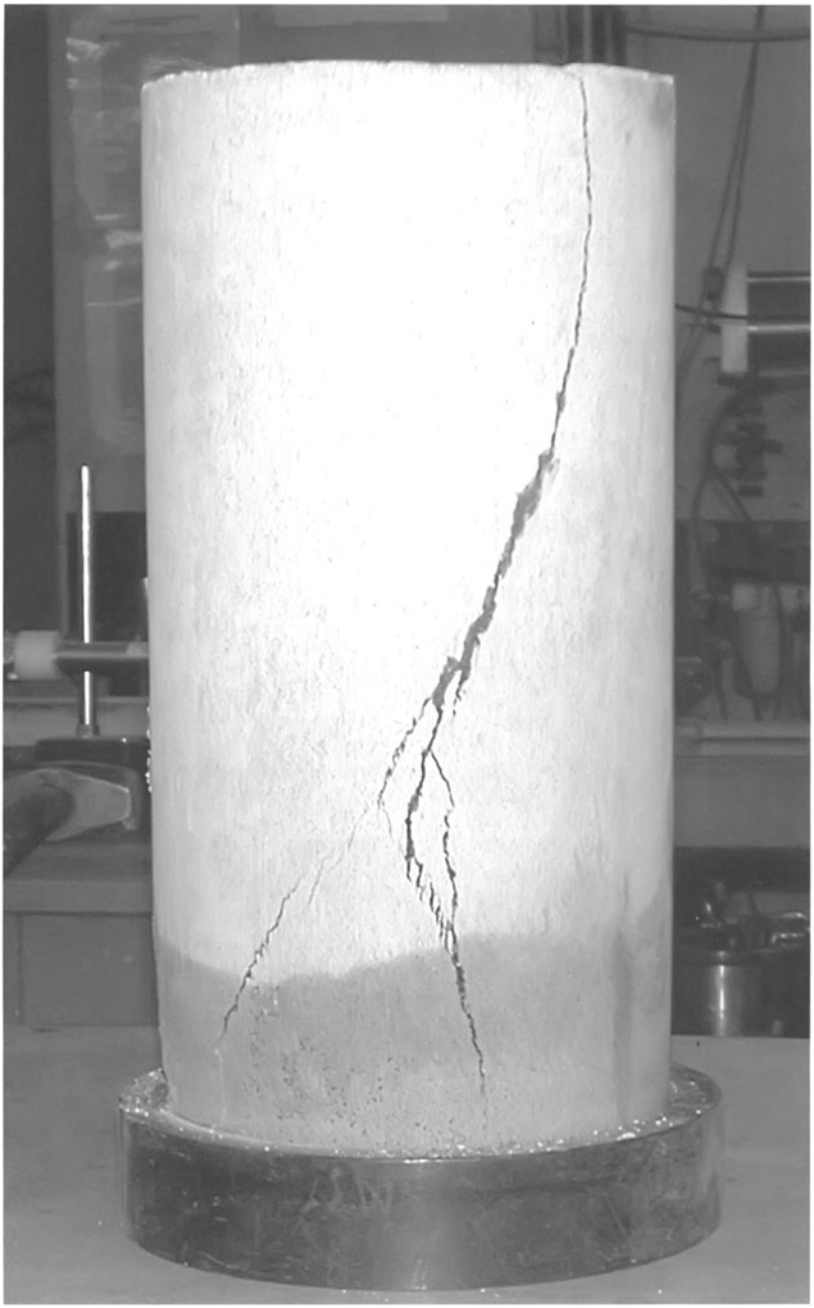

Figure 3-5. Sand injected with ultrafine cement-based grout cured and tested to failure.

Source: Henn et al. 2005; reproduced with permission from RETC/SME, http://www.smenet.org.

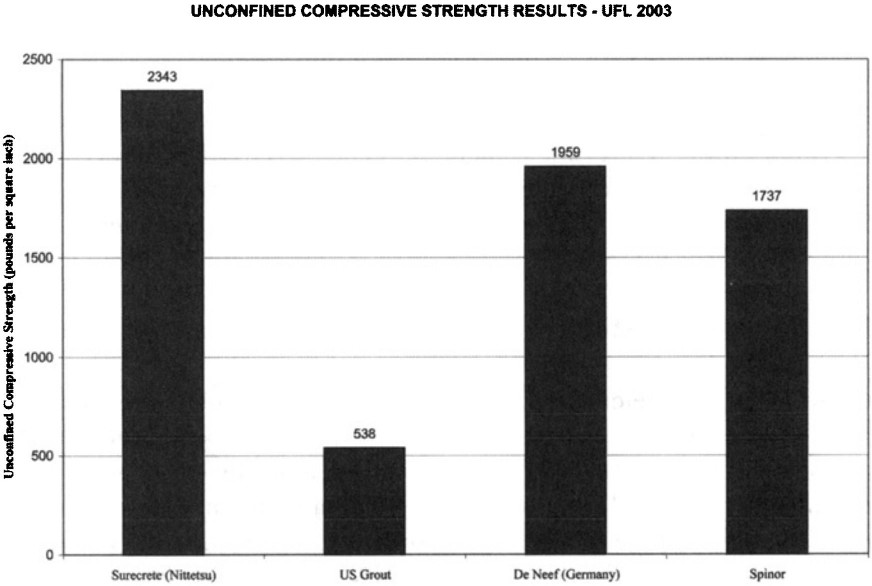

Figure 3-6. Results of 28-day compressive strength tests from a University of Florida "Fundamentals of Grouting" short course held in Denver, Colorado, in 2003. More compressive strength tests, some of which are higher than produced at this trial, have been reported. Refer to Table 3-4.

Source: From Henn et al. 2005; reproduced with permission from RETC/SME, http://www.smenet.org.

Set Times

Set time is directly proportional to the grain size and the chemistry of the cement particles. This is due to the increase in total surface area of the cement particles in a given quantity of cement, which is exposed to water as the grain size decreases. For example, type III (high early strength) portland cement is used to replace type I portland in a concrete or grout mix when high early strength is required. As shown earlier in Fig. 2-1, type III cement is ground much finer (~20 microns) than ordinary portland cement (~70 microns), which gives type III its early strength quality. Ultrafine cement is ground even finer than type III cement and, in pure form, can have very fast set times. Schwarz and Krizek (2000) studied slurries of ultrafine cement-based grout from initial hydration to 7 days of age. They found the grout undergoes substantial changes in the first 60 min of hydration. Prior to set, viscosity and yield strength increased up to 300%. The addition of dispersant or retarding admixtures delayed the development of the gel layer and the precipitation of crystalline structures, thus delaying initial set. The addition of retardants will increase the workability and set time, thereby increasing injection potential that allows the grout to penetrate the geologic material or existing structure to its fullest extent possible. Furthermore, the addition of sodium silicate solution to ultrafine cement has been used to achieve specific set times for project-specific needs (F. Sherrill, personal communication, 2008). Table 3-6 summarizes recorded set times found in the literature.

Bleed Characteristics

Grout bleed, also referred to as the stability of the grout, is the tendency for free water to segregate from the mix. Factors that control the stability of the grout include the water : cement (w : c) ratio, the composition and specific surface area of the cement, and the admixtures and the mixer type used. The percentage of bleed in a grout is proportional to the w : c ratio, with increased water contents tending to create greater bleed percentages. As a general rule, ultrafine cement-based grouts have a much lower bleed percentage than grouts made with OPC. This is because the fine grain size reacts with greater amounts of water in shorter time periods, and settling of the finer particles in ultrafine cement occurs more slowly than with the larger particles in OPC. Additives such as fly ash and bentonite, which are commonly used in OPC-based grouts to reduce bleed, are not regularly

Table 3-6. Set Times for Some Ultrafine Cement-Based Grout Mixes

Initial Set (min)	*Final Set (min)*	*Additives*	*Source/Reference*
560	590	0.9% superplasticizer	US Grout (Standard)
470	570	1.0% Mighty 150 superplasticizer	Nittetsu Super Fine cement
360	408	1.5% superplasticizer (usually premixed with the dry ultrafine)	US Grout (Premium)
183	248	20% fly ash, 1.0% retarder, 1.1% HRWRA	Sarkar and Wheeler (2001b)
85–140	120–330	3% bentonite, 3% retarder	Kumar et al, (2002)
6–56	15 ≥ 56	None to 10% silica fume + 10% bentonite	Schwarz and Krizek (1992)

HRWRA, high-range water-reducing admixture.

used and should not be used with in ultrafine cement-based grouts. Many additives have larger grain sizes (e.g., fly ash, ~20 microns) than ultrafine cement particles or increase the viscosity of the grout. This defeats the purpose of using ultrafine cement-based grout, which is generally used to penetrate soils and rock masses that OPC-based grout cannot. Experimental work with welan gum and ultrafine cement has shown that small amounts of welan gum (0.1%) added to the cement slurry can reduce bleed to zero (F. Sherrill, personal communication, 2008). However, the viscosity of the grout increased by about 50% to 100%.

Schwarz and Krizek (1992) found that high-speed mixers produced grouts with slower rates of bleed than when other types of mixers are used, but that the ultimate amount of bleed was about the same. They also reported that bleed rates for OPC grouts ranged from the same to twice as fast as for ultrafine cement-based grouts. Figure 3-7 shows graphically the difference in bleed amounts for ultrafine cement-based grout versus portland cements.

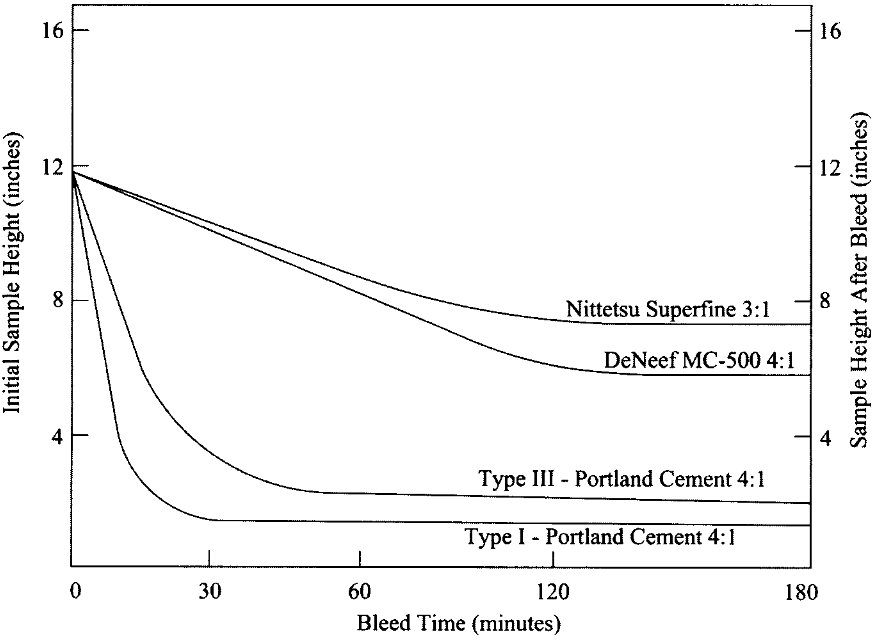

Figure 3-7. Bleed height versus time for Nittetsu Super Fine, De Neef MC-500, and type I and III portland cement.

Source: Adapted from data in Powers et al. 2007.

Rheology

Rheology is the study of the flow of matter: mainly liquid but also soft solids or solids under conditions in which they flow rather than deform elastically. The American Concrete Institute (ACI) "Cement and Concrete Terminology" (2009) defines rheology as "the science dealing with flow of material, including studies of deformation of hardened concrete, the handling placing of freshly mixed concrete, and the behavior of slurries, pasts, and the like." Fluids are broadly classified as Newtonian or non-Newtonian fluids. As an example, water is a Newtonian fluid. Cementitious grouts are examples of non-Newtonian fluids. In Newtonian fluids the shear stress or the force required to move the fluid is essentially constant, regardless of the rate of movement or shear rate and the fluid does not have a yield stress. Yield stress is the stress required to initially deform the fluid, below which the fluid will move elastically or not at all. In non-Newtonian fluids, the relationship between shear stress and shear rate may not be constant, or the fluid may exhibit a yield stress.

In grouting, the term "rheology" is used to describe a grout once mixing is complete through the setting process to its hardened state. A much more in-depth discussion of the subject of rheology is given by Warner (2004).

Pressure Filtration Characteristics

Pressure filtration can be described as the pushing out of water from the mixed grout by the pumping pressure applied during grout injection. Generally, the more unstable a grout mix is (a grout with a high bleed potential), the more susceptible it will be to pressure filtration. The result of pressure filtration is the formation of a cementitious filter cake. This filter cake can form in the geologic feature being grouted, in the bore hole, or in the grout delivery lines. This caking can block the flow of grout from reaching its intended target area. A more in-depth discussion of the subject of pressure filtration is given by Weaver and Bruce (2007).

CHAPTER 4

Manufacturing

Ultrafine grout may be made in one of three ways: (1) high-energy ball mill, (2) impact grinder, or (3) wet mill (De Paoli et al. 1992). The first two methods create dry powder that can be packaged and shipped, whereas wet milling is done at the project site immediately before the grout is placed. From a review of the literature, wet milling is not commonly used in the United States and is only occasionally used in other parts of the world. High-energy ball mills require large energy inputs for low volumes of product. Impact grinders shatter the cement particles, thereby creating high-surface-area grains. Most ultrafine cement is made by this method. In the ultrafine cement manufacturing process, as in the portland cement process, gypsum is added toward the end of the grinding process. Gypsum is used to regulate set times, reduce shrinkage, and improve strength development properties (Kosmatka et al. 2002). Figure 4-1 shows a schematic flow chart for the production of the ultrafine product.

In the cement manufacturing process, the clinker is processed and ground into OPC or ultrafine cement powder, which forms platy-shaped cement particles. Typically, the grinding mill will crush and compact the cement; this compaction creates unbalanced electrostatic charges in the particles. When water is introduced during the mixing process to produce concrete and grouts, the cement particles tend to flocculate, or lump together, as a result of the forces of attraction acting on them (Sottili and Padovani 2002). Shipping dry cement can also create electrical charges on the particles when they slip and slide past each other during transit and handling. The use of water-reducing agents helps counteract these opposing charges by creating a net negative charge on all surfaces of the cement, which acts to repel the particles from each other and reduce flocculation of the cement particles. Blast furnace slag, in contrast to portland cement, is much less susceptible to the buildup of unbalanced electrostatic

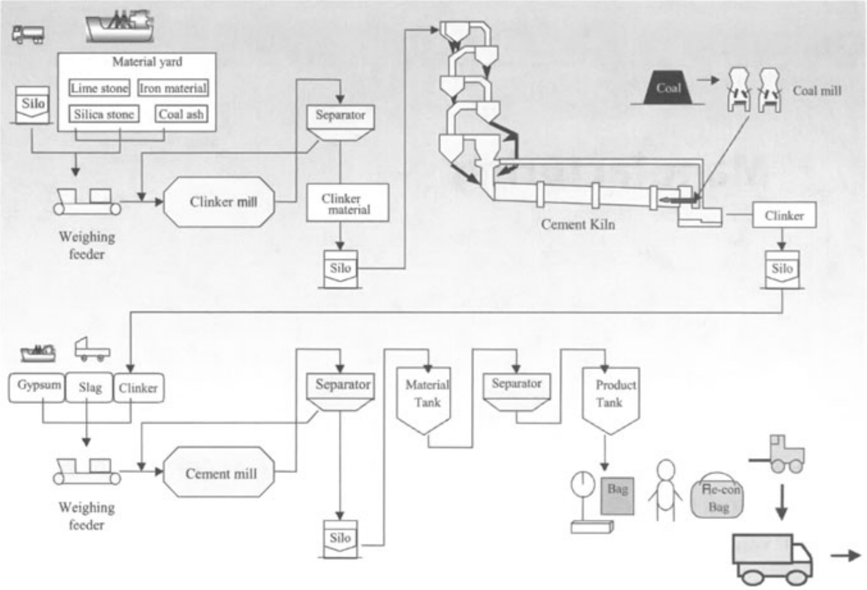

Figure 4-1. Schematic process for manufacturing of portland cement/slag blend ultrafine cements

Source: Courtesy of Surecrete Inc./Nittetsu, Seattle, WA.

charges and is therefore less susceptible to flocculation. The high percentage of slag in many ultrafine cement products reduces, but does not eliminate, flocculation problems. The use of water-reducing agents (superplasticizers) is recommended for most applications.

Dry processing of ultrafine cement has the advantage that large quantities can be produced at centralized locations with a higher level of quality control. The ultrafine cement product can be shipped the same way as ordinary cements. The disadvantages of dry processing are that the ultrafine cement product may not be locally available near the project site, thus incurring increased shipping costs. This can be especially true in remote locations or in developing countries (Kumar et al. 2002).

A cautionary note is offered regarding the production process of ultrafine cement. If OPC powder in its ready-for-use form is simply ground finer in an effort to produce ultrafine cement, problems with the grout properties from mixes produced from this reground OPC can be experienced. These problems include very fast setting times; very high heat of hydration; and strength retrogression—all due to the fine particle size and chemical composition of the product (Sarkar and Wheeler 2001a), as well as the amount of gypsum already in the ready-for-use OPC (Henn et al. 2001). If a ready-for-use OPC is ground finer to create ultrafine cement, the gypsum (which was proportioned based on the chemical analysis of the OPC during original manufacturing) will be ground disproportionately smaller due to its relatively low hardness as compared to the cement. This may make the set times of the newly created ultrafine cement unpredictable. Also, past experience has shown that lack of control in the grinding process produces submicron-sized cement particles, which makes flocculation uncontrollable (F. Sherrill personal communication, 2008). Another problem with regrinding OPC is that it tends to create large electrostatic charges on the particles, which can create severe flocculation problems. Therefore, production of quality ultrafine cement must begin with the grinding of the clinker. Shortcuts using existing portland cements and simply regrinding them to a finer consistency in an effort to produce ultrafine cement are discouraged. Numerous studies have been conducted to create ultrafine cements and grouts that will overcome these problems and we direct the reader to the following references for further information: Kaufman et al. (2004); Perret et al. (2002); Shuguang et al. (2002); Naudts and Landry (2001); Sarkar and Wheeler (2001b).

CHAPTER 5

Packaging and Storage Procedures

Currently, there are several types of ultrafine cements available in the United States. It is important to note that sack weights of ultrafine cement differ from standard OPC sacks supplied in the United States, as shown in Table 5-1 (Henn and Davenport 2005).

A complication with dry powder ultrafine cement has been moisture intrusion. Due to its extreme fineness, very small amounts of moisture can cause flocculation and hardening of the cement, which defeats the intended purpose. Extreme care must therefore be taken in the storage of ultrafine cement. It must be kept in a low-humidity environment and not allowed to remain unused for long periods of time. It has a relatively short shelf life when compared to OPC. Moisture is a primary concern for the portland cement-based portion of the ultrafine cement product. Blast furnace slag, which may make up to 75% of the ultrafine cement, is less affected by moisture or high-humidity environments. This is also true for ultrafine cement blends containing pumice.

With proper storage procedures and the use of plastic-lined bags, shelf life of ultrafine cement is typically in the range of 6 months. The use of heat-sealed bags can extend the shelf life up to 10 months. Beyond these ranges, testing is recommended to determine whether the moisture content is still below the acceptable range (0.3% to 0.5%). Some manufacturers of ultrafine cement recommend using loss on ignition rather than moisture content as a more accurate method to determine the condition of the cement. Loss on ignition is calculated by heating the cement sample to 900 to 1000 °C (1650 to 1830 °F) until a constant mass is obtained. The lost mass of the sample due to the heating is then determined. A high loss on ignition can indicate improper and/or prolonged storage. The prospective user should contact ultrafine cement suppliers directly

Table 5-1. Comparison of Typical Sack Weights from Suppliers of Ultrafine Cement and OPC

Type of Cement	*Sack Weight*	
Ordinary portland cement	42.6 kg	94 lb
Jumbo sacks of ordinary portland cement	907 kg	2,000 lb
	1,134 kg	2,500 lb
Ultrafine cement	20 kg	44 lb
Jumbo sacks of ultrafine cement	25 kg	55 lb
	1,000 kg	2,200 lb

for information on how to conduct loss on ignition tests specifically for ultrafine cements, and what the acceptable ranges are.

Proper packaging of ultrafine cement should utilize impermeable, sealed, plastic-lined bags. Due to the sensitivity of ultrafine cement to moisture, the use of a plastic moisture barrier in the container bags helps to improve the performance of the product and extend its shelf life. Powers et al. (2007) reported using Nittetsu Super Fine that was packaged in sealed plastic bags and was years old, and they noted no problems from moisture intrusion or performance issues. However, every effort should be made not to allow prolonged storage of ultrafine cements.

CHAPTER 6

Mixing and Pumping Procedures

Mixing

Mixing of ultrafine cement-based grouts must be performed properly to achieve the full benefits and performance of the product. The fine grain size of ultrafine cements creates a tendency to flocculate, which increases the effective grain size of the cement particles. Therefore, the mixing speed and duration can significantly affect the performance of the grout. Schwarz and Krizek (1992) performed a study on the effect of mixing on the rheological, or flow, properties of ultrafine cement-based grout. They tested mixers with differing rotational velocities and varied the time the grout was left in the mixers. Their study found that, in general, the use of high-energy, high-shear mixers (commonly called colloidal mixers) produced less bleed and longer set times. Viscosity and unconfined compressive strength were not greatly influenced by the energy imparted to the mixing, though longer mixing times substantially increased the viscosity, indicating that mixing times should be kept to a minimum. It is generally accepted practice that when using ultrafine cements in a grout, high-energy, high-shear mixers must be used. Standard paddle mixers, continuous-screw mixers, mortar mixers, and pug mills do not produce adequate dispersion of the ultrafine cement (Gallagher 2000; Håkansson et al. 1992). High-shear mixers are therefore the only type of mixers that should be allowed for mixing ultrafine cement-based grouts. Mixing rotor speeds of 1,400 to 2,000 rpm should be specified. A schematic of a high-shear mixer is shown in Fig. 6-1 and Fig. 6-2 is a photograph of an actual mixer.

Elevated temperatures of the grout experienced during mixing and placement can adversely affect the grout by decreasing the pumpability and set times. The ultrafine cement-based grout mix temperature is dependent

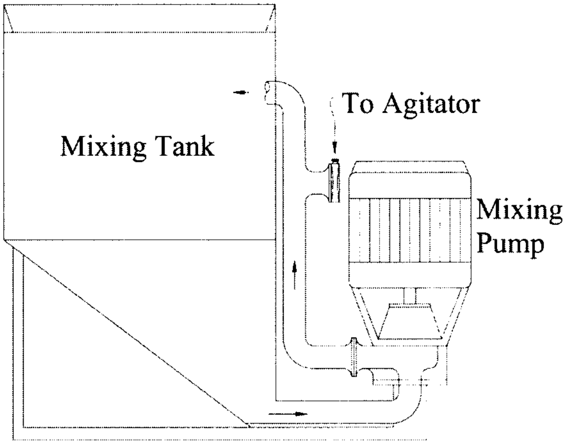

Figure 6-1. Schematic drawing of a high-shear mixer.

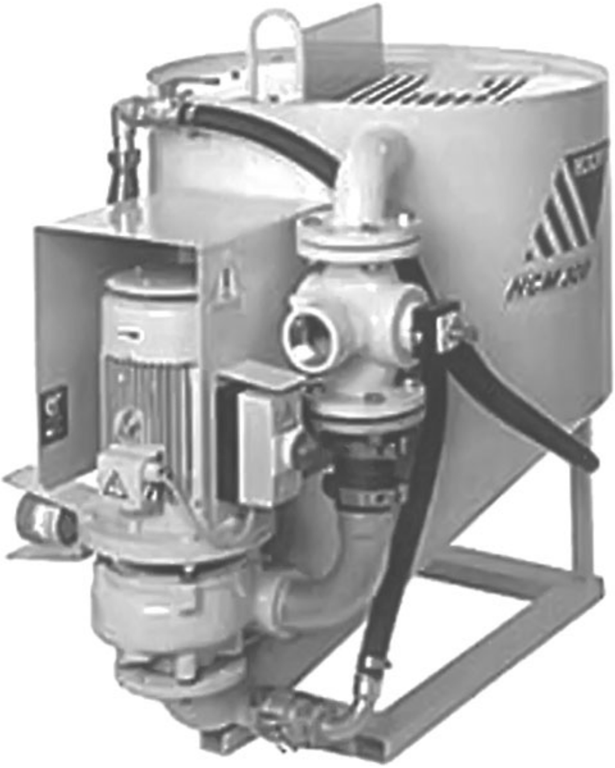

Figure 6-2. High-shear mixer.

Source: Courtesy of American Commercial, Bristol, Va.

on the temperature of the cement and the mix water. Also, when grouting during periods of high ambient air temperatures, the mixing and pumping equipment should be shielded from direct sunlight. Additionally, light-colored grout hoses should be utilized whenever possible when lines are exposed to sunlight. The more time a grout spends being mixed in a high-energy, high-shear mixer, the more heat is introduced into the grout. The amount of time required to thoroughly mix a batch of ultrafine cement-based grout in a high-energy, high-shear mixer will depend on the capacity (size) of the mixer, but will generally range from 15 to 90 seconds. To be thoroughly mixed, the grout should be cycled through the mixing pump approximately six times. In no case should the grout be mixed for more than two minutes.

Grouts made with ultrafine cements are not typically mixed with additives such as fly ash, bentonite, or silica fume. If one considers the average particle size of fly ash (20 microns) compared to ultrafine cement (10 microns), it is easy to see that the addition of fly ash defeats the advantage of using the more expensive ultrafine cement. However, an important admixture to ultrafine cement-based grouts is a superplasticizer or high-range water reducer (HRWR) such as naphthalene sulphonate (NS-200). The NS-200 content is typically about 1% by weight of the mix (Clarke et al. 1997; Schwarz and Krizek 1992). Ultrafine cement tends to flocculate when mixed with water, and HRWRs tend to reduce this problem. HRWRs have a net negative charge and surround the cement particles, causing them to repel each other. This has the effect of reducing flocculation, decreasing viscosity, and reducing the amount of water needed to create a flowable grout. Other admixtures may include retardants, accelerators, and anti-washout materials.

Agitators

After the grout is mixed it is sent to an agitator before moving to the pump to be injected into the grout hole. The agitator is essentially a holding tank for the mixed grout. A revolving paddle keeps the grout in motion to reduce settlement prior to injection. The stirring action alone does not necessarily prevent bleed or settlement of the cement particles, so baffles are attached to the sides of the tank to produce turbulence (Henn 1996). The agitator should have a minimum capacity of approximately 125% of the mixer capacity. The increased size allows the entire contents of the mixer to be discharged into the agitator, which will still have some grout from the last batch mixed in it, thus avoiding interruptions of the grout injection and any delay in mixing the new batch of grout. A typical agitator is shown in Fig. 6-3.

The authors could find no specific time limits in the literature regarding the storage and agitation of grout in the agitator tank. However, after talking with several grouting professionals, the consensus seemed to be that the "1½ hour limit rule" (ASTM C94/C94M-09a; ASTM 2009) from the time the water is first introduced to the cement during mixing should apply.

Pumping

Pumping of ultrafine cement-based grout is similar to pumping portland cement-based grout. Typically, because ultrafine cement-based grout has

Figure 6-3. Agitator.

Source: Courtesy of American Commercial, Bristol, Va.

very low apparent viscosity, pump pressures may be lower than pressures for more viscous mixes. Constant versus variable pressure pumps are a matter of preference and convention based on contractor preference and local area practices. Both methods have been successfully used to place ultrafine cement-based grout. The injection pressure(s) required may also govern the type of pump used.

Three main types of pumps are used in most grouting. A progressing helical cavity (also referred to as a Moyno) pump as shown in Fig. 6-4 delivers a relatively constant pressure and flow of grout with a minimum of pulsation. Typically, two-stage or three-stage pumps are used for this purpose, although more stages can be added. Each stage delivers about 87 psi; thus, a three-stage pump should be capable of delivering about 261 psi discharge pressure. Piston and plunger pumps deliver pulsating pressure and flows and max out at around 3,000 psi (Warner 2004). A typical piston pump configuration is shown in Fig. 6-5, and a plunger pump is shown in Fig. 6-6. All three of these types of pumps can be used for pumping grouts made with ultrafine cements.

Specific requirements for water meters, flow meters, pressure gauges, packers, hoses, and fittings should all be specified in the body of the grouting specification. All of these items and equipment utilized for OPC grouting should be applicable without modifications for ultrafine cement-based grouting.

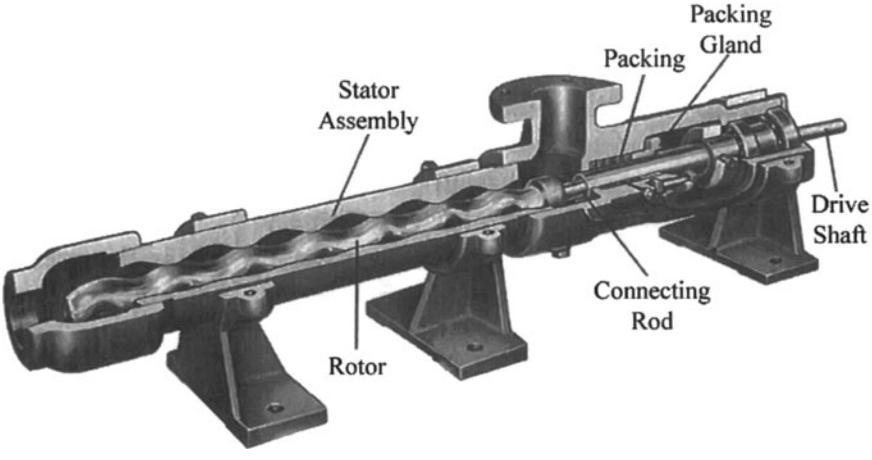

Figure 6-4. Progressing helical cavity (Moyno) pump cut-away.

Source: Warner 2004, with permission from John Wiley & Sons.

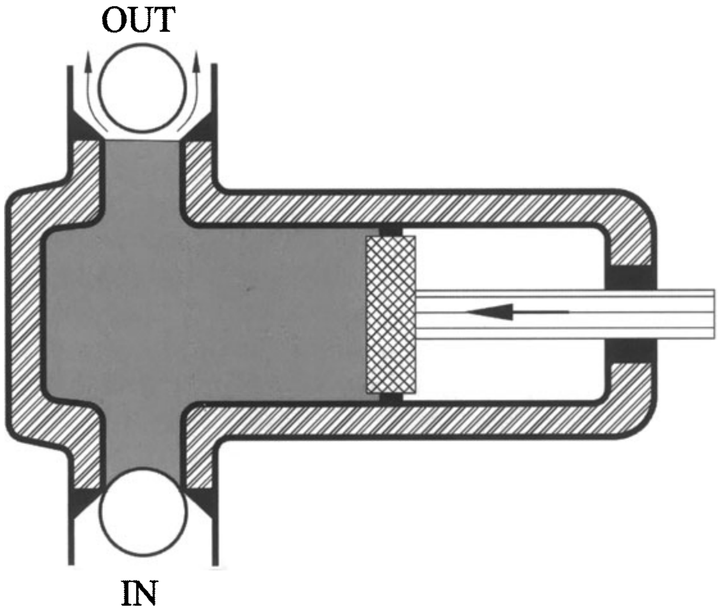

Figure 6-5. Piston pump.

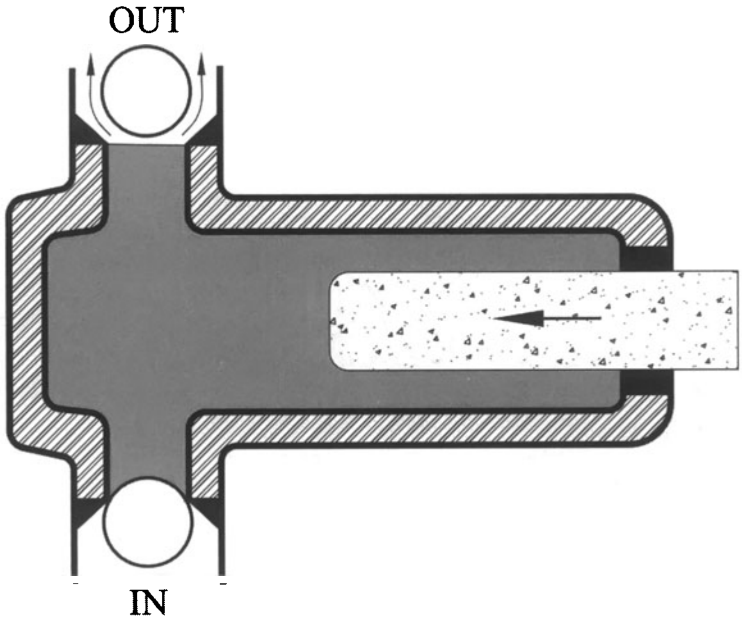

Figure 6-6. Plunger pump.

Mixers, agitators, and pumps are often combined into a single, portable grout plant. Depending on their size and required use, different volumes of grout can be mixed and pumped. Typical grout plants with high-shear mixers are shown in Figs. 6-7 through 6-10.

Measuring and Recording Equipment

During the planning and design phases of a grouting program, various required engineering and performance parameters are developed to ensure the grouting operation achieves its intended goals. Specifics such as hole diameter, spacing, and depth; hole water pressure testing requirements; mix designs; materials and equipment specifications; maximum injection pressures and flow rates; hole staging and sequencing; refusal criteria; and various other requirements are established. Many of these are inspection and verification functions performed manually by a field engineer or inspector, and others are measuring and recording functions.

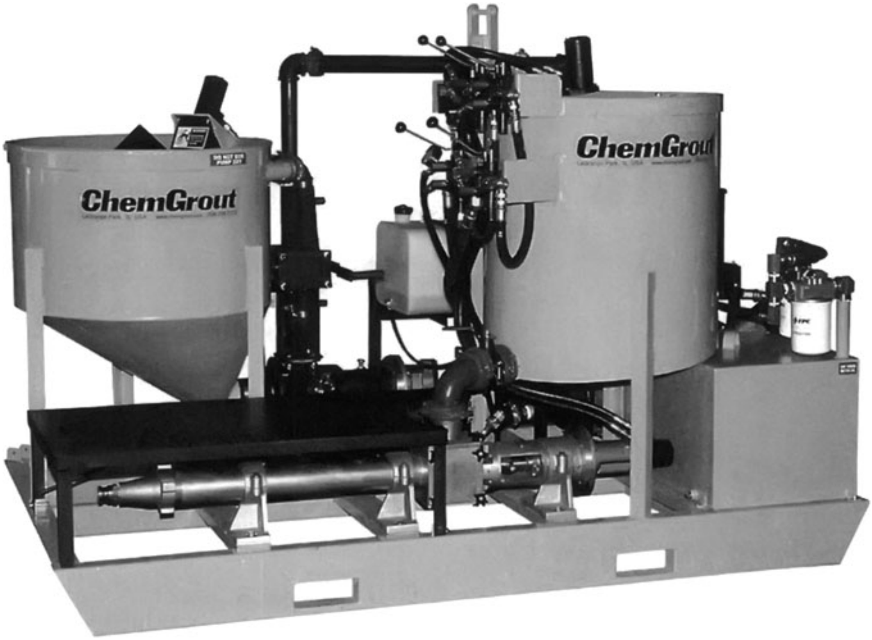

Figure 6-7. ChemGrout grout plant with high-shear mixer.

Source: Courtesy of ChemGrout, Inc., LaGrange Park, Ill.

Figure 6-8. Colcrete grout plant with high-shear mixer.

Source: Courtesy of Colcrete Eurodrill, Derbyshire, UK.

Some of these measuring and recording tasks are often performed automatically on a continuous real-time basis by automated monitoring and recording equipment specially designed for obtaining and recording the information required. The required data can be provided in real time on either disk or chart recorders, or entered into a computer-based data acquisition system for further processing. The type of data typically acquired includes pump discharge and injection pressures, flow rates, and density. However, on smaller projects much of this type of information is still measured and recorded by hand onto preprinted forms by field personnel.

Figure 6-9. Hany grout plant with high-shear mixer.

Source: Courtesy of American Commercial, Bristol, Va.

Figure 6-10. Atlas Copco grout plant with high-shear mixer.

Source: Courtesy of Atlas Copco AB, Stockholm, Sweden.

CHAPTER 7

Quality Control

Quality control of ultrafine cements as well as grouts made with them is crucial to achieve the desired results in field applications. There are a number of tests that should be conducted both at the manufacturing facility, in the laboratory, and in the field. Designers, engineers, and contractors should be familiar with the manufacturer's quality control systems and with the test data provided with the product to be better able to determine whether it meets the requirements of the project specifications and the field conditions. Table 7-1 lists common tests performed by portland and ultrafine cement manufacturers or in laboratories.

A special test that many engineers may not be familiar with is the minislump test. Although most engineers are familiar with slump tests for concrete (ASTM C 143; ASTM 2009), which are not used for grouts, the minislump is not frequently encountered. This test is based on the same principle as the standard slump test, but instead of measuring a vertical distance to obtain slump, the distance of lateral spread of the grout is measured as shown in Fig. 7-1. Due to the lack of aggregate in the grout, it is not necessary to use large volumes of grout to achieve a representative test.

Figure 7-2 shows the dimensions of a minislump cone, which are proportional to those of a standard slump cone. Khayat and Yahia (1998) describe the test procedure:

> The cone is positioned at the center of a horizontal Plexiglas base plate. After pouring the grout into the cone without causing it [to] overflow, the upper part of the cone is tamped lightly to bleed off any entrapped air pockets, and the cone is then gently lifted. The spread diameter of a given mixture represents the mean of two diameters recorded at the end of the flow. As in the case of the slump test for concrete, the measurement of spread is affected by

Table 7-1. Manufacturer or Laboratory Quality Control Tests

Parameter	*Test*	*Standard or Reference*	*Explanation*
Cement type	Standard Specification for Portland Cement	ASTM C 150	Describes what type of cement or material is used to create the ultrafine cement.
Specific gravity	Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate	ASTM C 128-07a	Measures the density and specific gravity of the cement.
Surface area	Standard Test Method for Carbon Black-Total and External Surface Area by Nitrogen Adsorption (BET method)	ASTM D 6556-04	Uses gas adsorption methods to determine the approximate surface area of the particles, typically given in cm^2/g.
Surface area	Standard Test Method for Fineness of Hydraulic Cement by Air Permeability Apparatus (Blaine Fineness)	ASTM C 204-05	Yields an approximate value of the surface area of the particles, typically given in cm^2/gm or m^2/kg. The higher the value, typically the finer the grain size.
Set time	Standard Test Method for Time of Setting of Hydraulic Cement by Vicat Needle	ASTM C 191-04b	Gives the initial set time of the grout at a prescribed w:c ratio and temperature.

Chemical constituents	Standard Test Methods for Chemical Analysis for Hydraulic Cement	ASTM C 114-06e1	Yields the chemical makeup of the cement including which elements and oxides are present.
Rheology	Coaxial Viscometer	Khayat and Yahia (1998)	Describes the cohesion and viscosity of the fluid. Typically, for the best permeation, both of these values should be minimized.
Stability	Pressure Filtration Test	Gelman Pressure Filter	Tests the stability of the grout under pressurized conditions such as exist during pumping.
Stability	Standard Test Method for Expansion and Bleeding of Freshly Mixed Grouts for Preplaced-Aggregate Concrete in the Laboratory	ASTM C 940-98a (2003)	Measures the at-rest bleed of the grout. Gives a measure of how readily the particles will settle out of suspension.
Particle size analysis	Particle Size Distribution of Powders by Laser Light Scattering	ASTM UOP856-85	Measures the particle sizes present in the cement for the generation of a gradation curve.
Consistency	Standard Test Method for Slump of Hydraulic-Cement Concrete	Modified from ASTM C 143 for grouts	The spread diameter of grout from a minislump cone is measured. Measures workability of the grout. The standard test method for slump of hydraulic-cement concrete.
Consistency	Standard Test Method for Marsh Funnel Viscosity of Clay Construction Slurries	ASTM D 6910-04 API Method 13B-2	An indirect measure of viscosity given in units of seconds. Water at 20 °C = 22.5 ± 0.5 sec. Measures the workability of the grout.

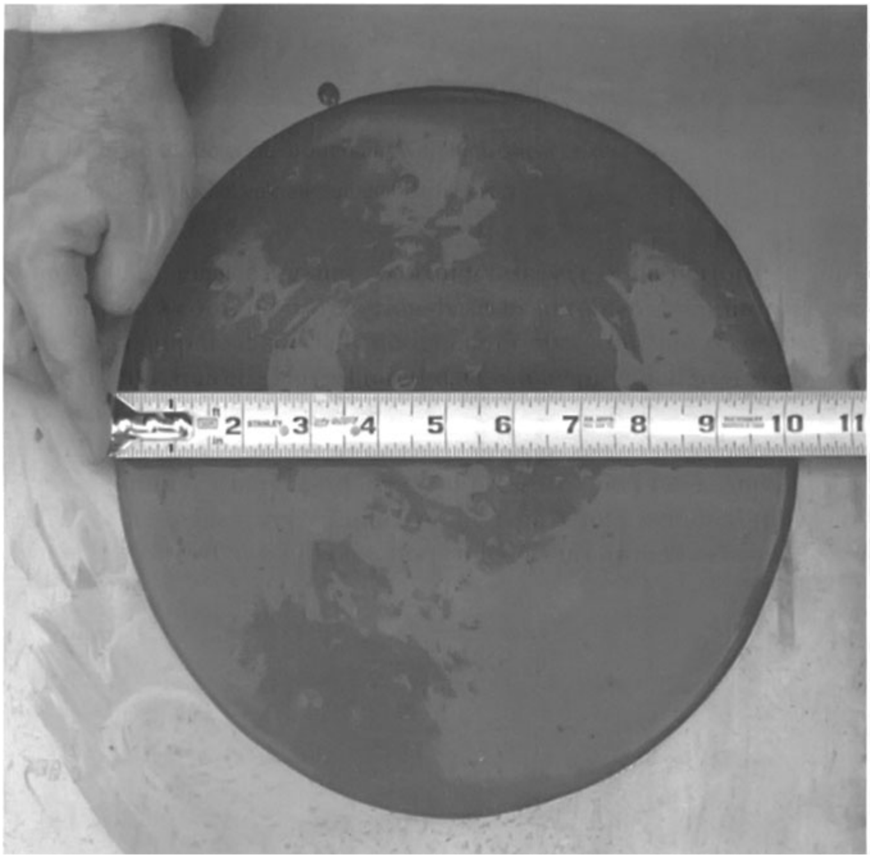

Figure 7-1. Measurement of a minislump test.

Source: Warner 2007, with permission from RETC/SME, http://www.smenet.org.

the moisture conditions of the cone and base plate as well as the smoothness of the various surfaces. Such parameters must be constant to minimize test fluctuation.

In addition to tests performed by manufacturers or laboratories to control the quality of the ultrafine cement product, a number a field tests should, depending on project-specific requirements, also be performed at the site where the grout is being mixed and placed. Table 7-2 describes field tests for quality control.

The results of the tests listed in Table 7-2 give good indications of how the grout mix is behaving. For engineers involved in writing specifications,

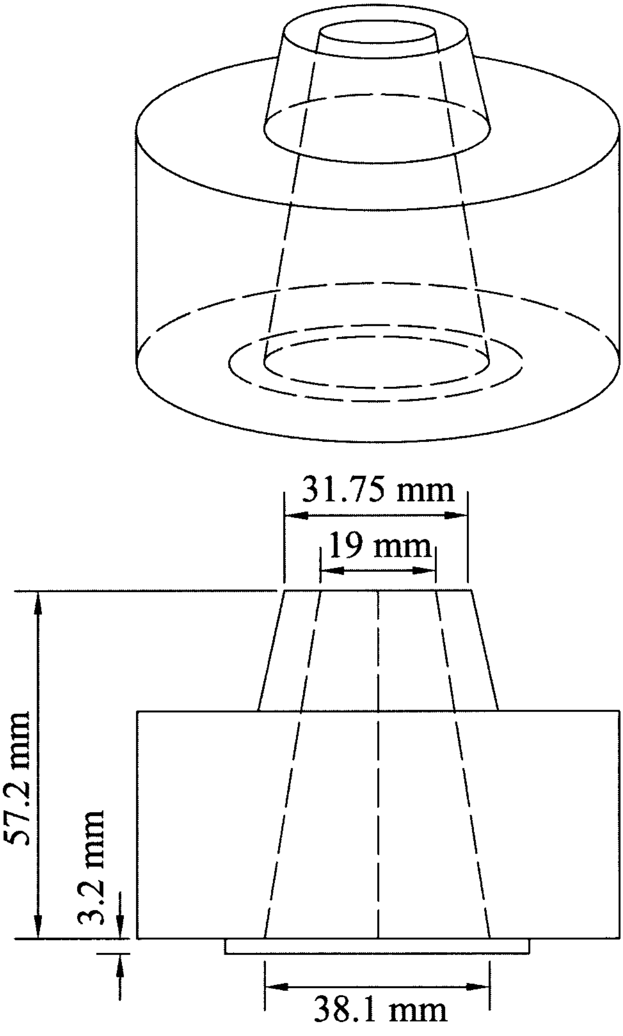

Figure 7-2. Minislump cone.

Source: Adapted from Khayat and Yahia 1998; with permission from ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428.

the tests listed are relatively easy to perform in the field or field laboratory. Equipment for the tests is readily available and inexpensive. If a test is specified, a range of values or some minimum and maximum value must be provided. Because the requirements for grouts are so varied, it is impossible to provide typical values; therefore, the person who drafts the

Table 7-2. Field Quality Control Tests

Parameter	*Test*	*Standard or Reference*	*Explanation*
Consistency	Standard Test Method for Marsh Funnel Viscosity of Clay Construction Slurries	ASTM D 6910-04 API Method 13B-2	An indirect measure of viscosity given in units of seconds. Water at 20 °C = 22.5 ± 0.5 sec. Measures the workability of the grout.
Specific gravity	Mud balance	API Method 13B-1	Measures the specific gravity of the grout by determining the weight of a known volume of fluid.
Stability	Washout	Khayat and Yahia (1998)	Measures the potential of the grout to be diluted by water.
	Standard Test Method for Expansion and Bleeding of Freshly Mixed Grouts for Preplaced-Aggregate Concrete in the Laboratory	ASTM C 940-98a (2003)	Determines the amount of expansion and accumulation of bleed water in cement-based grout.
Strength	Standard Practice for Making and Curing Concrete Test Specimens in the Field; Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens); Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens	ASTM C 31-06; ASTM C 109; ASTM C 39	Details how to cast grout cylinders or cubes and determine the compressive strength in the laboratory.

Note: For the parameters of consistency, specific gravity, and strength, field quality control tests that are more common than the ones listed here should be conducted as minimum requirements.

specifications should be familiar enough with the test to be able to accurately specify a relevant range of values. Most field tests ranges and maximum and minimum values are determined by the results of laboratory testing of trial grout mixes. The reader is also referred to Chapter 8, Recommendations for Contract Specifications.

The Marsh funnel is one of the most widely used tests for determining the consistency and workability of grout (Fig. 7-3). The test indirectly measures viscosity by measuring the time it takes for a predetermined volume of grout to flow through the funnel. The result is recorded in units of time (seconds). A standard Marsh funnel per ASTM D 6910-04 (ASTM 2004) has a capacity of 946 mL and a base discharge opening diameter of 3/16 in. (4.7 mm). The test is conducted by plugging the hole in the base of the funnel with a finger and pouring 946 mL of a representative sample of grout into the funnel through a 12-mesh sieve to avoid clogging. The discharge hole in the base is opened by removing the finger and recording the time it takes to fill a 1-quart (946-mL) cup. Henn et al. (2005) documented Marsh funnel flow times for numerous ultrafine cement-based grout mixes at various demonstrations and conferences. The results are given in Table 7-3.

Figure 7-3. Marsh funnel and measurement cup.

Table 7-3. Marsh Funnel Measurements for Various Ultrafine Cement-Based Grout Mixes

Supplier	*Name of Product*	*W:C Ratio (by weight)*	*Admixture Weight*	*Name of Admixture*	*Grout Temperature*	*Marsh Funnel Viscosity (sec/946 mL)*
Geo-Denver 2000						
Surecrete	Nittetsu Super Fine	0.67:1	0.6 kg (1.4 lb)	KAO Mighty 150	30 °C (86.0 °F)	59
De Neef	MC-500	0.67:1	0.6 kg (1.4 lb)	MC 200 Helper	34 °C (92.5 °F)	70
UFL 2000						
Surecrete	Nittetsu Super Fine	1.25:1	0.5 kg (1 lb)	KAO Mighty 150	29 °C (84 °F)	29
De Neef	MC-500-Japan	1.25:1	0.5 kg (1 lb)	MC 200 Helper	29 °C (84.5 °F)	30
De Neef	MC-500-Germany	1.25:1	0.5 kg (1 lb)	Rheobuild 1000	30 °C (85.5 °F)	31
US Grout	Ultrafine Grout V. Prem	1.25:1	0.5 kg (1 lb)	Superplasticizer	30 °C (86.5 °F)	32
UFL 2002						
Surecrete	Nittetsu Super Fine	1:1	0.4 kg (0.9 lb)	KAO Mighty 150	NA	36
De Neef	MC 500-Japan	1:1	0.0 kg (0.0 lb)	In product	NA	41
De Neef	MC 500-Germany	1:1	0.7 kg (1.6 lb)	KAO Mighty 150	NA	30
US Grout	Ultrafine Grout	1:1	0.6 kg (1.32 lb)	Superplasticizer (granular)	NA	33

UFL 2003						
Surecrete	Nittetsu Super Fine	1:1	0.7 kg (1.5 lb)	KAO Mighty 150	26 °C (78 °F)	30.6
De Neef	MC-500-Germany	1:1	0.7 kg (1.5 lb)	KAO Mighty 150	25 °C (77 °F)	30.4
De Neef	MC-500-Japan	1:1	0.7 kg (1.5 lb)	KAO Mighty 150	26 °C (79 °F)	37.8
US Grout	Ultrafine Grout	1:1	0.3 kg (0.7 lb)	Disal	26 °C (78 °F)	32.7
CSM 2009[a]						
Cemex	Type II portland cement	4:1	0 kg	None	84 °C (28.9 °F)	28
Surecrete	Nittetsu Super Fine	4:1	10 oz (296 mL) 3.3 oz (97.5 mL)	Mighty 150 (Kelco-Crete) Diutan Gum	83 °C (28.3 °F)	28
De Neef	MC-500	4:1	14 oz (414 mL)	Super P	76 °C (24.4 °F)	29
Surecrete	Nittetsu Super Fine	1:1	20 oz (591 mL)	Mighty 150 (Kelco-Crete)	78 °C (25.6 °F)	34
De Neef	MC-500	1:1	21 oz (621 mL)	NS-200 (Dispersant)	77 °C (25.0 °F)	32

Notes: Geo-Denver 2000 refers to the conference sponsored by the Geo-Institute of the American Society of Civil Engineers, held in Denver, Colorado, Aug. 5–8, 2000. UFL refers to the annual Fundamentals of Grouting course offered by the University of Florida Division of Continuing Education, held in Lakewood, Colorado, in the stated year (Sep. 10–15, 2000; May 19–24, 2002; May 18–23, 2003). CSM 2009 refers to the annual Grouting Fundamentals and Current Practices course offered by the Colorado School of Mines Office of Special Programs and Continuing Education, held in Golden, Colorado, June 22–26, 2009.

[a] Admixtures for CSM 2009 were measured by volume.

Source: Henn et al. 2005; reproduced with permission from RETC/SME, http://www.smenet.org.

Figure 7-4. Mud balance.

Another widely used field test is the mud balance as shown in Fig. 7-4. The mud balance is used to measure the density of the grout mix. Grout is placed into the cup that has a known volume. The scale is then adjusted such that a balance is achieved allowing the weight of the grout to be measured. The result is typically recorded in lb/gal or lb/ft^3.

Other properties of interest to ultrafine cement-based grouts, such as dispersion, flocculation, or percent of hydration, are difficult to measure without the use of specialized laboratory equipment. The use of test holes or even full-scale test sections at the actual project site prior to the start of production grouting is encouraged to maximize the probability of a successful operation.

CHAPTER 8

Recommendations for Contract Specifications

This section is intended to aid the person writing the project grouting specification(s) by offering language and some specific wording suggestions that should be incorporated into the project grouting specification(s) whenever the use of grout(s) made with ultrafine cement is planned. These recommendations are intended more for use in prescriptive-type specifications.

Some projects have only one general grouting specification, which can include grouts made with portland cement, ultrafine cements, or various chemicals. Other projects may have several stand-alone grouting specifications, each pertaining to a specific or related type of grouting method. The language and wording suggestions presented here are not intended to be considered a stand-alone specification; rather, they should be incorporated into a general or specific grouting specification as required. Some examples of possible specific stand-alone grouting specifications are:

- Permeation grouting of soil and/or fissure grouting of rock
- Probe hole drilling and pre-excavating grouting
- Contact and void-filling grouting
- Consolidation and seepage control grouting
- Backfill grouting
- Chemical grouting

In addition to requiring portland cement and various types of chemical grouts, several of these different grouting methods could also require the use of grouts made with ultrafine cements. Other grouting methods such as compaction, compensation, and jet grouting—all widely used in heavy construction—usually have separate stand-alone specifications.

However, none of those three methods utilizes ultrafine cement in the mix designs.

Several of the following language and wording suggestions include a brief commentary offering more information or an explanation of the suggestion. The language and wording suggestions are limited specifically to ultrafine cements with respect to material properties, storage and handling, mix properties, mixing, pumping, and injection of the grout. Subjects such as submittals; water pressure testing of the grout holes; grout hole diameter, layout, spacing, orientation, depth, and number of holes; allowable grouting pressures; flow measurement; refusal criteria; record keeping; and so forth should be covered in the body of the general or specific grouting specification based on project-specific requirements.

Part 1—General

The Part 1—General portion of the ultrafine cement grouting specification usually includes explanations and requirements for:

- Scope of work
- Related work
- Standards and references
- Definitions
- Qualifications
- Submittals
- Quality control/assurance
- Product handling and storage

Scope of Work

Project specifications sometimes specify two or more types of cement to be used for the same type of grouting. For example, permeation grouting specifications could specify the use of portland type I-II, type III, and ultrafine cements. When more than one type of cement is specified, it is very important to provide the physical limits as to location(s) or the conditions required for use of grout made with one or the other of the various types of cements. These limits or conditions might best be given as notes on the contract drawings or in the specifications based on the specific requirement. When the use of more than one type of cement is specified, the record-keeping requirements and the pay quantities must also reflect these requirements.

Related Work

The entire project-related work, which could require, be integrated with, or interface with the use of grouts made with ultrafine cement, should be listed in this portion of the specifications. The list could become extensive but it is good practice to list all the related work, even if the relationship is minor.

Standards and References

The important point here is to remember to add all of the ultrafine cement and grouts made with ultrafine cement-specific standards and references to the specifications. Some of these may be unfamiliar to the specification writer, owner, construction manager, and/or contractor.

Definitions

Again, as is done with standards and references, it must be remembered that definitions specific to ultrafine cement and grouts made from ultrafine cement must be added.

Qualifications

There is no need for additional or specific qualifications requirements for a grouting contractor utilizing ultrafine cement beyond those requirements that would normally be specified of the contractor in a standard soil permeation or rock fissure grouting specification.

Submittals

There are no additional submittal specification requirements beyond the normal ones required for a typical soil permeation or rock fissure grouting program. However, there would be specific submittal requirements for ultrafine cement, admixtures to be used with it, and mix design(s) for grouts made with ultrafine cement. These would be in addition to the ones provided for portland cement-based grouts.

Quality Control

There are no additional quality control requirements beyond the normal ones required for a typical soil permeation or rock fissure grouting program.

However, there would be quality control requirements relating specifically to ultrafine cement and grout made with it. Refer to Chapter 7, Quality Control, for these specific quality control requirements.

Product Handling and Storage

There are special and specific product handling and storage specification requirements for ultrafine cements which are more stringent than those required for portland cements. These additional requirements are outlined in Chapter 5, Packaging and Storage Procedures.

Part 2—Equipment, Products, and Materials

The Part 2—Equipment, Products, and Materials portions of the ultrafine cement grouting specification usually include requirements for equipment, including:

- Batching/proportioning (by weight or by volume)
- Mixers
- Water meters
- Agitators
- Grout pumps
- Flow meters (to be included with data acquisition systems)
- Pressure gages
- Packers
- Hoses

The equipment utilized for mixing and grouting with ultrafine cement-based grouts is the same as that used for soil permeation or rock fissure grouting with portland cement-based grouts. Therefore, no special specification language is required. However, only high-speed, high-shear (colloidal) mixers should be allowed to be used when utilizing ultrafine cements. This is also strongly encouraged when utilizing portland cements.

This section of the specifications should also list the required products and materials for:

- Admixtures
- Additives
- Mix designs

The admixtures and additives used in the formulation of a ultrafine cement-based grout mix design are the same as those used in the formulation of portland cement-based mix designs, except as noted in Chapter 3. Therefore, no special specification requirements are necessary.

With regard to mix design, the water:cement ratios (w:c) used for ultrafine cement-based grouts can range from 0.5:1 to 4:1 and higher. Most published information on w:c ratios for grouts made with portland cements advise keeping the ratio as low as possible to maximize the stability of the mix. However, some published information on ultrafine cement-based grouts also refer to high w:c ratios, greater than 4:1.

Part 3—Execution

The Part 3—Execution portion of the ultrafine cement grouting specification usually includes requirements for:

- General
- Grout header, delivery line, and return line arrangement (if used)
- Maximum injection rates
- Refusal criteria
- Allowable injection pressures
- Field quality control

The first two items and the Field Quality Control subsection should not entail any special requirements beyond those that would be found in these subsections of a typical soil permeation or rock fissure grouting specification. However, the designer may want to include the requirement for performing minislump tests, which are explained in Chapter 7, Quality Control.

Part 4—Measurement and Payment

The Part 4—Measurement and Payment portion of the ultrafine cement grouting specification usually includes requirements for:

- Method of measurement
- Basis of payment

There are no additional specification requirements beyond those that would be found in a typical measurement and payment section of a permeation grouting specification.

It must be remembered that the pay item for supplying ultrafine cement needs to be kept separate from the pay item(s) for supplying portland cement. If the cement is being paid for by the pound, ultrafine cement is approximately five times more costly than portland cement at today's prices. If the cement is being paid for by the bag, ultrafine cement is generally supplied in 44- or 55-lb bags, whereas portland cement is supplied in 94-lb bags.

When other performance-based payment methods are specified, they should be looked at carefully. Even when utilizing these other types of payment methods, it may be necessary to separate the portland cement-based grouting from the ultrafine cement-based grouting.

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Raymond W. Henn, Ph.D., P.G., is a senior consultant at Lyman Henn, a division of Brierley Associates, LLC, in Denver, Colorado, and has more than 40 years of heavy- and underground-construction experience, with concentrations in shafts and tunneling, water and wastewater, transportation, and hydroelectric projects. He holds degrees in geology, construction management, and engineering, receiving his Ph.D. in Mining and Earth Systems Engineering from the Colorado School of Mines. During his career, Dr. Henn has held positions ranging from field engineer through superintendent to construction manager on both direct-hire and construction-management assignments. He now serves primarily as a heavy- and underground-construction consultant. He has a strong background in general heavy civil construction, mass and specialty concrete placements, various grouting methods, and deep foundations, as well as shaft, tunnel, and chamber excavation and lining systems. He has also served as a member on 27 dispute review boards, an arbitrator, an expert witness, a construction appraiser, and a member of the value engineering teams.

Dr. Henn served as President of the American Underground Construction Association (now the Underground Construction Association of the Society of Mining Engineers) from 2003 to 2005. He received the 2002 Roebling Award for Innovations in Construction Engineering from the American Society of Civil Engineers and the 2008 Outstanding Individual Award from the Underground Construction Association of SME. He is the author of *Practical Guide to Grouting of Underground Structures* (ASCE Press, 1996) and editor of *AUA Guidelines for Backfilling and Contact Grouting of Tunnels and Shafts* (ASCE Press, 2003). He has also authored and co-authored numerous published technical papers and articles.

Dr. Henn is an adjunct professor at the Colorado School of Mines, teaching courses in tunneling and underground construction. He is also a lecturer for underground grouting at the Colorado School of Mines' annual Grouting Fundamentals and Current Practice course. Dr. Henn is a member of the American Society of Civil Engineers, the Underground Construction Association of the Society of Mining Engineers, the International Society of Explosive Engineers, the Dispute Resolution Board Foundation, the Beavers, and the Moles.

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Mr. Soule's career has also included geologic mapping, identification and mapping of geologic hazards, and landslide mitigation, as well as commercial and residential design and down-hole logging of large diameter borings.

Mr. Soule is a member of the American Society of Civil Engineers and the Association of Environmental and Engineering Geologists, for which he serves as chair of the Rocky Mountain Section. Mr. Soule is also a guest lecturer for both mining and geological engineering at the Colorado School of Mines.

References

American Concrete Institute (ACI). 233R-95. (2003). "Slag cement in concrete and mortar." ACI, Farmington Hills, Mich.

ACI. (2009). "ACI concrete terminology," <http://terminology.concrete.org> accessed Feb. 12, 2010.

American Petroleum Institute (API). 13 B-1. (2003). "Recommended practice for field testing water-based drilling fluids." API, Washington, D.C.

API. 13 B-2. (2005). "Recommended practice for field testing oil-based drilling fluids." API, Washington, D.C.

API 1991. (1991). "Bleed under pressure." API, Washington, D.C.

ASTM International (ASTM). C 94/C94M-09. (2009). "Standard specification for ready-mixed concrete." ASTM, West Conshohocken, Penn., *Book of Standards* vol. 04-02.

ASTM. C 39/C39M-09. (2009). "Standard test method for compressive strength of cylindrical concrete specimens." ASTM, West Conshohocken, Penn., *Book of Standards* vol. 04-02.

ASTM. C 109/C109M-08. (2008). "Standard test method for compressive strength of hydraulic cement mortars (using 2-in. or [50-mm] cube specimens)." ASTM, West Conshohocken, Penn., *Book of Standards* vol. 04-01.

ASTM. C 114-09b/C114-09. (2009). "Standard test methods for chemical analysis for hydraulic cement." ASTM, West Conshohocken, Penn., *Book of Standards* vol. 04-01.

ASTM. C 128-07a. (2007). "Standard test method for density, relative density (specific gravity), and absorption of fine aggregate." ASTM, West Conshohocken, Penn., *Book of Standards* vol. 04-02.

ASTM. C 143/C143M-09. (2009). "Standard test method for slump of hydraulic-cement concrete." ASTM, West Conshohocken, Penn., *Book of Standards* vol. 04-02.

ASTM. C 150/C150M-09. (2009). "Standard specification for portland cement." ASTM, West Conshohocken, Penn., *Book of Standards* vol. 04-01.

ASTM. C191-08. (2008). "Standard test method for time of setting of hydraulic cement by Vicat needle." ASTM, West Conshohocken, Penn., *Book of Standards* vol. 04-01.

ASTM. C204-07. (2007). "Standard test method for fineness of hydraulic cement by air permeability apparatus." ASTM, West Conshohocken, Penn., *Book of Standards* vol. 04-01.

ASTM. C 939-02. (2002). "Standard test method for flow of grout for preplaced-aggregate concrete (flow cone method)." ASTM, West Conshohocken, Penn., *Book of Standards* vol. 04-02.

ASTM. C 940-98a. (2003). "Standard test method for expansion and bleeding of freshly mixed grouts for preplaced-aggregate concrete in the laboratory." ASTM, West Conshohocken, Penn., *Book of Standards* vol. 04-02.

ASTM. D6556-09. (2009). "Standard test method for carbon black-total and external surface area by nitrogen adsorption." ASTM, West Conshohocken, Penn., *Book of Standards* vol. 09-01.

ASTM. D 6910-04. (2004). "Standard test method for Marsh funnel viscosity of clay construction slurries." ASTM, West Conshohocken, Penn., *Book of Standards* vol. 04-09.

ASTM. UOP856-07. (2007). "Particle size distribution of powders by laser light scattering." ASTM, West Conshohocken, Penn.

Clarke, W. J. (1984). "Performance characteristics of microfine cement." *Preprint 84-023*, ASCE Geotechnical Conference, Atlanta, Ga., May 14–18, ASCE, Reston, Va., 1–14.

Clarke, W. J., Boyd, M. D., and Helal, M. (1992). "Ultrafine cement test and dam grouting." *Grouting, soil improvement and geosynthetics,* New Orleans, La., February 25–28, ASCE Geotechnical Special Publication 30, R. H. Borden, R. D. Holtz, and I. Juran, eds., ASCE, Reston, Va., 626–638.

Clarke, W. J., Schwarz, L. D., Moreno, P. O., and Borja, R. C. (1997). "Ultrafine cement-based grouting of dry joints in Huites Dam, Choix, Mexico." *Proc., Geo-Logan Conference on Grouting: Compaction, Remediation, and Testing,* Utah, July 16–18, ASCE Geotechnical Special Publication 66, C. Vipulanandan, ed., ASCE, Reston, Va., 133–146.

De Paoli, B., Bosco, B., Granata, R., and Bruce, D. (1992). "Fundamental observations on cement based grouts. 2: Microfine cements and the CEMILL process." *Proc., Grouting, Soil Improvement and Geosynthetics,* New Orleans, La., February 25–28, ASCE Geotechnical Special Publication 30, R. H. Borden, R. D. Holtz, and I. Juran, eds., ASCE, Reston, Va., 474–485.

Engineering News Record (ENR). (2009). "Asphalt, cement, aggregate, concrete, brick, block, lime," Sept. 7, pp. 19–20.

Federal Highway Administration (FHWA). (2006). "Blast furnace slag: Material description." *Turner-Fairbank Highway Research Center*, <http://www.tfhrc.gov/hnr20/recycle/waste/bfs1.htm> accessed September 2, 2008.

Gallagher, P. M. (2000). "Passive site remediation for mitigation of liquefaction risk." Ph.D. dissertation, Virginia Polytechnic Institute and State University, Blacksburg, Va.

Garshol, K. F. (2007). *Pre-excavation grouting in rock tunneling*, UGC International, Division of BASF Construction Chemicals, Zürich, Switzerland.

Håkansson, U., Hässler, L., and Stille, H. (1992). "Rheological properties of microfine cement-based grouts with additives." *Proc., Grouting, Soil Improvement and Geosynthetics*, New Orleans, La., February 25–28, ASCE Geotechnical Special Publication 30, R. H. Borden, R. D. Holtz, and I. Juran, eds., ASCE, Reston, Va., 551–563.

Henn, R. W. (1996). *Practical guide to grouting of underground structures*, ASCE Press, Reston, Va.

Henn, R. W., Davenport, J. C., Tzobery, S., and Bandimere, S. (2005). "Additional test results for comparison of penetration of grout made with various ultrafine cement products." *Proc., Rapid Excavation and Tunneling Conference*, Seattle, June 26–30, Society of Mining, Metallury and Exploration.

Henn, R. W., and Davenport, J. C. (2005). "Ultrafine cement: A critical component of a grouting program." *Tunnels & Tunneling Int.*, 37(4), 27–29.

Henn, R. W., ed. (2003). *AUA guidelines for backfilling and contact grouting of tunnels and shafts*, ASCE Press, Reston, Va.

Henn, R. W., Ganse, P., Bandimere, S., Smoak, G., and Warner, J. (2001). "Comparison of penetration test results of grouts made with various ultrafine cement products." *Proc., Rapid Excavation and Tunneling Conference*, San Diego, June 10–14, Society of Mining, Metallurgy, and Exploration.

Houlsby, A. C. (1990). *Construction and design of cement grouting*, John Wiley & Sons, Inc., Hoboken, N.J.

International Society for Rock Mechanics (ISRM). (1995). *Final report of the commission on rock grouting*. ISRM, Lisbon, Portugal.

Kaufman, J., Winnefield, F., and Hesselbarth, D. (2004). "Effect of the additions of ultrafine cement and short fiber reinforcement on shrinkage, rheological and mechanical properties of portland cement," *Cement and Concrete Composites*, 26(5), 541–549.

Khayat, K. H., and Yahia, A. (1998). "Simple field tests to characterize fluidity and washout resistance of structural cement-based grout." *Cement, Concrete, and Aggregates*, 20(1), 145–156.

Kosmatka, S. H., Kerhoff, B., and Panarese, W. C. (2002). "*Design and control of concrete mixtures*, EB001, 14th ed., Portland Cement Association, Skokie, Ill.

Krizek, R. J., Liao, H., and Borden R. H. (1992). "Mechanical properties of microfine cement/sodium silicate grouted sand." *Proc., Grouting, Soil Improvement and Geosynthetics,* New Orleans, La., February 25–28, ASCE Geotechnical Special Publication 30, R. H. Borden, R. D. Holtz, and I. Juran, eds., ASCE, Reston, Va., 688–699.

Kumar, S., Singh, C. J., and Kachari, J. (2002). "Microfine cement: special superfine portland cement." *Oil and Natural Gas Corp., Ltd.,* <http://www.ongcindia.com/pring.asp?d=techpaper&cat=techpaper1.txt> accessed April 2, 2007.

Liao, H., Borden, R. H., and Krizek, R. J. (1992). "Microfine cement/sodium silicate grout." *Proc., Grouting, Soil Improvement and Geosynthetics,* New Orleans, La., February 25–28, ASCE Geotechnical Special Publication 30, R. H. Borden, R. D. Holtz, and I. Juran, eds., ASCE, Reston, Va., 676–687.

Lombardi, G. (1985). "The role of cohesion in cement-based grouting of rock." *Proc., Fifteenth Congress on Large Dams, International Commission on Large Dams,* Paris, 3(Q58, R13), Compania Anonima de Administracion y Fomento (CADAFE), Caracas, Venezuela, 235–261.

Naudts, A., and Landry, E. (2001). "New on-site wet milling technology for the preparation of ultrafine cement-based grouts," <http://www.ecogrout.com/wetmilling.pdf> accessed Feb. 2010.

Perret, S., Khayat, K. H., Gangnon, E., and Rhazi, J. (2002). "Repair of 130-year-old masonry bridge using high-performance cement-based grout," *Journal of Bridge Engineering,* 7(1), 31–38.

Powers, J. P., Corwin, A. B., Schmall, P. C., and Kaeck, W. E. (2007). *Construction dewatering and groundwater control: New methods and applications,* 3rd ed., John Wiley & Sons, Inc., Hoboken, N.J.

Risk and Policy Analysts Limited. (2000). "Risk reduction strategy and analysis of advantages and drawbacks for acrylamide." Prepared for the Department of the Environment, Transport and the Regions, Stage 4 Report, March, 2000, Contract No. CDEP 1/41/17.

Sarkar, S. L., and Wheeler, J. (2001a). "Important properties of an ultrafine cement: Part 1." *Cement and Concrete Res.*, 31(2), 119–123.

Sarkar, S. L., and Wheeler, J. (2001b). "Microstructural development in an ultrafine cement: Part 2." *Cement and Concrete Res.*, 31(2), 125–128.

Schwarz, L. G., and Krizek, R. J. (1992). "Effects of mixing on rheological properties of microfine cement-based grout." *Proc., Grouting, Soil Improvement and Geosynthetics,* New Orleans, La., February 25–28, ASCE Geotechnical Special Publication 30, R. H. Borden, R. D. Holtz, and I. Juran, eds., ASCE, Reston, Va., 512–525.

Schwarz, L. G., and Krizek, R. J. (2000). "Evolving morphology of early age microfine cement-based grout." *Advances in Grouting and Ground Modification, Proc., Sessions of Geo-Denver 2000,* Denver, Colo., August 5–8. ASCE Geotechnical

Special Publication 104, R. J. Krizek and K. Sharp, eds., ASCE, Reston, Va., 181–199.

Shuguang, H., Guan, X., and Ding, Q. (2002). "Research on optimizing components of microfine high-performance composite cementitious materials," *Cement and Concrete Research,* 32(12), 1871–1875.

Sottili, L., and Padovani, D. (2002). "Effect of grinding aids in the cement industry." Petrochem, St. Petersburg, Russia, April 14–16.

Sutch, P., and Dirth, L. (2006). *Geology study manual, 2006 review for the National (ASBOG) Geology Licensing Exam,* REG Review, Inc., Bedford, N.H.

Warner, J. (2007). "Types of grout and grout rheology." *Proc., Grouting Fundamentals and Current Practice,* Colorado School of Mines, April 30–May 4, Colorado School of Mines, Golden, Colo.

Warner, J. (2004). *Practical handbook of grouting, soil, rock, and structures,* John Wiley & Sons, Inc., Hoboken, N.J.

Weaver, K. D., and Bruce, D. A. (2007). *Dam foundation grouting,* ASCE Press, Reston, Va.

APPENDIX A

Price of Ordinary Portland Cement and Ultrafine Cement

City	*Ordinary Portland Cement ($/lb.)*	*Ultrafine Cement and Shipping ($/lb.)*
Atlanta	0.048	0.589
Baltimore	0.073	0.598
Birmingham	0.059	0.583
Boston	0.044	0.612
Chicago	0.050	0.560
Cincinnati	0.046	0.574
Dallas	0.047	0.566
Denver	0.048	0.534
Detroit	0.054	0.574
Kansas City	0.052	0.556
Los Angeles	0.049	0.517
Minneapolis	0.063	0.530
New Orleans	0.042	0.596
New York City	0.056	0.613
Philadelphia	0.042	0.602
Pittsburg	0.048	0.584
San Francisco	0.050	0.504
Seattle	0.041	0.466
St. Louis	0.055	0.564

Note: Due to the local availability of OPC, shipping is not included. Ultrafine cement is supplied from limited locations, so shipping to the job site must be included in the cost. Shipping costs included are from Seattle, WA. Surecrete also maintains a warehouse in the New York City area. The exchange rate of the U.S. dollar to the yen and euro may also be a cost factor since several of the ultrafine cements come from offshore. US Grout manufactures ultrafine cement in New Mexico and sells at $0.36/pound, not including shipping, in 2008 dollars.
Sources: Prices for OPC are as published in the *Engineering News Record* (ENR 2009). Prices for ultrafine cement were provided by Surecrete Inc./Nittetsu, Seattle, WA.

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