Design of normal concrete mixes

Second edition

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This second edition replaces the first, which was revised in 1988. The design of concrete mixes for most purposes, including roads, is covered in this combined work by Building Research Establishment Ltd, where it was prepared for publication, the Transport Research Laboratory and the British Cement Association.

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Foreword

The method of concrete mix design described in this publication is the same as that used in the first edition, which was published in 1975[1] and revised in 1988[2]. In this second edition, minor amendments have been made to allow for changes in the terminology and properties of the materials used and for changes in various British Standard Specifications.

The basic procedure for this mix design method is applicable to concrete for most purposes including pavements. It is restricted to designing concrete mixes to meet workability, compressive strength and durability requirements using Portland cements complying with BS 12[3] or BS 4027[4] and natural aggregates complying with BS 882[5], or coarse air-cooled slag complying with BS 1047[6]. It does not deal with special materials or special concretes such as lightweight aggregate concrete, or with flowing or pumped concrete. Guidance is given on the application of the method to mixes incorporating pulverised-fuel ash (pfa) for material complying with BS 3892:Part 1[7], or using Portland pulverised-fuel ash cement complying with BS 6588[8]. Guidance is also given on the design of mixes incorporating ground granulated blastfurnace slag (ggbs) complying with BS 6699[9] or using Portland-blastfurnace cements complying with BS 146[10] or BS 4246[11].

As in the first edition, the general principles and basic concepts are given in the Introduction. After this the publication is divided into three parts. Part one gives the background information which is required to understand the mix design procedure.

Part two describes the mix design process and contains all the basic information in the form of tables and graphs for the application of the method to most concretes designed for compressive strength. A standardised form has been developed for use with this method, and some worked examples are given.

Part three deals with modifications to the mix design method to deal with air-entrained concrete, and for the design of mixes incorporating pfa or ggbs.

This method is based on data obtained at the Building Research Establishment, the Transport Research Laboratory (formerly the Transport and Road Research Laboratory), and by the British Cement Association (formerly the Cement and Concrete Association).

1 Introduction

1.1 Principles of proposed method

Basically, the problem of designing a concrete mix consists of selecting the correct proportions of cement, fine and coarse aggregate and water to produce concrete having the specified properties. Sometimes additional ingredients such as ground granulated blastfurnace slag (ggbs), pulverised-fuel ash (pfa), or admixtures, are used as shown in Part three. There are many properties of concrete that can be specified, eg workability, strength, density, thermal characteristics, elastic modulus and durability requirements. The properties most usually specified are:

- The workability of the fresh concrete
- The compressive strength at a specified age
- The durability, by means of specifying the minimum cement content and / or the maximum free-water / cement ratio and, in some cases, requiring the use of selected types of materials

The mix design process must take account of those factors that have a major effect on the characteristics of the concrete, but can, at least at the first stage, ignore those which only have a minor effect on the concrete. There is little point in devising a complex method of mix design which takes into account factors which are difficult to measure or which are unlikely to remain constant during the progress of the job. The effects of various factors on the properties of concrete are described in Sections 2 and 3.

The principle behind the method described in this publication is that from the restricted data usually available at the mix design stage, mix proportions are derived in an attempt to produce a concrete having the required workability and strength. Typical data are given in Part two but where there is more appropriate information available related to local materials, this can be used instead. A trial mix is then made, but because of the assumptions made at this stage in the design it is probable that this trial mix will not completely comply with the requirements. If necessary it is possible, from the trial mix results and information given in this publication, to adjust the mix proportions and to use these for actual production or to prepare a revised trial mix.

1.2 Basic concepts

1.2.1 Strength margin

Because of the variability of concrete strengths[12] the mix must be designed to have a considerably higher mean strength than the strength specified. The method of specifying concrete by its minimum strength has been replaced in British Standards and Codes of Practice such as BS 5328[13] and BS 8110[14] by a ‘characteristic strength’. The difference between the specified characteristic strength and the target mean strength is called the ‘margin’ and is explained more fully in Section 4.

This margin is based on knowledge of the variability of the concrete strength obtained from previous production data expressed as a standard deviation, or alternatively a substantial margin is applied until an adequate number of site results is obtained.

1.2.2 Measurement of workability

In this publication two alternative test methods are used, the slump test[15] which is more appropriate for the higher workability mixes, and the Vebe time test[16] which is particularly appropriate for those mixes which are to be compacted by vibration. The compacting factor[17] is not used in this method since it is not possible to establish consistent relationships between it and the slump or Vebe time tests. If required, it can be used as a control test.

1.2.3 Free-water

The total water in a concrete mix consists of the water absorbed by the aggregate to bring it to a saturated surface-dry condition, and the free-water available for the hydration of the cement and for the workability of the fresh concrete. In practice aggregates are often wet and they contain both absorbed water and free surface water so that the water added at the mixer is less than the free-water required. The workability of concrete depends to a large extent on its free-water content; if the same total water content were used with dry aggregates having different absorptions, then the concrete would have different workabilities. Similarly the strength of concrete is better related to the free-water / cement ratio since on this basis the strength of the concrete does not depend on the absorption characteristics of the aggregates.

The water/cement ratios referred to in this publication are the ratios by mass of free-water to cement in the mix and these, as well as the free-water contents, are based on the aggregates being in a saturated surface-dry condition.

1.2.4 Types of aggregate

Early mix design methods used in the UK[18,19] classified the shape of aggregate as rounded, irregular or angular. There is insufficient difference between the behaviour of rounded and irregular aggregates in concrete to justify the use of separate classifications for these two shapes of aggregate, both of which are usually uncrushed, smooth-textured aggregates. There are however significant differences between these aggregates and angular aggregates which are usually rough in texture and invariably produced by a crushing process.

Two of the characteristics of aggregate particles that affect the properties of concrete are particle shape and surface texture. Particle shape affects the workability of the concrete, and the surface texture mainly affects the bond between the matrix and the aggregate particles and thus the strength of the concrete. Generally, crushed aggregates consist of rather angular particles having a rough surface texture resulting in a concrete of lower workability but higher strength compared with a similar mix made with uncrushed aggregates. There are naturally some exceptions to these generalisations, for example crushed flint has an extremely smooth surface texture whereas uncrushed rounded gritstone has a rough surface texture. However, in line with the principles of this publication of taking only major factors into account to design the initial trial mix, only two types of aggregate are considered, ie crushed and uncrushed.

The type of aggregate becomes of greater importance for concrete having a high specified strength. If the specified strength at 28 days is 50 N/mm^2 or more it may become necessary to use a crushed aggregate rather than an uncrushed gravel. The higher the specified strength the more critical is the selection of the source of the aggregate.

1.2.5 Aggregate grading

This publication deals with concrete made with aggregates having three nominal maximum sizes, ie 40 mm, 20 mm and 10 mm.

Early methods of mix design[18,19] used in the UK specified grading curves for the combined fine and coarse aggregates. These required the use of fine aggregates having a rather restricted range of gradings compared with the limits specified in BS 882. In many parts of the country fine aggregates having such restricted gradings are not available, although the gradings of the available fine aggregates are still suitable for making good quality concrete. Combined aggregate grading curves are not used in this method of mix design which refers instead to the percentage of fine aggregate passing the 600 µm test sieve. The higher the percentage passing the 600 µm test sieve, the finer the fine aggregate. This is a development from the previous edition of this publication which used the grading zones given in the 1973 edition of BS 882.

Fine aggregates should comply with the C, M, or F grading requirements of BS 882:1992[5], but these limits overlap and are too wide for mix design purposes. The method for deriving a suitable fines content takes into account the many relevant factors, ie the type and maximum size of coarse aggregate, the grading of the fine aggregate, characterised by the percentage passing the 600 µm test sieve, and the cement content and workability of the concrete.

1.2.6 Mix parameters

It was previously the general custom in the United Kingdom to specify concrete by a system of proportions or ratios, eg 1:2:4 (being the proportions of cement:fine aggregate:coarse aggregate) either by mass or by volume, or as cement/aggregate ratio, water/cement ratio and fine aggregate/coarse aggregate ratio, usually by mass.

Such systems have certain merits in terms of simplicity of expression. However, they are not so convenient when discussing the effect of mix parameters on the characteristics of the concrete, nor do they adequately describe the quantity of cement required to cast a given volume of concrete.

The most fundamental way to specify mix parameters is in terms of the absolute volumes of the different materials required in a concrete mix. A more practical method, based on similar principles, which has been adopted in this publication is to refer to the mass of materials in a unit volume of fully compacted concrete. This method of referring to concrete mix proportions has been in use for a long period in Europe and in the United States of America, and is becoming the general practice in the United Kingdom.

In order to use this approach, knowledge is required of the expected density of the fresh concrete. This depends primarily on the relative density* of the aggregate and the water content of the mix. The effect of changes in the cement content produces at the most about a 2% change in the expected density and thus, for the purpose of this publication, is ignored. The small quantity of air normally entrapped in compacted concrete is also ignored. Data are given from which an estimate of the wet density of the fresh concrete can be made.

The method of mix design given in this publication results in the mix being specified in terms of the mass in kilograms of the different materials required to produce one cubic metre of finished concrete.

1.2.7 Durability

A durable concrete is one which gives a satisfactory performance during an adequate life in a given environment; this includes providing protection of the steel against corrosion in reinforced concrete and prestressed concrete. There are some durability problems

*The internationally known term 'relative density' used in this publication is synonymous with 'specific gravity' and is the ratio of the mass of a given volume of substance to the mass of an equal volume of water.

associated with the constituent materials, and others due to the effect of hostile environments.

A major factor in providing durable concrete is the production of a dense, impermeable concrete, having an adequate cement content and low free-water / cement ratio, which is fully compacted and properly cured. To be durable in hostile environments, Codes and Standards may specify the use of particular materials, or limits on the cement content or free-water / cement ratio. Provision is made in the mix design method for these to override the values obtained from strength and workability requirements.

The problems of providing protection against corrosion of steel in concrete are discussed in BRE Digest 263[20]. To ensure adequate protection, BS 8110 requires higher strength grades of concrete as the severity of the exposure increases; it also specifies minimum cement contents and maximum free-water / cement ratios, depending on the degree of exposure. Corrosion problems are aggravated by the presence of chlorides in either aggregates or admixtures. Limits are specified in BS 882 and BS 8110 and materials complying with these requirements should be used.

Concrete in the ground may be subject to attack by sulfates as described in BRE Digest 363[21]. To minimise the effect of such attack requires the use of sulfate-resisting Portland cement or other materials, and the mix proportions should comply with the requirements given in BRE Digest 363 or in BS 5328[13].

Concrete that is exposed to freezing when wet and to the action of de-icing salts is liable to spall and deteriorate. The resistance of concrete to such deterioration is greatly improved if it contains entrained air as required in BS 5328. The method of mix design described in Part two requires modifications for air-entrainment which are given in Part three, Section 8.

Concrete that retains a high moisture content and that is made with certain aggregates may react with the alkalis from the cement to cause cracking and expansion, owing to the alkali–silica reaction as described in BRE Digest 330[22]. Measures to avoid such disruption are described in BRE Digest 330 and in an independent Working Party Report published by the Concrete Society[23]. These may require the use of a low-alkali Portland cement available under BS 4027 or the use of other materials.

Many of the measures described previously to give assurance of durability in adverse environmental conditions involve the specification of minimum cement contents or maximum free-water / cement ratios. Owing to the difficulties of testing for compliance with such requirements during concrete construction, an alternative approach is to specify a high strength requirement for durability[24]. However, the more fundamental requirements can be checked if required by using rapid analysis techniques, such as that provided by the RAM equipment available from Wexham Developments.

Part one: Background information

2 The workability of concrete

2.1 Measurement of workability

The word workability has been used to embrace many factors associated with the ease of placing concrete, such as its cohesiveness, mobility, compactibility and finishability. No satisfactory single test method has yet been devised to measure these combined characteristics. A workable concrete would be defined as a concrete suitable for placing and compacting under the site conditions using the plant available; thus in road construction a low-slump concrete is more suitable than one with a high slump.

It is not considered practical for this publication to define the workability required for various types of construction or placing conditions since this is affected by many factors. As explained in 1.2.2, this publication uses the slump and Vebe time tests as the means by which the workability of the concrete is specified as one of four ranges given in Table 3.

2.2 Water content

The water content expressed as mass per unit volume of concrete is the major factor influencing the workability of concrete. For a given type and maximum size of aggregate, the higher the water content the higher the slump and the lower the Vebe time.

The free-water content required to produce concrete of a specified slump or Vebe time depends upon the characteristics of the aggregate. Research work using 24 crushed rock aggregates[25] showed a range of water requirements from 170 kg/m^3 to 230 kg/m^3. A similar range was found during a nationwide survey[24] of mix design data from ready-mixed concrete producers. However, as a general rule it can be assumed that uncrushed aggregates require a lower water content than crushed aggregates to make concrete of equal workability, and that the smaller the maximum size of the aggregate the higher the water content needed. Table 3 gives typical values of the free-water content for use in the mix design at four different levels of slump or Vebe time, with different types and maximum sizes of aggregate. If there is more appropriate information available related to the local materials, this can be used instead of the values given in Table 3.

The grading of the coarse aggregate, provided that it complies with the requirements of BS 882, has little effect on the water requirement of a concrete mix

The grading of the fine aggregate has a considerable effect on the water requirement of the concrete. Changing the grading of a sand from a coarse one, (ie say 20% by mass passing the 600 µm test sieve) to a fine one (ie say 90% by mass passing the 600 µm test sieve), can result in an increase in the water content of 25 kg/m^3 in order to maintain the required workability of the concrete. Such a change in water content would considerably reduce the compressive strength of the concrete. However, the workability can be maintained at the same water content when using finer sand by reducing the fines content. Figure 6 shows how the fines content of the mix should be reduced as the sand becomes finer, ie as the percentage passing the 600 µm test sieve increases.

2.3 Type and strength class of cement

Different types and strength classes of cement have different water requirements to produce pastes of standard consistence. However, for the cements covered by this publication, such differences will generally have little effect on the workability of the concrete and therefore this factor is ignored in this mix design method (but see Part three for modifications for mixes containing pfa or ggbs).

3 The compressive strength of concrete*

3.1 Age at test and curing conditions

The strength developed by a concrete made with given materials and given proportions increases for many months under favourable conditions, but in the majority of specifications the strength is specified at an age of 28 days. The strength development of concrete made with all types of Portland cement depends on the temperature and humidity conditions during curing. Higher temperatures increase the speed of the chemical reaction

*Throughout this publication concrete strength is expressed in the units N/mm^2.
1 N/mm^2 = 1 MN/m^2 = 1 MPa. (N = newton; Pa = pascal.)

and thus the rate of strength development, and in order to achieve higher strengths at later ages loss of water from the concrete must be prevented. For test purposes the concrete test specimens are stored in water at a constant temperature as specified in BS 1881: Part 111[26].

3.2 Type and strength class of cement

Different types and strength classes of cement produce concretes having different rates of strength development. In class 52.5 Portland cements the chemical reaction initially proceeds at a faster rate than in class 42.5 Portland cements; the effect of this on typical concretes having a free-water / cement ratio of 0.5 is shown in Table 2. If there is more appropriate information available related to local materials, this can be used instead of the values given in Table 2. A class 42.5 sulfate-resisting Portland cement is assumed to have the same rate of strength development as a class 42.5 Portland cement.

3.3 Cement strength variation

Apart from the difference in the strength of concrete with different types and strength classes of cement described in 3.2, there is inevitably some variability in the strength of concrete due to the variability of any particular type or strength class of cement. This is due to the variability of cement supplied from different works and to normal variations in production from any one works over a period of time. Typically, the standard deviation of the strength of standard concrete cubes at 28 days made with Portland cement class 42.5 from different works is about 5 N/mm^2, while the standard deviation due to the variability of the cement from a single works is about 3 N/mm^2.

3.4 Aggregate type and grading

The type and source of the aggregate has a considerable influence on the compressive strength of concrete. As a general rule, an uncrushed coarse aggregate (generally smooth and rounded) makes a concrete with a lower strength than one with crushed coarse aggregate. Other factors such as the type of fine aggregate, the maximum size of aggregate, the overall grading, and particle shape and surface texture, have little direct effect on the compressive strength and are ignored for the purposes of this publication.

The combined effect of the aggregate characteristics does have an indirect effect on compressive strength through its influence on the water requirement to produce a workable concrete, as discussed in 2.2. In work on crushed rock aggregates[25] the 28-day compressive strength varied between 29 N/mm^2 and 53 N/mm^2 depending on which of 24 different aggregates was used. In order to produce very high-strength concrete, ie concrete with a specified strength of 50 N/mm^2 or more, it is generally necessary to obtain aggregates from selected sources.

Typical strength values when uncrushed or crushed coarse aggregates are used are given in Table 2. If there is more appropriate information available related to local materials this can be used instead of the values given in Table 2.

3.5 Relationship between compressive strength and free-water / cement ratio

One of the basic concepts of this publication is the representation in Figure 4 of the relationship between the compressive strength of concrete and the free-water / cement ratio as defined in 1.2.3. It should be noted that the curves shown in Figure 4 do not indicate any age of test. It has been explained (in 3.2 and 3.3) that the strength development varies for different types and strength classes of cement and that there is variation in the quality of cement, and also (in 3.4) that the type of aggregate can affect the strength of the concrete. The curves illustrate the form of the relationships between the compressive strength and the free-water / cement ratio and are obtained from a large number of different concrete mixes using different modern Portland cements and different types of aggregate, but for any particular sources of cement and aggregates a slightly different form of relationship may be obtained.

Table 2 gives typical data for a concrete having a free-water / cement ratio of 0.5 to give a datum point on Figure 4 appropriate to the age of test and materials to be used. The strength development shown in Table 2 applies to a concrete with a cement content of about 300 kg/m^3 cured in water at 20°C. Such a mix made with Portland cement class 42.5 has a 7-day strength about 70% of that attained at 28 days. However, richer mixes initially gain strength more rapidly so that 7-day strength may well exceed 75% of the 28-day strength. Conversely, for lean concretes this ratio is nearer 65%.

3.6 Type of mixing

The compressive strength of the concrete is not directly affected by the type of mixer used. Certain types of mixer require a higher degree of workability for efficient operation and this may have an indirect effect on the proportions of the concrete required for a particular value of free-water / cement ratio. However, hand-mixing is likely to produce a lower strength concrete than machine-mixed concrete of similar proportions.

4 Variability of concrete strength during production

4.1 Factors contributing to the overall variation

The main factors influencing the workability and strength of concrete that are taken into account when designing the mix are discussed in Sections 2 and 3. If these factors change during the progress of the job, the properties of the concrete must also change.

The overall variation in the measured strength of concrete that is obtained during a job can be considered to be made up of three component sources which are:

- Variation in the quality of the materials used
- Variation in the mix proportions due to the batching process
- Variation due to sampling and testing

During production there are inevitable variations in the characteristics of the materials used. For example the quality of different deliveries of cement may vary, or the grading and particle shape of aggregates may vary, requiring changes of the water/cement ratio in order to maintain the specified workability. It is known that considerable variations occur in the proportions from batch to batch irrespective of whether the batching is by volume or by weight; these can be attributed partly to the plant and partly to its operation. Finally, some of the variation in the measured concrete strength arises from the processes of sampling, making, curing and testing the test specimens even though these are carried out in accordance with BS 1881. There are few data on how these three groups contribute individually to the overall variation of concrete strength but there is considerable information on the magnitude of the overall variation[27].

4.2 The distribution of results

It is now generally accepted that the variation in concrete strengths follows the normal distribution such as that shown in Figure 1. The area beneath the curve represents the total number of test results, and the proportion of results less than some specified value is represented by the area beneath the curve to the left-hand side of a vertical line drawn through the specified value.

This normal distribution curve is symmetrical about its mean, has a precise mathematical equation and is completely specified by two parameters, its mean *m* and its standard deviation *s*. The standard deviation is a measure of the variability calculated from the equation:

$$s = \sqrt{\frac{\Sigma(x-m)^2}{n-1}}$$

where x = an individual result
n = the number of results
m = the mean of the n results

It is now generally accepted that at a given level of control the standard deviation increases as the specified characteristic strength increases up to a particular level, and is independent of the specified strength above this level. This type of relationship is shown in Figure 3, the standard deviation being independent of the specified characteristic strength above 20 N/mm^2.

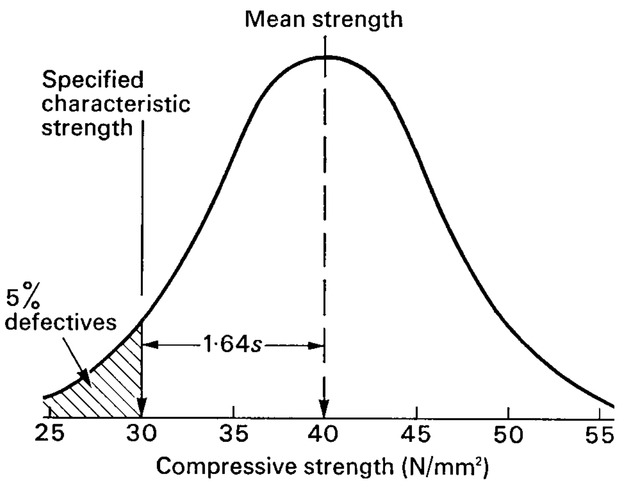

Figure 1 Normal distribution of concrete strengths

4.3 Characteristic strength

It has been shown that concrete cube strengths follow the normal distribution. There is therefore always the probability, however remote, that a result will be obtained less than the specified strength. It has therefore become the increasing practice to specify the quality of concrete not as a minimum strength but as a 'characteristic strength' below which a specified proportion of the test results, often called 'defectives', may be expected to fall. The characteristic strength may be defined to have any proportion of defectives, BS 5328 and BS 8110 adopt the 5% defective level in line with the CEB/FIP international recommendations for the design and construction of concrete structures[28].

BS 5328 specifies a system for testing for compliance with a specified characteristic strength. The compliance values have been derived by making certain assumptions to give reasonable levels of risk to both producer and purchaser that concrete of the specified quality is accepted by the testing scheme. However, as described in 4.4, it may be prudent to base the initial mix design on a proportion of defectives less than 5%.

4.4 Margin for mix design

As a result of the variability of concrete in production it is necessary to design the mix to have a mean strength greater than the specified characteristic strength by an amount termed the margin. Thus:

$$f_m = f_c + ks$$

where f_m = the target mean strength
f_c = the specified characteristic strength
ks = the margin, which is the product of:
s = the standard deviation, and
k = a constant

The constant k is derived from the mathematics of the normal distribution and increases as the proportion of defectives is decreased, thus:

k for 10% defectives = 1.28
k for 5% defectives = 1.64
k for 2.5% defectives = 1.96
k for 1% defectives = 2.33

For the 5% defective level specified in BS 5328, $k = 1.64$ and thus $f_m = f_c + 1.64s$. Figure 1 relates to a concrete having a specified characteristic strength of 30 N/mm^2 and a standard deviation of 6.1 N/mm^2. Hence:

Target mean strength $f_m = 30 + (1.64 \times 6.1)$
$= 30 + 10$
$= 40$ N/mm^2

Since the compliance rules given in BS 5328 operate on a small number of tests, producers may find that a margin based on the 5% defectives with *k* of 1.64 leads to an unacceptable rate of failing the compliance rules. To avoid this, it may be preferable at the mix design stage to use a greater margin by adopting a higher value for *k*.

The standard deviation used to calculate the margin should be based either on results obtained using the same plant, materials and supervision, as for example in ready-mixed concrete plants or precast concrete works, or, in the absence of such information, on a value taken from Figure 3 which should be used until adequate production data are available. It is very seldom that standard deviations less than 2.5 N/mm^2 or more than 8.5 N/mm^2 are obtained from concrete produced in the United Kingdom[12], and on about 60% of sites the standard deviation can be expected to be between 4.0 and 6.0 N/mm^2.

The standard deviation calculated from *n* results is only an estimate of the standard deviation of the total population. It is therefore subject to normal probability errors which are reduced as *n* becomes larger . If several groups of *n* results are taken where *n* is 20, the values of the standard deviation calculated from these may vary by about ±30% without being significantly different statistically. It is thus desirable that for mix design purposes the standard deviation should be calculated from at least 20 results. If fewer results are available a standard deviation of 8 N/mm^2 should be used for concrete with a characteristic strength of 20 N/mm^2 or more as shown by line A in Figure 3.

When the standard deviation is calculated from a large number of results it is a much better estimate of the true standard deviation and will generally include some long-term variables that might not be present with a small number of results. However, the value used for mix design should not be less than that shown by line B in Figure 3 (4 N/mm^2 for concrete with a characteristic strength of 20 N/mm^2 or more).

Various Specifications and Codes of Practice may impose different limits for the standard deviation of the margin, and if relevant the mix should be designed to comply with these requirements.

Part two: The mix design process

5 Flow chart of procedures

The manner in which this method links the various factors involved in the process of designing a mix is shown as a flow chart in Figure 2. Also a suitable mix design form for recording the values derived is shown in Table 1*. It will be seen from the flow chart that initial information is divided into two categories:

- specified variables, the values of which are usually nominated in specifications, and
- additional information, which is normally available to the producer of the concrete.

This initial information is used in conjunction with reference data, which appear in the form of figures or tables in this publication, to evaluate a number of 'derived values' which are also subdivided into two categories:

- the mix parameters, several of which form an intermediate step to the derivation of the second category, and
- the final unit proportions, which are defined in terms of mass of materials required to produce one cubic metre of compacted concrete, expressed to the nearest 5 kg.

In order to clarify the sequence of operation, and for ease of reference, the flow process is divided into five stages. Each of these stages deals with a particular aspect of the design and ends with an important parameter or final unit proportions.

Stage 1 deals with strength leading to the free-water/cement ratio
Stage 2 deals with workability leading to the free-water content
Stage 3 combines the results of Stages 1 and 2 to give the cement content
Stage 4 deals with the determination of the total aggregate content
Stage 5 deals with the selection of the fine and coarse aggregate contents

The mix design form shown in Table 1 is sub-divided into the same five stages and the separate item numbers correspond with the relevant boxes of the flow chart in Figure 2.

*The form is also printed at the end of this publication for ease of removal and subsequent use.

5.1 Selection of target water/cement ratio (Stage 1)

If previous information concerning the variability of strength tests comprises fewer than 20 results, the standard deviation to be adopted should be that obtained from line A in Figure 3. If previous information is available consisting of 20 or more results, the standard deviation of such results may be used provided that this value is not less than the appropriate value obtained from line B. The margin can then be derived from calculation C1:

$$M = k \times s \qquad \ldots\text{C1}$$

where M = the margin (Item 1.3)
k = a value appropriate to the 'percentage defectives' permitted below the characteristic strength (see 4.4)
s = the standard deviation.

Instead of working from the standard deviation and obtaining the margin through calculation C1, the margin itself may be specified direct. Hence Item 1.3 may be a derived value or an optional specified value as indicated in Figure 2.

Calculation C2 determines the target mean strength (expressed to two significant figures):

$$f_m = f_c + M \qquad \ldots\text{C2}$$

where f_m = the target mean strength
f_c = the specified characteristic strength
M = the margin

Next, a value is obtained from Table 2 for the strength of a mix made with a free-water/cement ratio of 0.5 according to the specified age, the strength class of the cement and the aggregate to be used. This strength value is then plotted on Figure 4 and a curve is drawn from this point and parallel to the printed curves until it intercepts a horizontal line passing through the ordinate representing the target mean strength. The

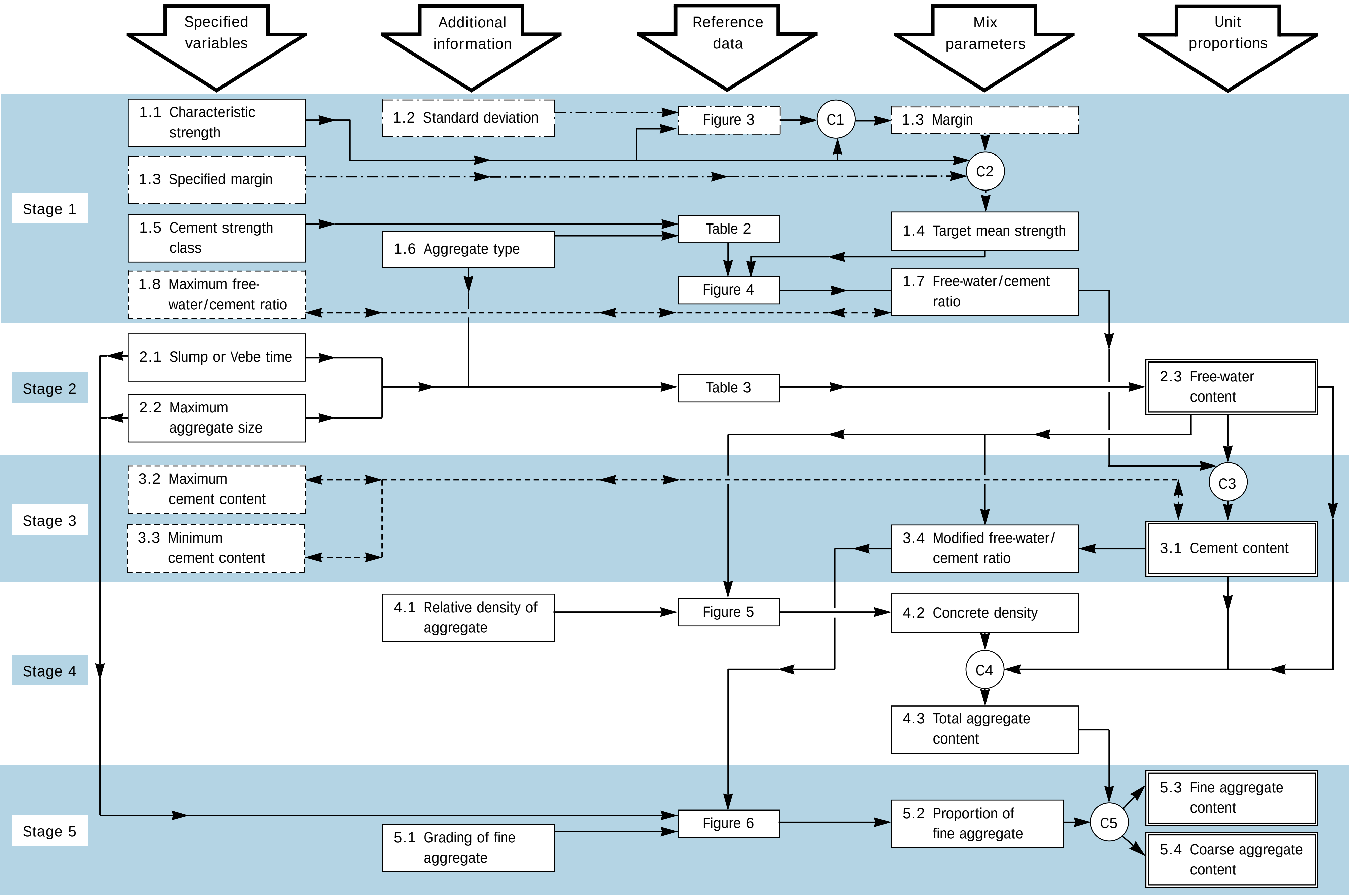

Figure 2 Flow chart of mix design procedure. Items in dashed boxes and with two-way arrows are optional limiting values that may be specified. Items in chain-dotted boxes are alternatives. C = calculation

Table 1 Concrete mix design form

Job title ....

Stage	Item		Reference or calculation	Values
1	1.1	Characteristic strength	Specified	{ .... N/mm^2 at .... days Proportion defective .... %
	1.2	Standard deviation	Fig 3	.... N/mm^2 or no data .... N/mm^2
	1.3	Margin	C1 or Specified	(k = ...) .... × .... = ... N/mm^2 .... N/mm^2
	1.4	Target mean strength	C2	.... + ... = ... N/mm^2
	1.5	Cement strength class	Specified	42.5/52.5
	1.6	Aggregate type: coarse Aggregate type: fine		Crushed/uncrushed Crushed/uncrushed
	1.7	Free-water/cement ratio	Table 2, Fig 4	.... } Use the lower value [ ]
	1.8	*Maximum free-water/ cement ratio*	*Specified*	.... }
2	2.1	Slump or Vebe time	Specified	Slump .... mm or Vebe time .... s
	2.2	Maximum aggregate size	Specified	.... mm
	2.3	Free-water content	Table 3	.... [ ] kg/m^3
3	3.1	Cement content	C3	.... ÷ .... = ... kg/m^3
	3.2	*Maximum cement content*	*Specified*	.... kg/m^3
	3.3	*Minimum cement content*	*Specified*	.... kg/m^3
				use 3.1 if ≤ 3.2 use 3.3 if > 3.1 [ ] kg/m^3
	3.4	Modified free-water/cement ratio		.... [ ]
4	4.1	Relative density of aggregate (SSD)		.... known/assumed
	4.2	Concrete density	Fig 5	.... kg/m^3
	4.3	Total aggregate content	C4	.... − .... − .... = ... kg/m^3
5	5.1	Grading of fine aggregate	Percentage passing 600 μm sieve	.... %
	5.2	Proportion of fine aggregate	Fig 6	.... %
	5.3	Fine aggregate content }	C5	{ .... × .... = [ ] kg/m^3
	5.4	Coarse aggregate content }		{ .... − .... = [ ] kg/m^3

Quantities	Cement (kg)	Water (kg or litres)	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm	20 mm	40 mm
per m^3 (to nearest 5 kg)	....	....	....	....	....	....
per trial mix of .... m^3	....	....	....	....	....	....

Items in italics are optional limiting values that may be specified (see Section 7).
Concrete strength is expressed in the units N/mm^2. 1 N/mm^2 = 1 MN/m^2 = 1 MPa. (N = newton; Pa = pascal.)
The internationally known term 'relative density' used here is synonymous with 'specific gravity' and is the ratio of the mass of a given volume of substance to the mass of an equal volume of water.
SSD = based on the saturated surface-dry condition.

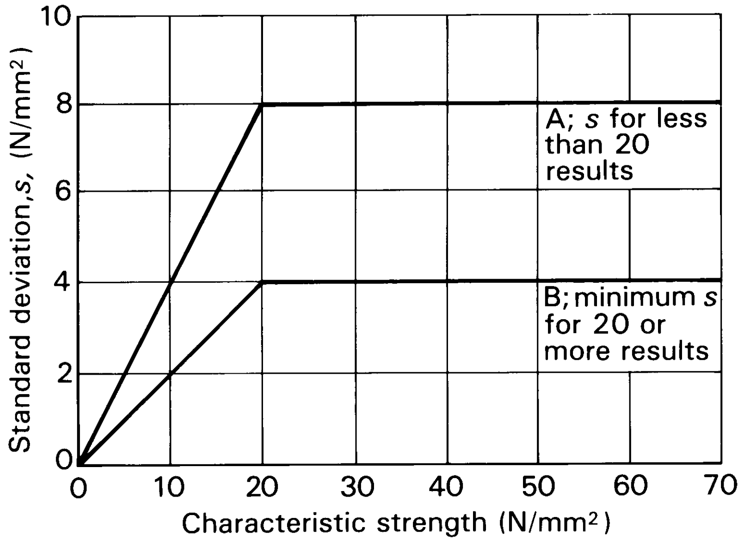

Figure 3
Relationship between standard deviation and characteristic strength

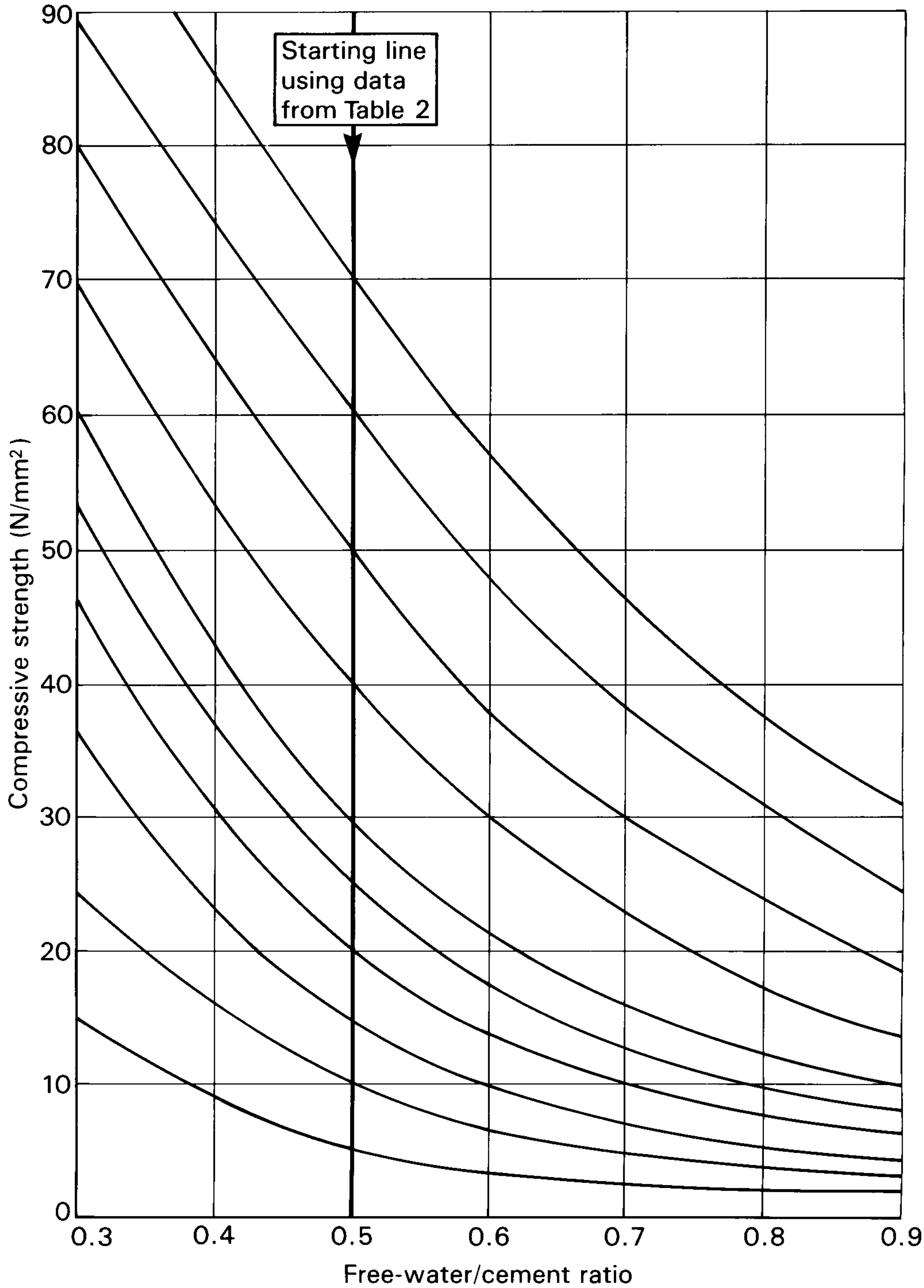

Figure 4
Relationship between compressive strength and free-water/cement ratio

Table 2 Approximate compressive strengths (N/mm²) of concrete mixes made with a free-water/cement ratio of 0.5

Cement strength class	Type of coarse aggregate	Compressive strengths (N/mm²) Age (days) 3	7	28	91
42.5	Uncrushed	22	30	42	49
	Crushed	27	36	49	56
52.5	Uncrushed	29	37	48	54
	Crushed	34	43	55	61

Throughout this publication concrete strength is expressed in the units N/mm².
1 N/mm² = 1 MN/m² = 1 MPa. (N = newton; Pa = pascal.)

corresponding value for the free-water/cement ratio can then be read from the abscissa. This should be compared with any maximum free-water/cement ratio that may be specified and the lower of these two values used.

5.2 Selection of free-water content (Stage 2)

Stage 2 consists simply of determining the free-water content from Table 3 depending upon the type and maximum size of the aggregate to give a concrete of the specified slump or Vebe time.

5.3 Determination of cement content (Stage 3)

The cement content is determined from calculation C3:

$$\text{Cement content} = \frac{\text{free-water content}}{\text{free-water/cement ratio}} \quad \ldots\text{C3}$$

The resulting value should be checked against any maximum or minimum value that may be specified. If the calculated cement content from C3 is below a specified minimum, this minimum value must be adopted and a modified free-water/cement ratio calculated which will be less than that determined in Stage 1. This will result in a concrete that has a mean strength somewhat higher than the target mean strength. Alternatively, the free-water/cement ratio from Stage 1 is used resulting in a higher free-water content and increased workability.

On the other hand, if the design method indicates a cement content that is higher than a specified maximum then it is probable that the specification cannot be met simultaneously on strength and workability requirements with the selected materials. Consideration should then be given to changing the type or strength class, or both, of cement, the type and maximum size of aggregate or the level of workability of the concrete, or to the use of a water-reducing admixture.

Table 3 Approximate free-water contents (kg/m³) required to give various levels of workability

Slump (mm)		0–10	10–30	30–60	60–180
Vebe time (s)		>12	6–12	3–6	0–3
Maximum size of aggregate (mm)	Type of aggregate				
10	Uncrushed	150	180	205	225
	Crushed	180	205	230	250
20	Uncrushed	135	160	180	195
	Crushed	170	190	210	225
40	Uncrushed	115	140	160	175
	Crushed	155	175	190	205

Note: When coarse and fine aggregates of different types are used, the free-water content is estimated by the expression:

$$\tfrac{2}{3} W_f + \tfrac{1}{3} W_c$$

where W_f = free-water content appropriate to type of fine aggregate
and W_c = free-water content approporiate to type of coarse aggregate.

5.4 Determination of total aggregate content (Stage 4)

Stage 4 requires an estimate of the density of the fully compacted concrete which is obtained from Figure 5 depending upon the free-water content and the relative density* of the combined aggregate in the saturated surface-dry condition (SSD). If no information is available regarding the relative density of the aggregate, an approximation can be made by assuming a value of 2.6 for uncrushed aggregate and 2.7 for crushed aggregate. From this estimated density of the concrete the total aggregate content is determined from calculation C4:

$$\text{Total aggregate content (saturated and surface-dry)} = D - C - W \quad \ldots\text{C4}$$

where D = the wet density of concrete (kg/m³)
C = the cement content (kg/m³)
W = the free-water content (kg/m³)

5.5 Selection of fine and coarse aggregate contents (Stage 5)

Stage 5 involves deciding how much of the total aggregate should consist of materials smaller than 5 mm, ie the sand or fine aggregate content. Figure 6 shows recommended values for the proportion of fine aggregate depending on the maximum size of aggregate, the workability level, the grading of the fine aggregate (defined by its percentage passing a 600 µm sieve) and the free-water/cement ratio. The best proportion of fines to use in a given mix will depend on the shape of the particular aggregate, the actual grading of shape of the particular aggregate, the actual grading of the fine aggregate and the use to which the concrete is to be put. However, adoption of a proportion obtained from Figure 6 will generally give a satisfactory concrete in the first trial mix which can then be adjusted as required for the exact conditions prevailing.

The final calculation, C5, to determine the fine and coarse aggregate contents, is made using the proportion of fine aggregate obtained from Figure 6 and the total aggregate content derived in Stage 4:

*The internationally known term 'relative density' used in this publication is synonymous with 'specific gravity' and is the ratio of the mass of a given volume of substance to the mass of an equal volume of water.

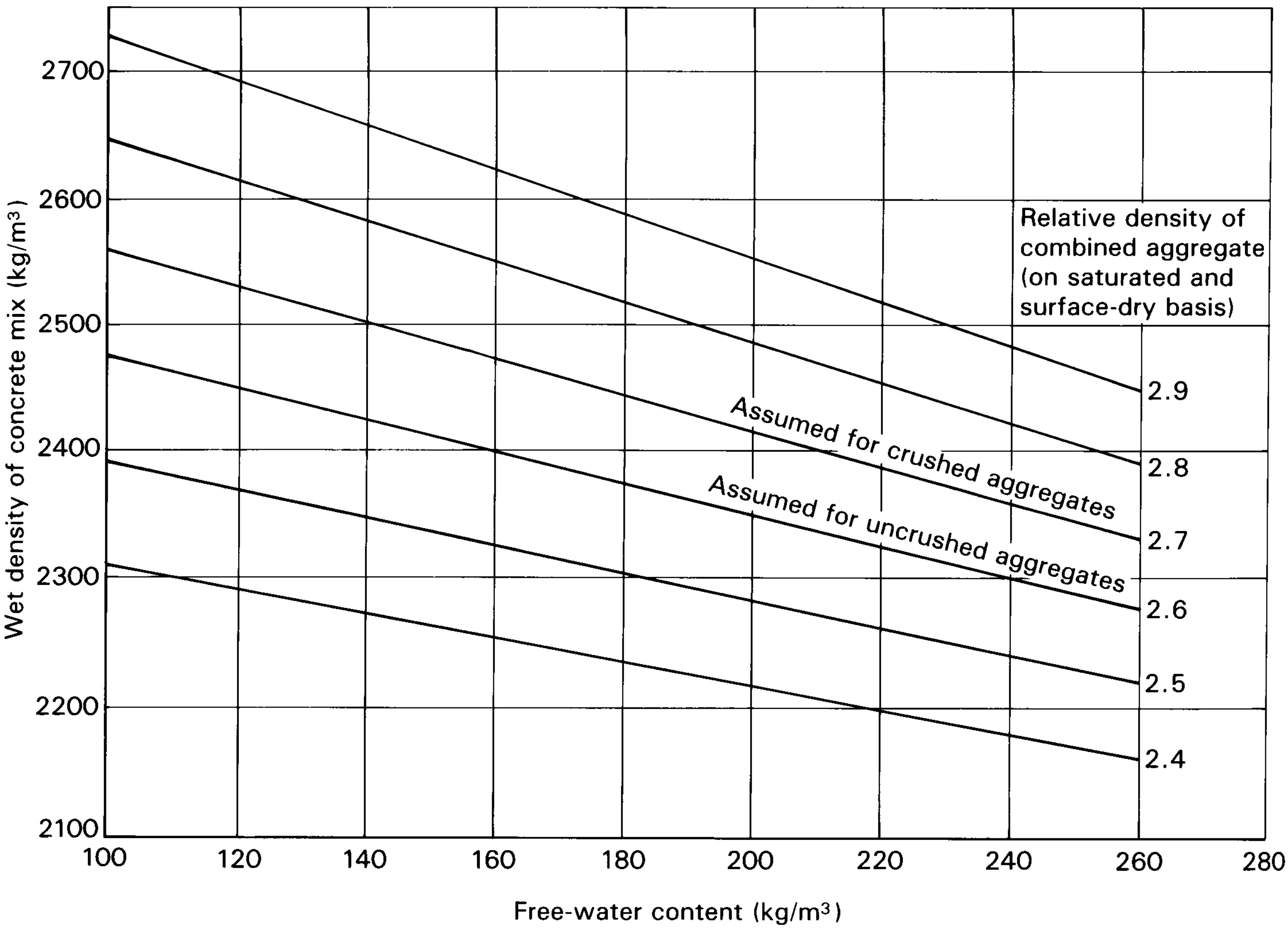

Figure 5 Estimated wet density of fully compacted concrete

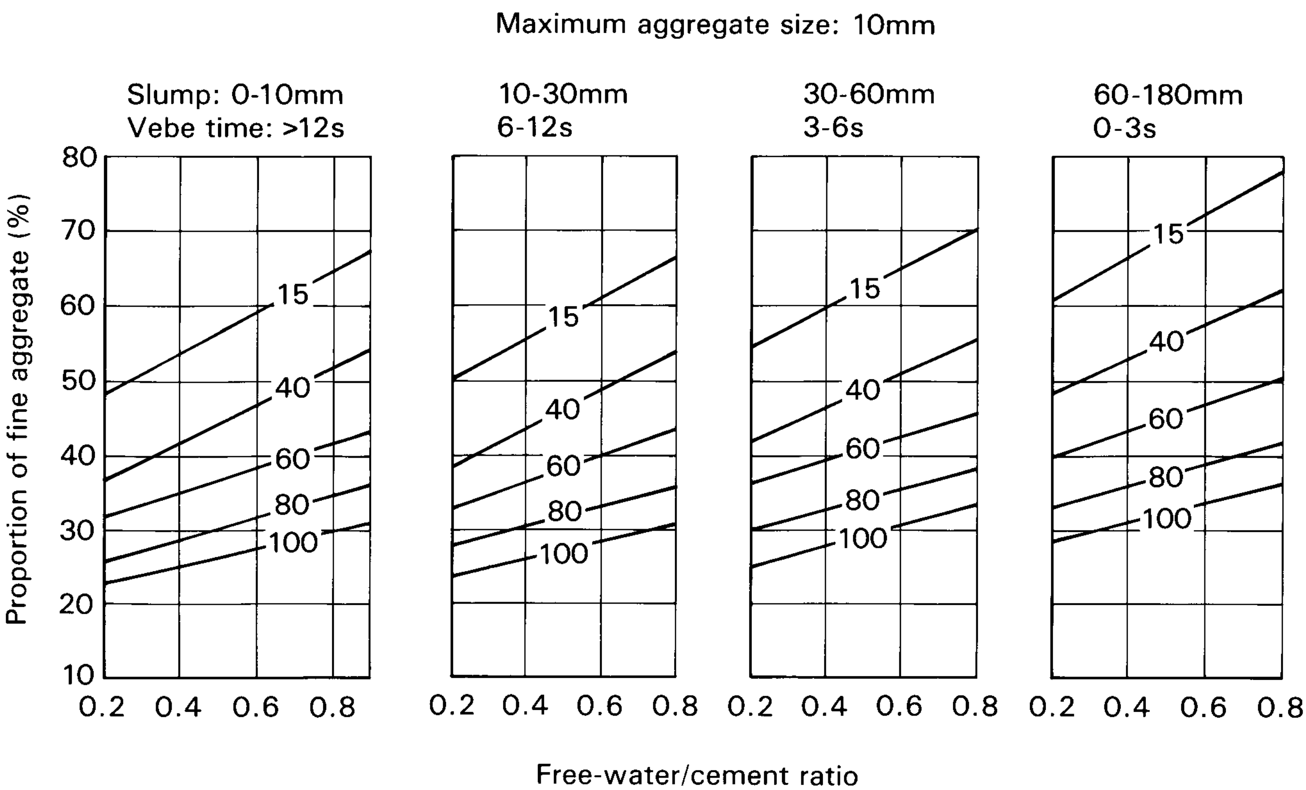

Figure 6 Recommended proportions of fine aggregate according to percentage passing a 600 µm sieve

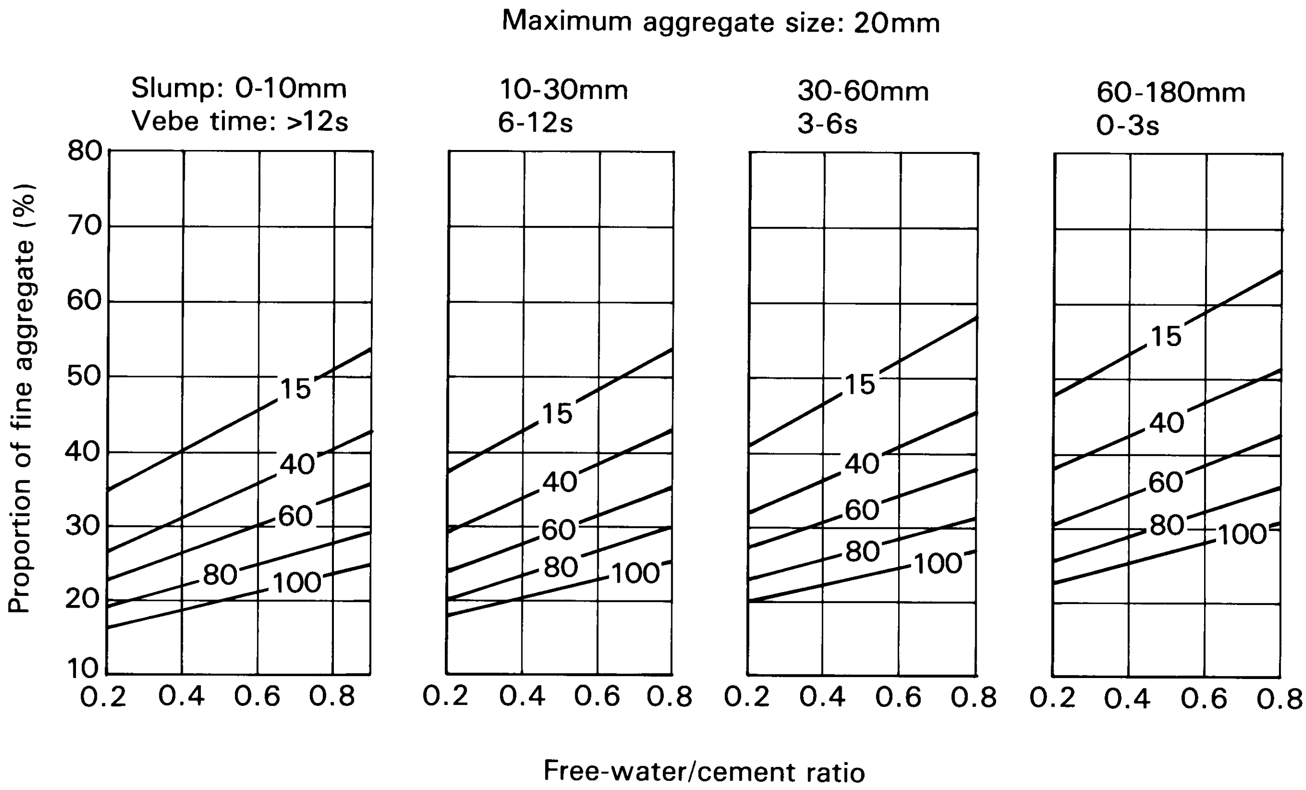

Figure 6 (continued)

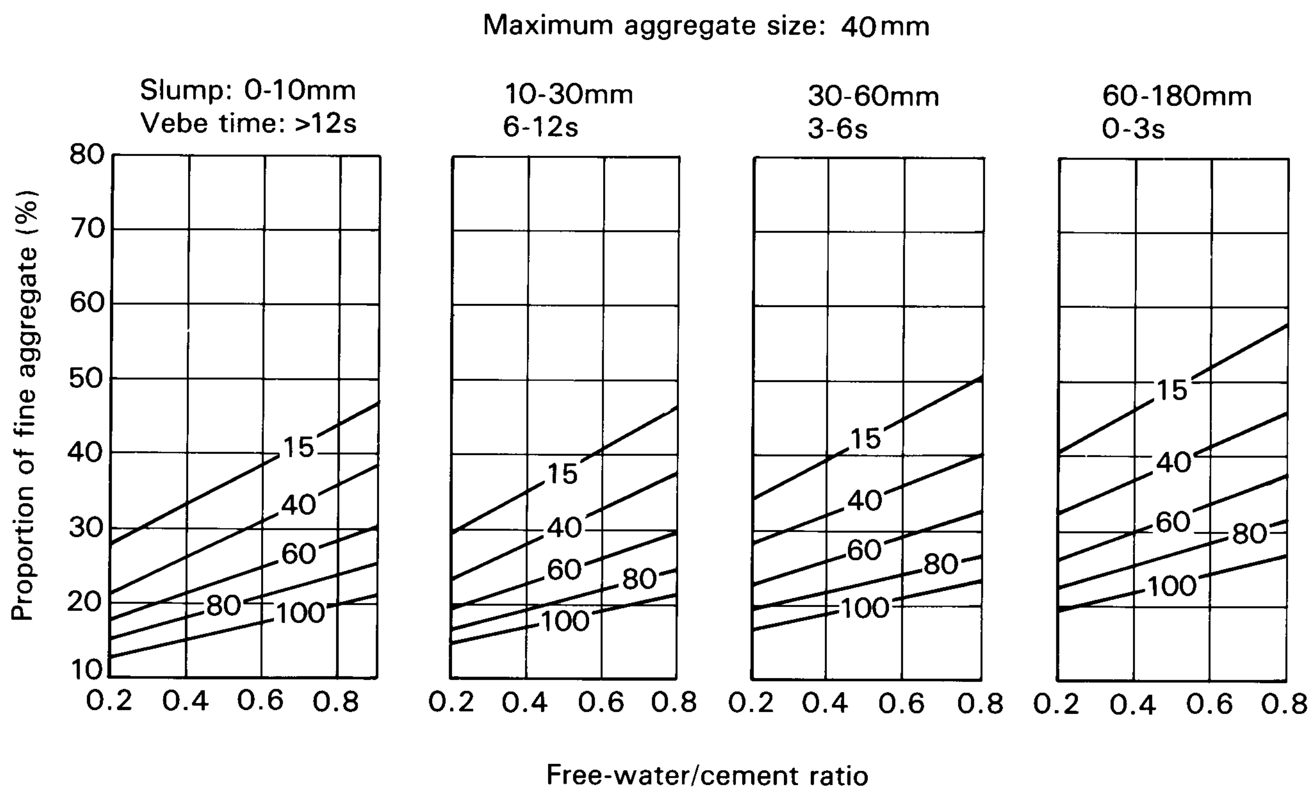

Figure 6 (continued)

$$\left.\begin{aligned}&\text{Fine aggregate content} = \\ &\quad \text{total aggregate content} \times \text{proportion of fines} \\ \\ &\text{Coarse aggregate content} = \\ &\quad \text{total aggregate content} - \text{fine aggregate content}\end{aligned}\right\} \ldots \text{C5}$$

The coarse aggregate content itself can be subdivided if single sized 10, 20 and 40 mm materials are to be combined. Again, the best proportions will depend on aggregate shape and concrete usage but the following ratios are suggested as a general guide:

1:2 for combination of 10 and 20 mm material
1:1.5:3 for combination of 10, 20 and 40 mm material.

6 Trial mixes

The preceding design method determines a set of mix proportions for producing a concrete that has approximately the required properties of strength and workability. The method, however, is based on simplified classifications for type and quality of the materials and it still remains to check whether or not the particular aggregates and cement selected for use in a given case will behave as anticipated. This is the object of making the trial mix, and the subsequent feedback of information from the trial mix is an essential part of the mix design process.

In order to avoid the possible delay caused by a need to prepare a second trial mix as a result of strength tests, it may be expedient to prepare two or more initial trial mixes with the same water content but with different water/cement ratios.

Normally, when typical materials are to be used, a single trial mix would be sufficient although some Codes of Practice may stipulate not only the number of trial mixes to be made but also requirements for accepting them as suitable. Adjustments to be made to the original mix proportions, if necessary, will differ according to how much the results of the trial mixes differ from the designed values which will depend partly upon how typical the materials are of their classifications. Depending on these, there are three courses of action open:

- To use the trial mix proportions in the production mixes
- To modify the trial mix proportions slightly in the production mixes
- To prepare further trial mixes incorporating major changes to the mix proportions

6.1 Production of trial mixes

The design method gives the mass in kilograms of the different materials required to produce one cubic metre of compacted concrete. The batch quantities for the trial mix can be obtained directly, therefore, by multiplying each of the constituent contents by the volume of the mix required. Typically, a 50 litre (0.05 m^3) mix is sufficient to make six cubes of 150 mm side and to carry out, separately, measurements of slump, Vebe time and density. The individual batch quantities (in kg) would then be equal to the appropriate contents, obtained in 5.2, 5.3 and 5.5, multiplied by 0.05.

Trial mixes should be prepared in accordance with the requirements of BS 1881:Part 125[29]. This British Standard allows the use of aggregates in any one of four moisture conditions, ie

(a) oven-dry,
(b) air-dried,
(c) saturated surface-dry, or
(d) saturated by soaking in water for at least 24 hours.

The batch quantities determined in the mix design process are based on saturated surface-dry aggregates as in (c) above. If the aggregates are surface-wet or saturated as in (d) above, the amount of free-water that is present should be determined so that adjustments can be made to the mass of aggregate and water added at the mixer.

When aggregates are to be batched in a dry condition as in (a) or (b) above, the batch quantities of the aggregate should be reduced and the mass of mixing water increased to allow for the absorption of some of the mixing water by the dry aggregate. The mass of the fine and coarse aggregate required for the trial mix should be calculated by multiplying the batch quantities derived from calculation C5 by $100/(100 + A)$ where A is the percentage by mass of water needed to bring the dry aggregate to the saturated surface-dry condition. The mass of the mixing water should be increased by the amount required for absorption by the aggregates.

When dry aggregates are used they should be allowed to soak with some of the mixing water before other materials are added, to avoid obtaining false values for the workability and possibly for the strength of the concrete. This is achieved, in accordance with BS 1881:Part 125, by mixing the aggregate with about half of the total water and allowing it to stand for a period so that the aggregate takes up most of the water it will ultimately absorb, before adding the cement, the rest of the water and continuing to mix for the periods specified.

6.2 Tests on trial mixes

Tests on the fresh concrete, the making of test specimens, the curing of the specimens and their method of test should be in accordance with the relevant part of BS 1881 as follows:

Slump test	BS 1881:Part 102[15]
Vebe time test	BS 1881:Part 104[16]
Density test	BS 1881:Part 107[30]
Making test cubes	BS 1881:Part 108[31]
Normal curing	BS 1881:Part 111[26]
Compression testing of cubes	BS 1881:Part 116[32]

6.3 Adjustments to mix proportions

6.3.1 Workability

During the mixing of the trial mix an experienced technician is able to adjust the water content by inspection if the workability of the mix is much outside the specified range. It is thus useful, initially, to withhold a small proportion, say 10%, of the mix water until the technician has assessed visually that its addition is needed to achieve the required workability. Furthermore, if at the designed water content the workability of the trial mix appears below that required, additional water should be added to obtain the required workability.

After completion of the mixing cycle and workability measurements a change of water content may still be needed, either for use in the production mix or for a further trial mix, and this can be estimated by reference to Table 3.

During the measurement of workability the concrete should also be assessed subjectively for its other rheological properties; this may indicate a need to change the relative aggregate proportions.

6.3.2 Density

After the density of the fresh concrete is measured, the resultant value is compared with the density value used during the design (Item 4.2). If there is an appreciable difference, the constituent contents per cubic metre, referred to as the unit proportions of the trial mix, will differ from those intended in the initial design. In this case, the initial design values should be corrected by the ratio of measured density to assumed density in order to determine the actual masses per cubic metre in the trial mix.

6.3.3 Strength

When results of the strength tests become available they are compared with the target mean strength (and any other existing requirements or guides in other Specifications or Codes). If necessary an adjustment is made to the water/cement ratio by using the curves of Figure 4. Two examples of this adjustment are shown in Figure 7, where:

A represents the reference data given in Table 2 for the particular types of aggregate and cement to be used and the appropriate age of test

B represents the free-water/cement ratio estimated for the trial mix

B' represents the actual free-water/cement ratio used in the trial mix when different from B. (This situation arises if the water content of the concrete is adjusted during the manufacture of the trial mix as in example 2)

C represents the strength result of the test specimens made from the trial mix

D represents the new estimate of the free-water/cement ratio required to give the target mean strength

Minor adjustments may be made to the mix proportions for use in production mixes without the need to carry out further trials. Exceptionally, when large adjustments seem to be necessary to the water/cement ratio it is advisable to make a second trial mix using the revised proportions and recalculated batch quantities based on the updated value for density of the mix.

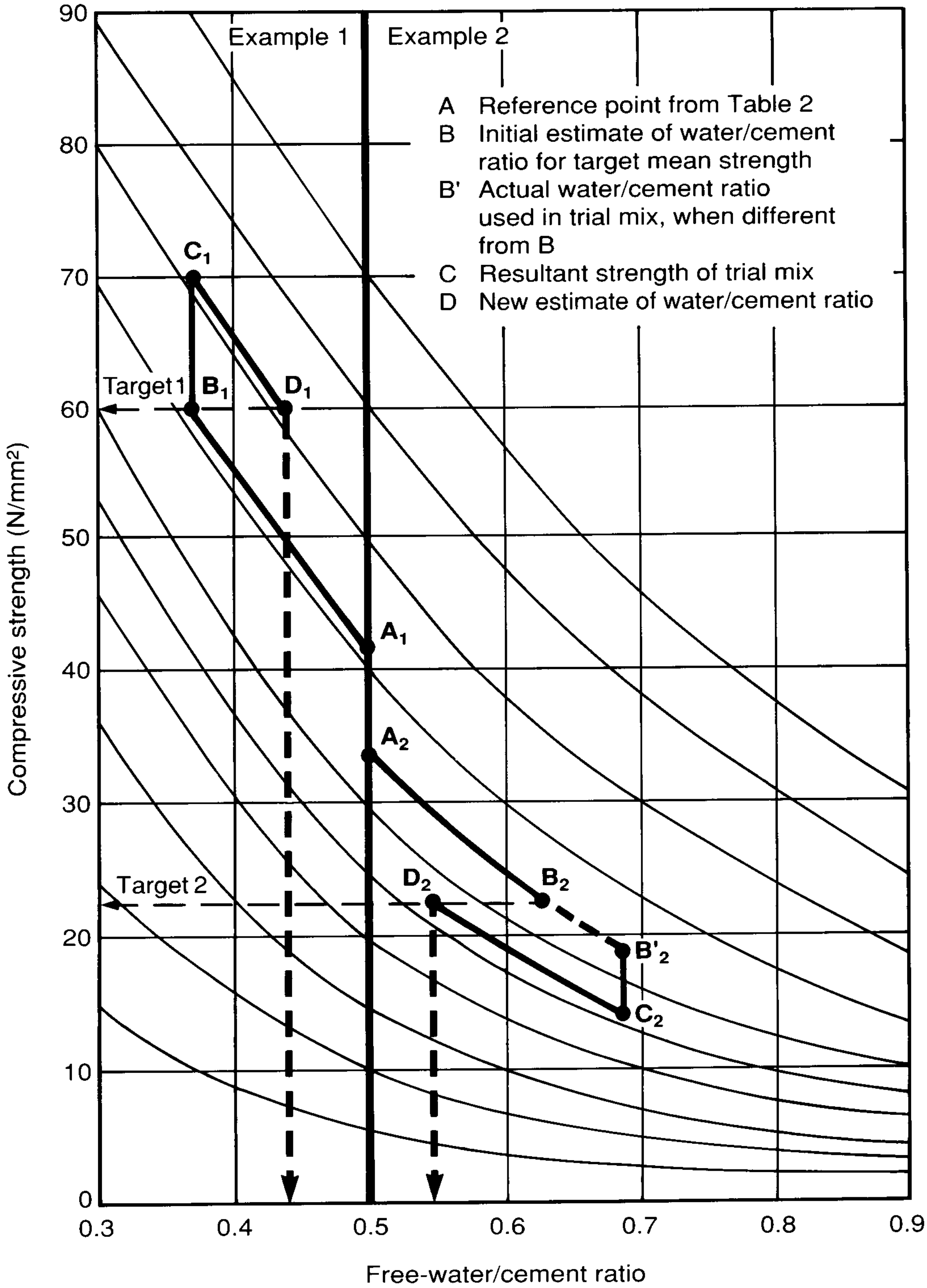

Figure 7 Two examples of the process for adjusting a water/cement ratio using the results of a trial mix

7 Examples of mix design

The following examples are given to illustrate the use of this mix design procedure. The relevant details and calculations are entered on the standard mix design form (shown in Table 1) and the examples are chosen to illustrate the various options that may arise. Although there are eight items listed in the specified variables (see Figure 2), ie 1.1, 1.3, 1.5, 1.8, 2.1, 2.2, 3.2 and 3.3, only four of them are essential for the process. Three are optional limiting values that may be specified: Item 1.8 maximum free-water/cement ratio; Item 3.2 maximum cement content; Item 3.3 minimum cement content. These are therefore shown in italics on the standard mix design form (Table 1) and by two-way arrows in Figure 2.

The final specified variable is Item 1.3 specified margin. This is an alternative method for dealing with the margin required to determine the target mean strength. The other method is to use the permitted percentage of defectives in Item 1.1 so that the appropriate constant k can be used in Item 1.3 (mix parameter) to calculate the margin using Item 1.2, standard deviation, as described in 4.4.

7.1 Example 1: unrestricted design

The following requirements are specified and thus entered under the relevant item on the mix design form, as shown in Table 4.

1	Characteristic compressive strength, 30 N/mm^2 at 28 days, with a 2.5% defective rate (k = 1.96)	Item 1.1
2	Portland cement class 42.5	Item 1.5
3	Slump required, 10–30 mm	Item 2.1
4	Maximum aggregate size, 20 mm	Item 2.2
5	Maximum free-water/cement ratio, 0.55	Item 1.8
6	Minimum cement content, 290 kg/m^3	Item 3.3

A maximum cement content is not specified and thus there is no entry under Item 3.2. There are no previous control data and thus a standard deviation of 8 N/mm^2 obtained from Figure 3 is used in Item 1.2. The fine and coarse aggregates to be used are uncrushed, the relative density is unknown and is assumed to be 2.6 as stated in 5.4, and the fine aggregate has 70% passing a 600 μm sieve. These details are entered in Table 4 under Items 1.6, 4.1 and 5.1 respectively.

The target mean strength is obtained by performing calculations C1 and C2 and found to be 46 N/mm^2. Table 2 shows that for the materials being used, the estimated 28-day strength at a free-water/cement ratio of 0.5 is 42 N/mm^2. This value is then applied to Figure 4, and for the target mean strength of 46 N/mm^2 it is found that a free-water/cement ratio of 0.47 (Item 1.7) is required. This is less than the specified maximum value of 0.55 and is thus suitable for the design. This completes Stage 1.

Stage 2 is completed by obtaining the required free-water content of 160 kg/m^3 (Item 2.3) from Table 3 appropriate to the specified requirements.

The cement content of 340 kg/m^3 (Item 3.1) is obtained from calculation of C3 and, since this is greater than the specified minimum of 290 kg/m^3, it is suitable for the design. This completes Stage 3.

Using the assumed relative density of 2.6 and the free-water content of 160 kg/m^3, a wet density of concrete of 2400 kg/m^3 (Item 4.2) is obtained from Figure 5, and calculation C4 gives a total aggregate content of 1900 kg/m^3 (Item 4.3) completing Stage 4.

Finally the fine and coarse aggregate contents are obtained in Stage 5 by selecting the proportion of fine aggregate of 27% (Item 5.2) from Figure 6 for the given maximum aggregate size, required slump and derived free-water/cement ratio. The fine and coarse aggregate contents (Items 5.3 and 5.4) are obtained through calculations C5.

If single-sized 10 mm and 20 mm coarse aggregates are used the coarse aggregate content is proportioned 1:2 as described in 5.5.

Thus the quantities of the constituent materials per m^3 are:

Cement	340 kg
Water	160 kg
Fine aggregate	515 kg (saturated surface-dry)
Coarse aggregate	1385 kg (saturated surface-dry)
consisting of	460 kg 10 mm single-size and
	925 kg 20 mm single-size

Assuming that the aggregates are used in a saturated surface-dry condition, the quantities for a 50 litre (0.05 m^3) trial mix are therefore:

Cement	17.0 kg
Water	8.0 kg
Fine aggregate	25.7 kg (satuated surface-dry)
Coarse aggregate	69.2 kg (satuated surface-dry)
consisting of	23.0 kg 10 mm single-size and
	46.2 kg 20 mm single-size

To obtain the mass of the oven-dry aggregates when aggregates are to be batched in an oven-dry condition, the masses of the saturated surface-dry aggregates derived from calculations C5 are multiplied by 100/(100 + A) where A is the percentage by mass of water needed to bring the dry aggregates to a saturated surface-dry condition. The amount of the mixing water should be increased by the mass of water absorbed by the aggregates to reach the saturated surface-dry condition.

Thus if the absorption of the fine aggregate is 2% and of the coarse aggregate is 1%, then in the above trial mix:

Mass of oven-dry fine aggregate =

$$25.7 \times 100/102 = 25.2 \text{ kg}$$

Mass of oven-dry coarse aggregate =

$$69.2 \times 100/101 = 68.5 \text{ kg}$$

Water required for absorption =

$$(25.7 - 25.2) + (69.2 - 68.5) = 0.5 + 0.7 = 1.2 \text{ kg}$$

Table 4 Completed concrete mix design form for unrestricted design

Stage	Item		Reference or calculation	Values
1	1.1	Characteristic strength	Specified	30 N/mm² at 28 days; Proportion defective 2·5 %
	1.2	Standard deviation	Fig 3	……… N/mm² or no data 8 N/mm²
	1.3	Margin	C1 or Specified	(k = 1·96) 1·96 × 8 = 16 N/mm²; ~~……~~ N/mm²
	1.4	Target mean strength	C2	30 + 16 = 46 N/mm²
	1.5	Cement strength class	Specified	42.5/~~52.5~~
	1.6	Aggregate type: coarse Aggregate type: fine		~~Crushed~~/uncrushed ~~Crushed~~/uncrushed
	1.7	Free-water/cement ratio	Table 2, Fig 4	0·47 } Use the lower value **0·47**
	1.8	*Maximum free-water/ cement ratio*	*Specified*	0·55 }
2	2.1	Slump or Vebe time	Specified	Slump 10 – 30 mm or Vebe time ~~……~~ s
	2.2	Maximum aggregate size	Specified	20 mm
	2.3	Free-water content	Table 3	**160** kg/m³
3	3.1	Cement content	C3	160 ÷ 0·47 = 340 kg/m³
	3.2	*Maximum cement content*	*Specified*	~~……~~ kg/m³
	3.3	*Minimum cement content*	*Specified*	290 kg/m³
				use 3.1 if ≤ 3.2 use 3.3 if > 3.1 — **340** kg/m³
	3.4	Modified free-water/cement ratio		~~……~~
4	4.1	Relative density of aggregate (SSD)		2·6 ~~known~~/assumed
	4.2	Concrete density	Fig 5	2400 kg/m³
	4.3	Total aggregate content	C4	2400 – 340 – 160 = 1900 kg/m³
5	5.1	Grading of fine aggregate	Percentage passing 600 µm sieve	70 %
	5.2	Proportion of fine aggregate	Fig 6	25 to 30, say 27 %
	5.3	Fine aggregate content	C5	1900 × 0·27 = **515** kg/m³
	5.4	Coarse aggregate content	C5	1900 – 515 = **1385** kg/m³

Quantities	Cement (kg)	Water (kg or litres)	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm	20 mm	40 mm
per m³ (to nearest 5 kg)	340	160	515	460	925	~~……~~
per trial mix of 0·05 m³	17·0	18·0	25·7	23	46·2	~~……~~

Items in italics are optional limiting values that may be specified (see Section 7).

Concrete strength is expressed in the units N/mm². 1 N/mm² = 1 MN/m² = 1 MPa. (N = newton; Pa = pascal.)

The internationally known term 'relative density' used here is synonymous with 'specific gravity' and is the ratio of the mass of a given volume of substance to the mass of an equal volume of water.

SSD = based on the saturated surface-dry condition.

The quantities for the trial mix are:

Cement	17.0 kg
Water	9.2 kg
Fine aggregate	25.2 kg (oven-dry)
Coarse aggregate	68.5 kg (oven-dry)
consisting of	22.8 kg 10 mm single-size and
	45.7 kg 20 mm single-size

7.2 Example 2: mix restricted by maximum water/cement ratio

The following requirements are specified and thus entered under the relevant item on the mix design form, as shown in Table 5:

1	Characteristic compressive strength, 25 N/mm^2 at 28 days	Item 1.1
2	Portland cement class 42.5	Item 1.5
3	Slump required, 30–60 mm	Item 2.1
4	Maximum aggregate size, 40 mm	Item 2.2
5	Maximum free-water/cement ratio, 0.50	Item 1.8
6	Minimum cement content, 290 kg/m^3	Item 3.3

There are no previous control data but a margin of 10 N/mm^2 is specified and is used in Item 1.3.

The following information is known concerning the aggregates to be used and the data are entered under the relevant items on the mix design form, as shown in Table 5:

Aggregate type, uncrushed	Item 1.6
Aggregate relative density, 2.5	Item 4.1
Fine aggregate, 90% passing a 600μm sieve	Item 5.1

The design process continues as in the previous example but under Item 1.7 it is found that the free-water/cement ratio for the required strength is 0.57; this is higher than the specified maximum value of 0.50, so this latter value is used in the rest of the mix design but Figure 4 indicates a mean strength of 42 N/mm^2 instead of 35 N/mm^2. The remaining stages of the mix design are completed as in the previous example.

7.3 Example 3: mix restricted by minimum cement content

In this example the same requirements and materials are specified as in Example 2 but the workability required is reduced to a slump of 0–10 mm.

The mix design proceeds as before and is shown on the mix design form in Table 6.

Owing to the lowered workability requirement, the free-water content is reduced to 115 kg/m^3 (Item 2.3) and this results in a reduced cement content of 230 kg/m^3 (Item 3.1) which is less than the specified minimum of 290 kg/m^3 (Item 3.3). This higher value must be used and Item 3.4 calculated to give a modified free-water/cement ratio of 0.40 which supersedes the value chosen in Stage 1 (Item 1.8). At this lower water/cement ratio Figure 4 indicates a strength of 55 N/mm^2.

This is an example of the required strength being very low in relation to the other specified parameters of low workability, maximum free-water/cement ratio and minimum cement content.

7.4 Example 4: mix restricted by maximum cement content

The following requirements are specified and thus entered under the relevant item in the mix design form, as shown in Table 7:

1	Characteristic compressive strength, 50 N/mm^2 at 7 days, defective rate 1% (k = 2.33)	Item 1.1
2	Portland cement class 52.5	Item 1.5
3	Slump required, 30–60 mm	Item 2.1
4	Maximum aggregate size, 10 mm	Item 2.2
5	Maximum cement content, 550 kg/m^3	Item 3.2

Previous control data indicated an expected standard deviation of 5 N/mm^2 and this is used in Item 1.2.

The following information is known concerning the aggregates to be used and the data are entered under the relevant item on the mix design form (Table 7):

Aggregate type: coarse, crushed	
fine, uncrushed	Item 1.6
Aggregate relative density, unknown, assume 2.7	Item 4.1
Fine aggregate, 45% passing a 600 μm sieve	Item 5.1

The mix design continues as in the previous examples giving a free-water/cement ratio of 0.37 (Item 1.7) at the end of Stage 1 and a free-water content of 215 kg/m^3 (Item 2.3) at the end of Stage 2. The free-water content is calculated as described in the Note to Table 3.

In Stage 3 the cement content required is found to be 580 kg/m^3 (Item 3.1) compared with the specified maximum of 550 kg/m^3. It is thus not possible to proceed further with the mix design for the original specified requirements and changes should be considered as described in 5.3.

Table 5 Completed concrete mix design form for a mix restricted by maximum water/cement ratio

Stage	Item		Reference or calculation	Values
1	1.1	Characteristic strength	Specified	25 N/mm^2 at 28 days; Proportion defective / %
	1.2	Standard deviation	Fig 3	/ N/mm^2 or no data / N/mm^2
	1.3	Margin	C1 or Specified	(*k* = /) / × / = / N/mm^2; 10 N/mm^2
	1.4	Target mean strength	C2	25 + 10 = 35 N/mm^2
	1.5	Cement strength class	Specified	42.5/~~52.5~~
	1.6	Aggregate type: coarse Aggregate type: fine		~~Crushed~~/uncrushed ~~Crushed~~/uncrushed
	1.7	Free-water/cement ratio	Table 2, Fig 4	0·57 } Use the lower value: **0·50**
	1.8	*Maximum free-water/cement ratio*	*Specified*	0·50 }
2	2.1	Slump or Vebe time	Specified	Slump 30 – 60 mm or Vebe time / s
	2.2	Maximum aggregate size	Specified	40 mm
	2.3	Free-water content	Table 3	**160** kg/m^3
3	3.1	Cement content	C3	160 ÷ 0·50 = 320 kg/m^3
	3.2	*Maximum cement content*	*Specified*	/ kg/m^3
	3.3	*Minimum cement content*	*Specified*	290 kg/m^3
				use 3.1 if ≤ 3.2 use 3.3 if > 3.1: **320** kg/m^3
	3.4	Modified free-water/cement ratio		/
4	4.1	Relative density of aggregate (SSD)		2·5 known/~~assumed~~
	4.2	Concrete density	Fig 5	2325 kg/m^3
	4.3	Total aggregate content	C4	2325 − 320 − 160 = 1845 kg/m^3
5	5.1	Grading of fine aggregate	Percentage passing 600 μm sieve	90 %
	5.2	Proportion of fine aggregate	Fig 6	20 to 23, say 22 %
	5.3	Fine aggregate content	C5	1845 × 0·22 = **405** kg/m^3
	5.4	Coarse aggregate content	C5	1845 − 405 = **1440** kg/m^3

Quantities	Cement (kg)	Water (kg or litres)	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm	20 mm	40 mm
per m^3 (to nearest 5 kg)	320	160	405	260	395	785
per trial mix of 0·08 m^3	25·6	12·8	32·4	20·8	31·6	62·8

Items in italics are optional limiting values that may be specified (see Section 7).

Concrete strength is expressed in the units N/mm^2. 1 N/mm^2 = 1 MN/m^2 = 1 MPa. (N = newton; Pa = pascal.)

The internationally known term 'relative density' used here is synonymous with 'specific gravity' and is the ratio of the mass of a given volume of substance to the mass of an equal volume of water.

SSD = based on the saturated surface-dry condition.

Table 6 Completed concrete mix design form for a mix restricted by minimum cement content

Stage	Item		Reference or calculation	Values
1	1.1	Characteristic strength	Specified	25 N/mm² at 28 days Proportion defective .... %
	1.2	Standard deviation	Fig 3	.... N/mm² or no data .... N/mm²
	1.3	Margin	C1 or Specified	(k = ...) .... × .... = ... N/mm² 10 N/mm²
	1.4	Target mean strength	C2	25 + 10 = 35 N/mm²
	1.5	Cement strength class	Specified	42.5/52.5
	1.6	Aggregate type: coarse Aggregate type: fine		Crushed/uncrushed Crushed/uncrushed
	1.7	Free-water/cement ratio	Table 2, Fig 4	0·57 } Use the lower value **0·50**
	1.8	*Maximum free-water/cement ratio*	*Specified*	0·50 }
2	2.1	Slump or Vebe time	Specified	Slump 0 – 10 mm or Vebe time .... s
	2.2	Maximum aggregate size	Specified	40 mm
	2.3	Free-water content	Table 3	115 kg/m³
3	3.1	Cement content	C3	115 ÷ 0·50 = 230 kg/m³
	3.2	*Maximum cement content*	*Specified*	.... kg/m³
	3.3	*Minimum cement content*	*Specified*	290 kg/m³
				use 3.1 if ≤ 3.2 use 3.3 if > 3.1 — **290** kg/m³
	3.4	Modified free-water/cement ratio		115 ÷ 290 — **0·40**
4	4.1	Relative density of aggregate (SSD)		2·5 known/assumed
	4.2	Concrete density	Fig 5	2375 kg/m³
	4.3	Total aggregate content	C4	2375 – 290 – 115 = 1970 kg/m³
5	5.1	Grading of fine aggregate	Percentage passing 600 μm sieve	90 %
	5.2	Proportion of fine aggregate	Fig 6	15 to 18, say 17 %
	5.3	Fine aggregate content	C5	1970 × 0·17 = 335 kg/m³
	5.4	Coarse aggregate content	C5	1970 – 335 = 1635 kg/m³

Quantities	Cement (kg)	Water (kg or litres)	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm	20 mm	40 mm
per m³ (to nearest 5 kg)	290	115	335	300	445	890
per trial mix of 0·08 m³	23·2	9·2	26·8	24·0	35·6	71·2

Items in italics are optional limiting values that may be specified (see Section 7).
Concrete strength is expressed in the units N/mm². 1 N/mm² = 1 MN/m² = 1 MPa. (N = newton; Pa = pascal.)
The internationally known term 'relative density' used here is synonymous with 'specific gravity' and is the ratio of the mass of a given volume of substance to the mass of an equal volume of water.
SSD = based on the saturated surface-dry condition.

Table 7 Completed concrete mix design form for a mix restricted by maximum cement content

Stage	Item		Reference or calculation	Values
1	1.1	Characteristic strength	Specified	{ 50 N/mm² at 7 days; Proportion defective 1 %
	1.2	Standard deviation	Fig 3	.... N/mm² or no data ~~......~~ N/mm²
	1.3	Margin	C1 or Specified	(k = 2·33) 2·33 × 5 = 11·6 N/mm²; ~~......~~ N/mm²
	1.4	Target mean strength	C2	50 + 11·6 = 62 N/mm²
	1.5	Cement strength class	Specified	~~42.5~~/52.5
	1.6	Aggregate type: coarse Aggregate type: fine		Crushed/~~uncrushed~~ ~~Crushed~~/uncrushed
	1.7	Free-water/cement ratio	Table 2, Fig 4	0·37 } Use the lower value **0·37**
	1.8	*Maximum free-water/ cement ratio*	*Specified*	~~......~~
2	2.1	Slump or Vebe time	Specified	Slump 30 – 60 mm or Vebe time ~~......~~ s
	2.2	Maximum aggregate size	Specified	10 mm
	2.3	Free-water content	Table 3	$\frac{2}{3}(205) + \frac{1}{3}(230)$ **215** kg/m³
3	3.1	Cement content	C3	215 ÷ 0·37 = 580 kg/m³
	3.2	*Maximum cement content*	*Specified*	550 kg/m³
	3.3	*Minimum cement content*	*Specified*	~~......~~ kg/m³
				use 3.1 if ≤ 3.2 use 3.3 if > 3.1 ~~......~~ kg/m³
	3.4	Modified free-water/cement ratio		.... ~~......~~
4	4.1	Relative density of aggregate (SSD)		2·7 ~~known~~/assumed
	4.2	Concrete density	Fig 5	.... kg/m³
	4.3	Total aggregate content	C4	.... − .... − .... = ... kg/m³
5	5.1	Grading of fine aggregate	Percentage passing 600 µm sieve	45 %
	5.2	Proportion of fine aggregate	Fig 6	.... %
	5.3	Fine aggregate content	C5	.... × .... = kg/m³
	5.4	Coarse aggregate content	C5	.... − .... = kg/m³

Quantities	Cement (kg)	Water (kg or litres)	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm	20 mm	40 mm
per m³ (to nearest 5 kg)	....	....	....	....	....	....
per trial mix of .... m³	....	....	....	....	....	....

Items in italics are optional limiting values that may be specified (see Section 7).
Concrete strength is expressed in the units N/mm². 1 N/mm² = 1 MN/m² = 1 MPa. (N = newton; Pa = pascal.)
The internationally known term 'relative density' used here is synonymous with 'specific gravity' and is the ratio of the mass of a given volume of substance to the mass of an equal volume of water.
SSD = based on the saturated surface-dry condition.

Part three: Modifications to mix design method

8 Design of air-entrained mixes

Concrete that is exposed in service to temperatures below freezing point whilst in a saturated condition may be susceptible to surface spalling, cracking and general deterioration. The types and characteristics of damage are numerous and are collectively referred to as frost damage. The extent of this type of damage is markedly increased when de-icing salts are used.

The incorporation of entrained air into a mix enables the concrete better to withstand the action of frost and de-icing salts and is consequently specified where concrete is particularly subject to such damage, eg in airfield and road pavements.

Guidance is given in this part of the publication for making allowance for the effects of entrained air on the strength, the workability and the density of the concrete. The effects of entrained air vary according to the mix proportions, the type and grading of aggregate, the cement and the actual air-entraining agent[33]. The following allowances should therefore be considered only as an approximation over the range of air contents of 3 to 7% normally specified and consequently adjustments to the trial mix proportions are more likely to be necessary.

8.1 Effect of entrained air on strength

In general, the strength of concrete is reduced by the addition of entrained air. The amount of the reduction varies according to a number of factors as mentioned above. However, for the range of air contents that is likely to be required in the mixes covered by this publication, it may be assumed that a loss of 5.5% in compressive strength will result for each 1% by volume of air entrained in the mix.

In order to estimate the water/cement ratio required for an air-entrained concrete an allowance for strength reduction is incorporated by aiming for an appropriately higher target mean strength. The appropriate target mean strength for an air-entrained mix is therefore given by:

$$\frac{f_c + M}{1 - 0.055a}$$

where f_c = specified characteristic strength
M = the margin (see 4.4)
a = percentage by volume of air entrained

This modified target mean strength is then used in Figure 4.

8.2 Effect of entrained air on workability

Basically, the introduction of entrained air into a mix increases the workability of a concrete, although, as for strength, the size of the effect depends on a number of factors. In terms of the ranges of workability and air contents used in this publication, the effect in the majority of cases is to produce a mix with a workability in the next more-workable category to that shown in Table 3 for a particular water content.

This means that when designing an air-entrained mix, for example, which is required to have a slump in the range 30–60 mm, a water content should be chosen from Table 3 to give a slump of 10–30 mm.

In addition to affecting the workability of the concrete in terms of its slump or Vebe time, the entrainment of air modifies the character of the fresh concrete, making it more plastic and cohesive. It may sometimes be possible, therefore, to reduce the proportion of fine aggregate by up to 5% of the total aggregate, thereby permitting a further small reduction in the water content.

8.3 Density of air-entrained mixes

Estimation of the density of air-entrained mixes may be made by the use of Figure 5. The correct value of the wet density of air-entrained concrete is obtained by subtracting from the wet density shown in Figure 5, an amount:

$$10 \times a \times RD_A$$

where a = the required percentage by volume of entrained air
RD_A = the relative density of the aggregate calculated on a saturated surface-dry basis. (When unknown an approximation can be made by assuming a value of 2.6 or 2.7 as appropriate).

8.4 Modifications to the design process

The design process is basically unchanged from the normal method. However, it is necessary to allow for the factors discussed in 8.1 to 8.3 by making the following modifications and substitutions to the items enumerated in Table 1 and Figure 2.

- **Item 1.4 Target mean strength**
  The target mean strength derived from the specified characteristic strength and the appropriate margin from Item 1.3 is modified as shown in 8.1.
- **Item 2.3 Free-water content**
  To allow for the improved workability the free-water content is derived from Table 3 for one level of workability lower than that specified.
- **Item 4.2 Concrete density**
  To allow for the reduced density of air-entrainment concrete the wet-density for the non-air-entrained concrete derived from Figure 5 is reduced as described in 8.3.

8.5 Trial mixes of air-entrained concrete

In addition to the tests listed in 6.2 to be carried out on the trial mix, it is necessary to measure the air content of the fresh concrete; this should be carried out according to BS 1881:Part 106[34]. The result of this measurement takes precedence over the other test results because, as explained above, their values are in turn influenced by the level of air content. It is usually necessary, therefore, to produce a trial mix of the required air content before the appropriate values of workability and strength can be confidently established, although rough estimates can be made even if the air content is outside the required range.

8.6 Example of mix design

An example of the use of the mix design method is shown in Table 8* . This example deals with the case of designing an air-entrained concrete mix using a crushed coarse aggregate with an uncrushed fine aggregate.

The following requirements are specified and thus entered under the relevant item on the mix design form, as shown in Table 8:

1	Characteristic compressive strength, 30 N / mm^2 at 28 days, 1% defective rate (k = 2.33)	Item 1.1
2	Portland cement class 42.5	Item 1.5
3	Slump required, 25 mm	Item 2.1
4	Maximum aggregate size, 20 mm	Item 2.2
5	Maximum free-water / cement ratio, 0.55	Item 1.8
6	Minimum cement content, 285 kg / m^3	Item 3.3
7	Air content, 4.5%	Item 1.4.1

Previous control data gave a standard deviation of 5 N / mm^2 and this is used in Item 2.

The following information is known concerning the aggregates to be used and the data are entered under the relevant item on the mix design form (Table 8):

Aggregate type: coarse, crushed fine, uncrushed	Item 1.6
Aggregate relative density, 2.65	Item 4.1
Fine aggregate, 50% passing a 600 µm sieve	Item 5.1

The design process continues as in the examples given in Section 7 subject to the modifications described in this section.

In Stage 1, Item 1.4 is modified to allow for the air content as described in 8.1.

Further, the determination of the free-water content (Item 2.3) involves the calculation given in Table 3 to deal with the different types of fine and coarse aggregates used. In Stage 2 it should be noted that, although the specified slump is 25 mm, ie in the 10–30 mm category, the water content is taken from the lower workability category, ie a slump from 0 to 10 mm as described in 8.2.

The only other modification to the process occurs in Stage 4 where the wet density of the concrete (Item 4.2) is adjusted to allow for its air content as described in 8.3.

*The form is printed at the end of this publication for ease of removal and subsequent use.

Table 8 Completed concrete mix design form for air-entrained concrete

Stage	Item		Reference or calculation	Values
1	1.1	Characteristic strength	Specified	30 N/mm² at 28 days; Proportion defective 1 %
	1.2	Standard deviation	Fig 3	5 N/mm² or no data / N/mm²
	1.3	Margin	C1 or Specified	(k = 2·33) 5 × 2·33 = 11·7 N/mm²; / N/mm²
	1.4	Target mean strength	C2 & Para 8.1*	30 + 12 = 42 N/mm²
	*1.4.1	Air content		4·5 %
	*1.4.2	Modified target mean strength		42 ÷ (1 − 0.055 × 4·5) = 56 N/mm²
	1.5	Cement strength class	Specified	42.5/~~52.5~~
	1.6	Aggregate type: coarse Aggregate type: fine		Crushed/~~uncrushed~~ ~~Crushed~~/uncrushed
	1.7	Free-water/cement ratio	Table 2, Fig 4	0·45 — Use the lower value **0·45**
	1.8	*Maximum free-water/cement ratio*	*Specified*	0·55
2	2.1	Slump or Vebe time	Specified	Slump 25 mm or Vebe time / s
	2.2	Maximum aggregate size	Specified	20 mm
	2.3	Free-water content	Table 3 & Para 8.2*	²/₃ (135) + ¹/₃ (170) → **145** kg/m³
3	3.1	Cement content	C3	145 ÷ 0·45 = 320 kg/m³
	3.2	*Maximum cement content*	*Specified*	/ kg/m³
	3.3	*Minimum cement content*	*Specified*	285 kg/m³
				use 3.1 if ≤ 3.2 use 3.3 if > 3.1 → **320** kg/m³
	3.4	Modified free-water/cement ratio		
4	4.1	Relative density of aggregate (SSD)		2·65 known/~~assumed~~
	4.2	Concrete density	Fig 5 & Para 8.3*	2460 − (10 × 4·5 × 2·65) = 2340 kg/m³
	4.3	Total aggregate content	C4	2340 − 320 − 145 = 1875 kg/m³
5	5.1	Grading of fine aggregate	Percentage passing 600 µm sieve	50 %
	5.2	Proportion of fine aggregate	Fig 6	29 to 35, say 32 %
	5.3	Fine aggregate content	C5	1875 × 0·32 = **600** kg/m³
	5.4	Coarse aggregate content	C5	1875 − 600 = **1275** kg/m³

Quantities	Cement (kg)	Water (kg or litres)	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm	20 mm	40 mm
per m³ (to nearest 5 kg)	320	145	600	425	850	/
per trial mix of 0·04 m³	12·8	5·8	24·0	17·0	34·0	/

*Modifications for air entrainment.
Items in italics are optional limiting values that may be specified (see Section 7).
Concrete strength is expressed in the units N/mm². 1 N/mm² = 1 MN/m² = 1 MPa. (N = newton; Pa = pascal.)
The internationally known term 'relative density' used here is synonymous with 'specific gravity' and is the ratio of the mass of a given volume of substance to the mass of an equal volume of water.
SSD = based on the saturated surface-dry condition.

9 Design of Portland cement/pfa mixes

9.1 Introduction to pulverised-fuel ash (pfa)

There is a growing use of pfa in concrete, particularly where the concrete is required to have specific properties. Pulverised-fuel ash is used to replace some of the cement in the mix but in order to obtain concrete having the same strength at 28 days, the combined mass of the cement plus pfa needs to be greater than that of the cement in a cement-only mix. Pulverised-fuel ash which is suitable for concrete initially assists in reducing the water demand of the concrete, but later, acting as a pozzolana, it increases the strength of the concrete. Pozzolanas, including pfa, react in the presence of moisture with the calcium hydroxide released by the hydration of the Portland cement to form additional strength-producing compounds at later ages.

Pulverised-fuel ash is particularly beneficial in large concrete sections in reducing thermal cracking problems due to the heat evolution during hydration of the cement[35]. The use of pfa may also be beneficial when concrete is placed in sulfate-bearing soil conditions as described in BRE Digest 363[21] and when there is the possibility of disruption of the concrete due to the alkali–silica reaction (ASR) as described in BRE Digest 330[22] and the independent Working Party Report[23] published by the Concrete Society.

However, the use of pfa also has the effects of increasing the sensitivity of the concrete to poor curing, although with a greater potential for recovery, and increasing the setting times and formwork pressures.

As with cements and aggregates, the quality of pfa varies from source to source and it also varies with time from a given source. Not all pfa is suitable for concrete. Pulverised-fuel ash of suitable quality is covered by British Standard BS 3892:Parts 1[7] and 2[36]. Pulverised-fuel ash complying with the requirements of either part of this standard can be used for making concrete. However, the requirements of BS 3892:Part 1 are more stringent than those of Part 2 and this quality of pfa is required for structural use in BS 5328[13]. These more stringent requirements mean that the characteristics of the pfa will be less variable, for example the loss on ignition is restricted to 7.0% and the residue on the 45 μm sieve is restricted to 12.5%. For the purposes of this publication the pfa is assumed to comply with BS 3892:Part 1.

9.2 Changes to the background information

When pfa is used in concrete it is necessary to consider the following aspects of the background information given in Part one and the reference data given in Part two:

- Workability and water content
- Strength development and free-water/cement ratio
- Cement content
- Variability of concrete strength
- Density of concrete and aggregate content

9.2.1 Workability and water content

Pulverised-fuel ash acts as a water-reducing agent, the water reduction depending on the characteristics of the cement and pfa used and on the pfa and cement contents of the mix. For the purpose of mix design, Hobbs[37] has shown that the water content can normally be reduced by 3% for each 10% proportion of pfa in the combined cement plus pfa. Thus the values given in Table 3 are reduced according to the proportion of pfa and the level of workability required as shown in Part B of Table 9. Part A is the same as Table 3 but is repeated for convenience.

Table 9 Approximate free-water contents required to give various levels of workability

Part A: Portland cement concrete

Slump (mm)		0–10	10–30	30–60	60–180
Vebe time (s)		>12	6–12	3–6	0–3
Maximum size of aggregate (mm)	Type of aggregate	Water content (kg/m^3)			
10	Uncrushed	150	180	205	225
	Crushed	180	205	230	250
20	Uncrushed	135	160	180	195
	Crushed	170	190	210	225
40	Uncrushed	115	140	160	175
	Crushed	155	175	190	205

Part B: Portland cement/pfa concrete

Slump (mm)	0–10	10–30	30–60	60–180
Vebe time (s)	>12	6–12	3–6	0–3
Proportion, *p*, of pfa to cement plus pfa (%)	Reductions in water content (kg/m^3)			
10	5	5	5	10
20	10	10	10	15
30	15	15	20	20
40	20	20	25	25
50	25	25	30	30

9.2.2 Strength development and free-water/cement ratio

As a pozzolana, pfa contributes to the strength of the concrete, this contribution increasing with age. The mass of pfa in a mix can be regarded as providing strength equivalent to a smaller mass of cement. This led Smith[38] to propose the use of a 'cementing efficiency factor', k, where kF is the mass of Portland cement class 42.5 equivalent to a mass F of pfa. This k factor varies with the pfa and generally increases with age. The strength of Portland cement/pfa concrete depends upon the free-water/'equivalent cement' ratio in the same way as Portland cement class 42.5 concrete. A Portland cement/pfa concrete will have the same strength as a Portland cement concrete of similar workability if:

$$\frac{W}{C + kF} = \frac{W_1}{C_1}$$

where W, C and F are the free-water, cement and pfa contents respectively, and W_1 and C_1 the free-water and

Table 10 Approximate compressive strengths of Portland cement/pfa made with a $W/(C+0.30F)$ ratio of 0.5

Cement strength class	Type of coarse aggregate	Compressive strength at 28 days (N/mm^2)
42.5	Uncrushed	42
	Crushed	49
52.5	Uncrushed	48
	Crushed	55

cement contents of the Portland cement concrete.

Although the *k* factor may vary from 0.20 to 0.45 depending upon the particular pfa and Portland cement used, for the purpose of this mix design method based on 28-day strengths, it is taken as 0.30. The 28-day strengths given in Table 10 apply to Portland cement/pfa concrete made with a $W/(C+0.30F)$ ratio of 0.50 (these are the same 28-day strengths given in Table 2). Strengths at other ages could be used but these would require different values for the *k* factor. Provided that the Portland cement/pfa concrete has the same strength at 28 days as a Portland cement class 42.5 concrete, its strength at later ages will be greater than the equivalent Portland cement class 42.5 concrete cured under the same conditions. To design a Portland cement/pfa concrete mix to have a specified 28-day strength, the curves given in Figure 4 apply but the value of the $W/(C + 0.30F)$ ratio shall be used as the free-water/cement ratio.

9.2.3 Cement content

With Portland cement concrete, the cement content is determined from the free-water content and the free-water/cement ratio as shown in 5.3. With Portland cement/pfa concrete a similar calculation is made but knowledge of the proportion of pfa, *p*, is required. The proportion of pfa is specified as a percentage, by mass, of the combined mass of cement and pfa, ie

$$p = \frac{100F}{C + F}$$

where *C* and *F* are the cement and pfa contents respectively. Typical proportions for pfa lie in the range of from 15 to 40%. For use in sulfate-bearing soils BRE Digest 363 requires a proportion of pfa of between 25 and 40%. To minimise the risk of cracking due to ASR, BRE Digest 330 recommends a minimum proportion of pfa of 30%.

The total mass of cement plus pfa in a mix will be greater than the equivalent mix made with Portland cement alone and the free-water/(cement + pfa) ratio will be less. These total masses of cement plus pfa are used for comparison with specified limiting minimum or maximum 'cement contents' or 'water/cement ratios' as specified in documents such as BRE Digest 363 or BS 8110.

9.2.4 Variability of concrete strength

Although the use of pfa needs an extra weighing to be made for each concrete mix, there is no evidence of an increase in the variability of concrete strength when using pfa concrete. No changes need to be made when fixing the margin for Portland cement/pfa concrete mix design.

9.2.5 Density of concrete and aggregate content

No change is required in determining the wet density of Portland cement/pfa concrete. With this concrete, the cement which has the highest relative density is reduced and replaced with pfa which has a lower relative density. However, a greater mass of pfa is included, and the mass of water, the lightest component, is reduced. The changes result in a change to the wet density of fresh concrete of about 1%. This is not significant in this mix design process and Figure 5 can be used to determine the wet density of Portland cement/pfa concrete.

The total aggregate content is determined by subtracting the cement, pfa and water contents from the wet density of the concrete. The fine aggregate content is obtained by using the same diagrams given in Figure 6 except that the value of the $W/(C + F)$ ratio shall be used as the free-water/cement ratio.

9.3 Modifications to the mix design method

The design of a Portland cement/pfa concrete mix follows the same five stages as described in Section 5, but includes the restrictions and modifications as described in 9.2. The modified mix design process is given below in which the following symbols are used:

free-water content (kg/m^3)	W
Portland cement content (kg/m^3)	C
pfa content (of the mix) (kg/m^3)	F
proportion of pfa (%)	$p = \frac{100F}{C + F}$

The same mix design form shown as Table 1 can be used with Portland cement/pfa mix design but owing to the changes resulting from using an extra constituent a supplementary additional mix design form is required. A completed version of this is given as Table 12*.

9.3.1 Selection of target $W/(C + 0.30F)$ ratio (Stage 1)

The same standard deviations and associated *k* factors, or specified margins, appropriate for Portland cement concrete are used. The 28-day strength of a mix having a $W/(C + 0.30F)$ ratio of 0.5 is taken from Table 10 according to the type of cement and coarse aggregate to be used. This strength is then plotted on Figure 4 at the starting line shown and the value of the ratio $W/(C + 0.30F)$ required for the target mean strength is taken as the free-water/cement ratio appropriate for this strength. (This ratio is **not** compared with a specified maximum free-water/cement ratio which for Portland cement/pfa concrete is given as Item 3.8 in Table 12

*The form is printed at the end of this publication for ease of removal and subsequent use.

instead of the usual Item 1.8. The maximum value given in 3.8 is compared with the $W/(C+F)$ ratio determined in Stage 3 and given as Item 3.7 in Table 12).

9.3.2 Selection of free-water content (Stage 2)
The free-water content is obtained from Part A of Table 9 for the maximum size and type of coarse aggregate to be used, and the required level of workability for Portland cement concrete. This value is then modified by reducing the water content by the value given in Part B appropriate to the proportion of pfa specified.

9.3.3 Determination of cement content and pfa content (Stage 3)
The proportion of pfa, p, is specified as a percentage of the combined weight of cement and pfa. Modifications are made to calculation C3 given in 5.3 to reduce the Portland cement content and to establish the pfa content.

The Portland cement content is determined from calculation C6:

Portland cement content =

$$\frac{(100-p)\,W}{(100-0.7p)\,[W/(C+0.30F)]} \qquad \ldots C6$$

where:
the ratio $W/(C+0.30F)$ is derived from Stage 1, and
the free-water content W is obtained from Stage 2.

The pfa content of the mix is determined from calculation C7:

$$\text{pfa content} = \frac{pC}{100-p} \qquad \ldots C7$$

The comparison with specified limited cement contents in Items 3.2 and 3.3 is made on the basis of the combined weights of Portland cement and pfa, $(C+F)$, which is given as Item 3.1 in Table 12. Some specifications specify a minimum Portland cement limit for a Portland cement/pfa concrete mix; if so, this should be compared with the value obtained from calculation C6, given as Item 3.5 in Table 12.

Having determined both C and F the value of the ratio

$$\frac{W}{(C+F)} \qquad \ldots C8$$

can be determined and compared with the maximum free-water/cement ratio specified as Item 3.8.

9.3.4 Determination of the total aggregate content (Stage 4)
The density of the fresh concrete is estimated from Figure 5 as described in 5.4. The total aggregate content is obtained by subtracting the mass of cement, pfa and water from the wet density of the concrete obtained from Figure 5. This involves an additional subtraction for the mass of pfa compared with calculation of C4. This is modified to become calculation C9:

Total aggregate content (saturated and surface-dry) $= D-(C+F)-W$ ...C9

where D = wet density of concrete (kg/m^3) (from Figure 5).

9.3.5 Selection of fine aggregate content (Stage 5)
The same diagrams given in Figure 6 apply to Portland cement/pfa concrete except that the value of the $W/(C+F)$ ratio shall be used as the free-water/cement ratio. The proportion of fine aggregate is obtained from Figure 6 for the appropriate conditions of maximum aggregate size, the workability required, the grading of the fine aggregate and the $W/(C+F)$ ratio. The final calculation (C5) to determine the fine and coarse aggregate contents is made using the proportion of fine aggregate obtained from Figure 6 and the total aggregate content derived from calculation C9:

Fine aggregate content =
total aggregate content × proportion of fines

Coarse aggregate content =
total aggregate content – fine aggregate content
…C5

9.3.6 Trial mixes and adjustments
As with Portland cement concrete this mix design process determines a set of mix proportions that has approximately the required strength and workability. However, the method is based on assuming typical characteristics of all the mix constituents; the actual materials used may differ and it is therefore necessary to make trial mixes to establish the actual properties of the concrete as described in Section 6.

9.4 Example of mix design
The following requirements are specified and thus entered under the relevant item on the basic and additional mix design forms as shown in Tables 11 and 12.

1	Characteristic compressive strength, 35 N/mm^2 at 28 days	Item 1.1
2	Portland cement class 42.5	Item 1.5
3	pfa to BS 3892:Part 1	add '+pfa' to Item 1.5
4	Proportion of pfa, 30%	Table 12, Item 2.2a
5	Slump required, 10–30 mm	Item 2.1
6	Maximum aggregate size, 20 mm	Item 2.2
7	Maximum free-water/cement ratio, 0.6	Item 3.8
8	Minimum cement content, 300 kg/m^3	Item 3.3

From previous control data it is known that a margin of 12 N/mm^2 is required to produce concrete of a specified characteristic strength and this is used in Item 1.3. The following information is known concerning the aggregate to be used and the data are entered under the relevant items in Table 11.

Aggregate type, uncrushed	Item 1.6
Aggregate relative density, 2.60	Item 4.1
Fine aggregate, 70% passing a 600 µm sieve	Item 5.1

The design process continues as in the examples given in Section 7 subject to the modification described in 9.3. The target mean strength is determined using calculation C2 and is found to be 47 N/mm^2, which is entered under Item 1.4. From Table 10 and Figure 4 this gives a value of 0.46 for the $W/(C + 0.30F)$ ratio. This is entered under Item 1.7 in Table 12 and completes Stage 1 (9.3.1).

For the specified materials and requirements, the free-water content, W, is found from Parts A and B of Table 9 to be:

$$60 - 15 = 145 \text{ kg/m}^3$$

This is entered under Item 2.3 in Table 12 and completes Stage 2 (9.3.2).

Stage 3 requires the additional calculations C6 and C7 to calculate the Portland cement content and the pfa content as described in 9.3.3.

For a specified proportion of pfa of 30%, $p = 30$.
Hence from calculation C6:

$$\text{Portland cement content} = \frac{(100-30)\times 145}{(100-0.7\times 30)\times 0.46}$$

$$= \frac{70\times 145}{79\times 0.46}$$

$$= 280 \text{ kg/m}^3 \quad \text{(Item 3.5)}$$

From calculation C7:

$$\text{pfa content} = \frac{30\times 280}{100-30}$$

$$= 120 \text{ kg/m}^3 \quad \text{(Item 3.6)}$$

The combined Portland cement content and pfa content, ie 280 + 120 = 400 kg/m^3, is entered under Item 3.1 in Table 12. This exceeds the minimum cement content of 300 kg/m^3 specified in Item 3.3.

From calculation C8:

$$\frac{W}{(C+F)}\text{ ratio} = \frac{145}{280+120} = 0.36 \quad \text{(Item 3.7)}$$

This is less than the maximum free-water/cement ratio of 0.60 specified in Item 3.8.

Using the relative density of 2.60, the free-water content of 145 kg/m^3, and Figure 5:
the wet density = 2420 kg/m^3 (Item 4.2)

From calculation C9:
the total aggregate content = 2420 – 400 – 145
= 1875 kg/m^3 (Item 4.3)

This completes Stage 4 (9.3.4).

In the final Stage 5 (9.3.5) the proportion of fine aggregate is obtained from Figure 6 for the given requirements. In this case the fine aggregate proportion may range from about 23 to 27%. It is decided to use a fine aggregate proportion of 26% (Item 5.2).

The fine aggregate content = 0.26×1875
= 490 kg/m^3 (Item 5.3)

The coarse aggregate content = 1875 – 490
= 1385 kg/m^3 (Item 5.4)

Thus the quantites of the constituent materials for one cubic metre of concrete are:

Portland cement	280 kg/m^3
pfa	120 kg/m^3
Water	145 kg/m^3
Fine aggregate	490 kg/m^3
Coarse aggregate	1385 kg/m^3

The individual fractions of the coarse aggregate, 20–10 mm and 10–5 mm, are determined as described in 5.5 and shown in Table 12.

9.5 Use of Portland pulverised-fuel ash cement

The same modified mix design method can be used with Portland pulverised-fuel ash cement complying with BS 6588[8]. With these cements the manufacturers will declare the proportion of pfa in the cement by mass of the nucleus* of the cement. The same mix design process as described in 9.3 is carried out, but in Stage 3, although the separate proportions of Portland cement (Item 3.5) and of pfa (Item 3.6) are determined, the value used in practice is the combined value of $(C + F)$ given in Item 3.1.

*The nucleus is the mass of cement excluding calcium sulfate and any additives.

Table 11 Completed concrete mix design form for Portland cement/pfa concrete

Stage	Item		Reference or calculation	Values
1	1.1	Characteristic strength	Specified	**35** N/mm² at **28** days; Proportion defective / %
	1.2	Standard deviation	Fig 3	/ N/mm² or no data / N/mm²
	1.3	Margin	C1 or Specified	(k = /) / × / = / N/mm²; **12** N/mm²
	1.4	Target mean strength	C2	**35** + **12** = **47** N/mm²
	1.5	Cement strength class	Specified	42.5/~~52.5~~ **+ pfa**
	1.6	Aggregate type: coarse Aggregate type: fine		~~Crushed~~/uncrushed ~~Crushed~~/uncrushed
	1.7	Free-water/cement ratio	Table 2, Fig 4	**See pfa sheet** Use the lower value
	1.8	*Maximum free-water/ cement ratio*	*Specified*	
2	2.1	Slump or Vebe time	Specified	Slump **10 – 30** mm or Vebe time / s
	2.2	Maximum aggregate size	Specified	**20** mm
	2.3	Free-water content	Table 3	**See pfa sheet** / kg/m³
3	3.1	Cement content	C3	/ ÷ / = / kg/m³
	3.2	*Maximum cement content*	*Specified*	/ kg/m³ **See pfa sheet**
	3.3	*Minimum cement content*	*Specified*	**300** kg/m³; use 3.1 if ≤ 3.2; use 3.3 if > 3.1; / kg/m³
	3.4	Modified free-water/cement ratio		/
4	4.1	Relative density of aggregate (SSD)		**2·60** known/~~assumed~~
	4.2	Concrete density	Fig 5	**See pfa sheet** **2420** kg/m³
	4.3	Total aggregate content	C4	– – = **1875** kg/m³
5	5.1	Grading of fine aggregate	Percentage passing 600 μm sieve	**70** %
	5.2	Proportion of fine aggregate	Fig 6	**26** %
	5.3	Fine aggregate content	C5	**1875** × **0·26** = **490** kg/m³
	5.4	Coarse aggregate content	C5	**1875** – **490** = **1385** kg/m³

Quantities	Cement (kg)	Water (kg or litres)	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm	20 mm	40 mm
per m³ (to nearest 5 kg)		**See pfa sheet**				
per trial mix of ……… m³						

Items in italics are optional limiting values that may be specified (see Section 7).
Concrete strength is expressed in the units N/mm². 1 N/mm² = 1 MN/m² = 1 MPa. (N = newton; Pa = pascal.)
The internationally known term 'relative density' used here is synonymous with 'specific gravity' and is the ratio of the mass of a given volume of substance to the mass of an equal volume of water.
SSD = based on the saturated surface-dry condition.

Table 12 Completed additional mix design form for Portland cement/pfa concrete

Stage	Item		Reference or calculation	Values		
1	1.1 – 1.4		← On standard form →			
	1.5	Cement strength class	Specified	42.5/~~52.5~~ + pfa		
	1.6		← On standard form →			
	1.7	Free-water/cement ratio	Table 10, Fig 4	$W/(C + 0.30F)$	=	0·46
	1.8		Transferred to 3.8			
2	2.1 – 2.2		← On standard form →			
	2.2a	Proportion of pfa	Specified		p =	30 %
	2.3	Free-water content	Table 9	160 – 15	=	145 kg/m³
3	3.5	Portland cement	C6		C =	280 kg/m³
	3.6	pfa content	C7		F =	120 kg/m³
	3.1	Total	—		$(C + F)$ =	400 kg/m³
	3.2 — 3.4		← On standard form →			
	3.7	$W/(C + F)$	C8	145 ÷ 400	=	0.36
	3.8 (1.8)	Maximum free-water/cement ratio	Specified			0.60
4	4.1 – 4.2		← On standard form →			
	4.3	Total aggregate content	C9	2420 – 400 – 145	=	1875 kg/m³
5	5.1 – 5.4		← On standard form →			

Quantities		per m³ (to the nearest 5 kg)	per trial mix of 0.05 m³
Cement	kg	280	14.0
pfa	kg	120	6.0
Water	kg	145	7.25
Fine aggregate	kg	490	24.5
Coarse aggregate:			
10 mm	kg	460	23.0
20 mm	kg	925	46.25
40 mm	kg	/	/

Note: Pulverised-fuel ash (pfa) to comply with BS 3892:Part 1.

Concrete strength is expressed in the units N/mm². 1 N/mm² = 1 MN/m² = 1 MPa. (N = newton; Pa = pascal.)
The internationally known term 'relative density' used here is synonymous with 'specific gravity' and is the ratio of the mass of a given volume of substance to the mass of an equal volume of water.
SSD = based on the saturated surface-dry condition.

10 Design of Portland cement / ggbs mixes

10.1 Introduction to ground granulated blastfurnace slag (ggbs)

Granulated blastfurnace slag has been used as a constituent of Portland-blastfurnace cement for more than sixty years. The British Standard Specification for Portland-blastfurnace cement, BS 146[10], was first published in 1923. It applies to cements containing not more than 65%, by mass of the nucleus* of the cement, of blastfurnace slag. Blastfurnace slag contents of between 50 and 90% by mass of the nucleus of the cement are allowed in BS 4246[11], the British Standard Specification for high slag blastfurnace cement. There is thus ample experience of using this material in the UK.

Ground granulated blastfurnace slag *complying with BS 6699* [9] may also be added to Portland cements class 42.5 and 52.5 complying with BS 12[3] in the mixer to give similar performance to Portland-blastfurnace cement, BS 146, and high slag blastfurnace cement, BS 4246. Blending in the mixer has the advantage that the producer can vary the proportions of Portland cement and ggbs to suit the particular application. Ground granulated blastfurnace slag for use in concrete should comply with BS 6699.

When ggbs is used as a replacement for some of the Portland cement in the mix it is generally done on the basis of a direct mass for mass replacement of Portland cement by ggbs. Generally replacements are in the order of from 30 to 50% by mass, although higher replacements of 70% or more are required for some purposes. The replacement of Portland cement by ggbs generally improves the workability of the concrete allowing for a small reduction in the water content. Portland cement / ggbs concrete has a different rate of strength development from Portland cement concrete; it is slower at early ages, but its strength gain after 28 days is normally higher than that of a comparable Portland cement concrete.

Ground granulated blastfurnace slag is particularly beneficial in large concrete sections in reducing thermal cracking problems due to the heat evolution during the hydration of the cement[35]. The use of certain ggbs can also be beneficial when concrete is placed in sulfate-bearing soil conditions as described in BRE Digest 363[21] and when there is the possibility of disruption of the concrete due to the alkali–silica reaction (ASR) as described in BRE Digest 330[22] and the independent Working Party Report[23] published by the Concrete Society. However, the use of ggbs also has the effects of increasing the sensitivity of the concrete to poor curing, although with a greater potential for recovery, and increasing the setting times and formwork pressures.

10.2 Information on Portland cement / ggbs concrete

Information is given in Sections 1, 2, 3 and 4 on various aspects of concrete which is used as background information for the specific method of mix design described in Part two. When the cement is a Portland blastfurnace cement to BS 146 or BS 4246, or when the cement is a combination of Portland cement to BS 12 and ggbs to BS 6699, its characteristics are influenced by those of its constituents of Portland cement and ggbs and their relative proportions (see also 10.3). Despite this, however, the background information also applies generally to concrete made with combinations of Portland cement and ggbs. The following particular items should be noted.

10.2.1 Workability and water content
When ggbs is used as a replacement for Portland cement in a mix it normally acts as a water-reducing agent. The workability of the concrete can be obtained with a lower water content, the reduction depending on the characteristics of the materials used. As a rough guide the water contents given in Table 3 should be reduced by about 5 kg / m^3.

10.2.2 Variability of concrete strength (see Section 4)
This is a major factor in any mix design to establish the margin to obtain a target mean strength (see 5. 1, Stage 1). There is substantial evidence[39] that the on-site variability of Portland cement / ggbs concrete is no greater than that of Portland cement concrete, even though the production process does involve the weighing of an extra constituent. Standard deviations of about 3 N / mm^2 to 4 N / mm^2 have been obtained on sites in the UK. There is thus no need to make changes in fixing the margin for Portland cement / ggbs concrete.

10.2.3 Density of Portland cement / ggbs concrete
The relative density of ggbs is 2.9, slightly less than that of Portland cement, so replacing Portland cement on an equal basis by weight results in a small increase in cement volume and a theoretical decrease in density. However, the water content, the lightest component, is normally reduced and the total result is that there is no significant change to the wet density of the concrete compared with that of Portland cement concrete.

10.3 Advice on methods of mix design for Portland cement / ggbs concrete

The basic principles of mix design apply to Portland blastfurnace cements complying with BS 146 or BS 4246 and to combinations of Portland cement to BS 12 and ggbs to BS 6699 produced in the concrete mixer. Information should be obtained from the manufacturer of the Portland blastfurnace cement or from the supplier of the ggbs relating to the particular materials to be used and the level of ggbs replacement appropriate for the work. Guidance on the proportion of ggbs in the total of Portland cement plus ggbs for different purposes is as follows:

*The nucleus is the mass of cement excluding calcium sulfate and any additives.

Type of use	Proportion of ggbs
● general use, including structures,	about 40%
● improved resistance to sulfates, (see BRE Digest 363)	70–90%
● improved resistance to alkali–silica reaction (see BRE Digest 330 and reference 21)	often 50%
● reduced temperature rise	50–90%

The actual proportion of ggbs and the cement content of the mix will depend upon the 28-day compressive strength and other requirements of the job.

For general use, Portland blastfurnace cement to BS 146 having a maximum ggbs content of about 40% by mass of the nucleus of the cement, and combinations of Portland cement to BS 12 and ggbs to BS 6699 produced in the concrete mixer with a maximum ggbs content of about 40%, should be used. With this proportion of ggbs the compressive strength of concrete at 28 days is comparable to that of Portland cement class 42.5 concrete of the same cement content. In this case, an ordinary Portland cement concrete is first designed as described in Section 5 and then modified to replace some of the cement by ggbs. The cement content obtained in Stage 3 is divided, for example, between 60% Portland cement class 42.5 and 40% ggbs. Final adjustments to the mix proportions can be made at the trial mix stage as described in Section 6.

For other uses, requiring higher proportions of ggbs in the cement, Portland blastfurnace cements to BS 146 or to BS 4246, having the requisite proportion, or appropriate combinations, of Portland cement to BS 12 and ggbs to BS 6699 produced in the concrete mixer, should be used. In such cases it is generally necessary to increase the content of cement plus ggbs above that of Portland cement class 42.5 concrete to achieve comparable compressive strengths at 28 days. Typically, an additional cement/plus ggbs content of about 10 kg/m^3 to 50 kg/m^3 is required.

As with pfa, ggbs itself is not defined as a cement but it can be given a 'cementing efficiency factor' as described in 9.2.2. However, the cementing efficiency factor, *k*, for ggbs is far more dependent on the characteristics of the particular Portland cement and the proportion of replacement used than is the case for Portland cement/pfa concrete. For the compressive strength at 28 days, the *k* factor varies from about 0.4 to over 1.0. At a given age, the strength of Portland cement/ggbs concrete depends upon the free-water/'equivalent cement' ratio as does Portland cement class 42.5 concrete. However, owing to the large range of *k* factors it is not possible to recommend a standard modification to Figure 4 as was the case in 9.2.2 for pfa. For these reasons this publication does not give a detailed standard procedure for the design of mixes applicable for Portland cement/ggbs concretes with high proportions of ggbs. For mixes in which the cement is required to contain more than 40% ggbs, therefore, the best procedure is to consult the cement manufacturer or the supplier of the ggbs who will have detailed information on the properties of the materials to be used in a particular area.

When the mix parameters of Portland cement/ggbs concrete are compared against specified limits of minimum or maximum cement content or maximum free-water/cement ratio, the 'cement' is the combined sum of Portland cement plus ggbs.

References

[1] Teychenné D C, Franklin R E and Erntroy H C. *Design of normal concrete mixes.* Department of the Environment. London, HMSO, 1975.

[2] Teychenné D C, Franklin R E and Erntroy H C. *Design of normal concrete mixes.* Building Research Establishment. Garston, CRC, 1988 (reprinted with corrections 1992).

[3] British Standards Institution. BS 12:1996. Specification for Portland cement. London, BSI.

[4] British Standards Institution. BS 4027:1996. Specification for sulfate-resisting Portland cement. London, BSI.

[5] British Standards Institution. BS 882:1992. Specification for aggregates from natural sources for concrete. London, BSI.

[6] British Standards Institution. BS 1047:1983. Air-cooled blastfurnace slag aggregate for use in construction. London, BSI.

[7] British Standards Institution. BS 3892:Part 1:1993. Specification for pulverized-fuel ash for use with Portland cement. London, BSI.

[8] British Standards Institution. BS 6588:1996. Specification for Portland pulverized-fuel ash cements. London, BSI.

[9] British Standards Institution. BS 6699:1992. Specification for ground granulated blastfurnace slag for use with Portland cement. London, BSI.

[10] British Standards Institution. BS 146:1996. Specification for Portland-blastfurnace cements. London, BSI.

[11] British Standards Institution. BS 4246:1996. Specification for high slag blastfurnace cement. London, BSI.

[12] Metcalf J B. The specification of concrete strength. Part II. The distribution of strength of concrete for structures in current practice. *RRL Report* LR 300. Crowthorne, Road Research Laboratory, 1970.

[13] British Standards Institution. BS 5328:1997. Concrete. London, BSI.

[14] British Standards Institution. BS 8110:1985. The structural use of concrete. London, BSI.

[15] British Standards Institution. BS 1881:Part 102:1983. Method for determination of slump. London, BSI.

[16] British Standards Institution. BS 1881:Part 104:1983. Method for determination of Vebe time. London, BSI.

[17] British Standards Institution. BS 1881:Part 103:1993. Method for determination of compacting factor. London, BSI.

[18] Road Research Laboratory. Design of concrete mixes. *Road Note* No 4. London, HMSO, 1950 (2nd edition).

[19] McIntosh J D and Erntroy H C. The workability of concrete mixes with 3/8 in. aggregates. *Research Report* 2. Wexham Springs, Cement and Concrete Association, 1955.

[20] Building Research Establishment. The durability of steel in concrete: Part 1. Mechanism of protection and corrosion. *BRE Digest* 263. Garston, CRC, 1982.

[21] Building Research Establishment. Sulfate and acid resistance of concrete in the ground. *BRE Digest* 363. Garston, CRC, 1996.

[22] Building Research Establishment. Alkali–silica reaction in concrete. *BRE Digest* 330. Garston, CRC, 1997.

[23] The Concrete Society. Alkali silica reaction: minimising the risk of damage to concrete. *Technical Report* No 30. The Concrete Society, 1987.

[24] Deacon C and Dewar J D. Concrete durability: specifying more simply and surely by strength. *Concrete,* Feb 1982.

[25] Teychenné D C. *The use of crushed rock aggregates in concrete.* Building Research Establishment Report. Garston, CRC, 1978. Also Teychenné D C. Concrete made with crushed rock aggregate, *BRE Current Paper* CP63/78. Garston, BRE, 1978.

[26] British Standards Institution. BS 1881:Part 111:1983. Method of normal curing of test specimens (20°C method). London, BSI.

[27] Teychenné D C. Recommendations for the treatment of the variations of concrete strength in codes of practice. *Materials and Structures,* (1973) 6 (34) 259–267. (Also published as *BRE Current Paper* CP6/74.)

[28] CEB/FIP (European Committee for Concrete/International Federation of Prestressed Concrete). CEB/FIP Model Code for concrete structures. *CEB Bulletin* No 125. Paris, CEB/FIP, April 1978.

[29] British Standards Institution. BS 1881:Part 125:1986. Methods for mixing and sampling fresh concrete in the laboratory. London, BSI.

[30] British Standards Institution. BS 1881:Part 107:1983. Method for determination of density of compacted fresh concrete. London, BSI.

[31] British Standards Institution. BS 1881:Part 108:1983. Method of making test cubes from fresh concrete. London, BSI.

[32] British Standards Institution. BS 1881: Part 116:1983. Method for determination of compressive strength of concrete cubes. London, BSI.

[33] Cornelius D F. Air-entrained concretes: a survey of factors affecting air content and a study of concrete workability. *RRL Report* LR 363. Crowthorne, Road Research Laboratory, 1970.

[34] British Standards Institution. BS 1881:Part 106: 1983. Method for determination of air content of fresh concrete. London, BSI.

[35] Bamforth P B. In-situ measurement of the effect of partial Portland cement replacement using either fly ash or ground granulated blastfurnace slag on the performance of mass concrete. *Proceedings Institution of Civil Engineers, Part 2,* Sep 1980.

[36] British Standards Institution. BS 3892:Parts 1 and 2:1984. Specification for pulverised-fuel ash for use in grouts and for miscellaneous uses in concrete. London, BSI.

[37] Hobbs D W. The effect of pulverised-fuel ash upon the workability of cement paste and concrete. *Magazine of Concrete Research*, (1980) 32 (113).

[38] Smith I A. The design of fly-ash concretes. *Journal Institution of Civil Engineers,* (1967) 36.

[39] Atwell J S F. Some properties of ground granulated slag and cement. *Proceedings Institution of Civil Engineers, Part 2,* June 1974.

Also available from BRE

Alkali–silica reaction in concrete

BRE Digest 330 £4.50 each part; £13.50 the set

Concrete can deteriorate as a result of an interaction between alkaline pore fluids (principally originating from the Portland cements) and reactive minerals in certain types of aggregates. The mechanism of deterioration is known as alkali–aggregate reaction (AAR); it can occur in a number of forms, the most common being alkali–silica reaction (ASR). This Digest give guidance for general concreting applications; highly specialised applications are outside its scope. It is in four parts: Part 1 gives the background to the detailed and simplified guidance contained in Parts 2 and 4; Part 2 gives detailed guidance for minimising the risk of ASR in new construction; Part 3 gives worked examples; Part 4 gives simplified guidance for new constuction using aggregates of normal reactivity.

Sulfate and acid resistance of concrete in the ground

BRE Digest 363

This Digest discusses the factors responsible for sulfate and acid attack on concrete below ground and recommends the type of cement and quality of concrete to provide resistance. Sites are classified on the basis of their sulfate concentration but recommendations also take into account water movement and acidity and their individual effects on various forms of cast-in-situ and precast constructions.

Assessment of existing high alumina cement concrete construction in the UK

BRE Digest 392 £4.50

After a few collapses in the early 1970s, reference to high alumina cement concrete (HACC) was deleted from the code of practice for the structural use of concrete. This Digest explains current guidance for the assessment of HAC construction, taking account of developments and research since 1975. Most of the new information comes from site investigations of structures; the findings have a bearing on how HAC construction should be appraised. The main conclusions are that, in the absence of chemical attack, the strength assessment guidance issued in 1975 by the Department of the Environment has been shown to be safe without being over pessimistic but that the risk of corrosion to reinforcement is increasingly important in the assessment of HAC components. This Digest describes a testing regime to identify cases of chemical attack and assesses the current level of protection afforded to the reinforcement.

Carbonation of concrete and its effects on durability

BRE Digest 405 £4.50

This Digest discusses the carbonation of normal dense concrete which results from the reaction of atmospheric carbon dioxide gas with hydrated cement compounds. It relates particularly to the assessment of the risk of corrosion to embedded steel. The Digest describes the carbonation process and how the depth of carbonation can be measured; it outlines the various factors influencing the depth and rate of carbonation, indicates the possible effects produced in hardened concrete and briefly discusses maintenance.

Concrete mix design form

Job title ....

Stage	Item		Reference or calculation	Values
1	1.1	Characteristic strength	Specified	{ .... N/mm^2 at .... days Proportion defective .... %
	1.2	Standard deviation	Fig 3	.... N/mm^2 or no data .... N/mm^2
	1.3	Margin	C1 or Specified	(*k* = ...) .... × .... = ... N/mm^2 .... N/mm^2
	1.4	Target mean strength	C2	.... + ... = ... N/mm^2
	1.5	Cement strength class	Specified	42.5/52.5
	1.6	Aggregate type: coarse Aggregate type: fine		Crushed/uncrushed Crushed/uncrushed
	1.7	Free-water/cement ratio	Table 2, Fig 4	.... } Use the lower value [ ]
	1.8	*Maximum free-water/ cement ratio*	*Specified*	.... }
2	2.1	Slump or Vebe time	Specified	Slump .... mm or Vebe time .... s
	2.2	Maximum aggregate size	Specified	.... mm
	2.3	Free-water content	Table 3	.... [kg/m^3]
3	3.1	Cement content	C3	.... ÷ .... = ... kg/m^3
	3.2	*Maximum cement content*	*Specified*	.... kg/m^3
	3.3	*Minimum cement content*	*Specified*	.... kg/m^3
				use 3.1 if ≤ 3.2 use 3.3 if > 3.1 [kg/m^3]
	3.4	Modified free-water/cement ratio		.... [ ]
4	4.1	Relative density of aggregate (SSD)		.... known/assumed
	4.2	Concrete density	Fig 5	.... kg/m^3
	4.3	Total aggregate content	C4	.... − .... − .... = ... kg/m^3
5	5.1	Grading of fine aggregate	Percentage passing 600 µm sieve	.... %
	5.2	Proportion of fine aggregate	Fig 6	.... %
	5.3	Fine aggregate content }	C5	{ .... × .... = [kg/m^3]
	5.4	Coarse aggregate content }		{ .... − .... = [kg/m^3]

Quantities	Cement (kg)	Water (kg or litres)	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm	20 mm	40 mm
per m^3 (to nearest 5 kg)	....	....	....	....	....	....
per trial mix of .... m^3	....	....	....	....	....	....

Items in italics are optional limiting values that may be specified (see Section 7).
Concrete strength is expressed in the units N/mm^2. 1 N/mm^2 = 1 MN/m^2 = 1 MPa. (N = newton; Pa = pascal.)
The internationally known term 'relative density' used here is synonymous with 'specific gravity' and is the ratio of the mass of a given volume of substance to the mass of an equal volume of water.
SSD = based on the saturated surface-dry condition.

Concrete mix design form for air-entrained concrete

Job title ....

Stage	Item		Reference or calculation	Values
1	1.1	Characteristic strength	Specified	{ .... N/mm^2 at .... days Proportion defective .... %
	1.2	Standard deviation	Fig 3	.... N/mm^2 or no data .... N/mm^2
	1.3	Margin	C1 or Specified	(k = ...) .... × .... = ... N/mm^2 .... N/mm^2
	1.4	Target mean strength	C2 & Para 8.1*	.... + ... = ... N/mm^2
	*1.4.1	Air content		.... %
	*1.4.2	Modified target mean strength		.... ÷ (1 − 0.055 × ....) = ... N/mm^2
	1.5	Cement strength class	Specified	42.5/52.5
	1.6	Aggregate type: coarse Aggregate type: fine		Crushed/uncrushed Crushed/uncrushed
	1.7	Free-water/cement ratio	Table 2, Fig 4	.... } Use the lower value [ ]
	1.8	*Maximum free-water/ cement ratio*	*Specified*	.... }
2	2.1	Slump or Vebe time	Specified	Slump .... mm or Vebe time .... s
	2.2	Maximum aggregate size	Specified	.... mm
	2.3	Free-water content	Table 3 & Para 8.2*	.... [kg/m^3]
3	3.1	Cement content	C3	.... ÷ .... = ... kg/m^3
	3.2	*Maximum cement content*	*Specified*	.... kg/m^3
	3.3	*Minimum cement content*	*Specified*	.... kg/m^3
				use 3.1 if ≤ 3.2 use 3.3 if > 3.1 [kg/m^3]
	3.4	Modified free-water/cement ratio		.... [ ]
4	4.1	Relative density of aggregate (SSD)		.... known/assumed
	4.2	Concrete density	Fig 5 & Para 8.3*	.... − (10 × .... × ....) = ... kg/m^3
	4.3	Total aggregate content	C4	.... − .... − .... = ... kg/m^3
5	5.1	Grading of fine aggregate	Percentage passing 600 µm sieve	.... %
	5.2	Proportion of fine aggregate	Fig 6	.... %
	5.3	Fine aggregate content }	C5	{ .... × .... = [kg/m^3]
	5.4	Coarse aggregate content }		{ .... − .... = [kg/m^3]

Quantities	Cement (kg)	Water (kg or litres)	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm	20 mm	40 mm
per m^3 (to nearest 5 kg)	....	....	....	....	....	....
per trial mix of .... m^3	....	....	....	....	....	....

*Modifications for air entrainment.
Items in italics are optional limiting values that may be specified (see Section 7).
Concrete strength is expressed in the units N/mm^2. 1 N/mm^2 = 1 MN/m^2 = 1 MPa. (N = newton; Pa = pascal.)
The internationally known term 'relative density' used here is synonymous with 'specific gravity' and is the ratio of the mass of a given volume of substance to the mass of an equal volume of water.
SSD = based on the saturated surface-dry condition.

Additional mix design form for Portland cement/pfa concrete   Job title ....

Stage	Item		Reference or calculation	Values		
1	1.1 – 1.4		◄	On standard form ►		
	1.5	Cement strength class	Specified	42.5/52.5 + pfa		
	1.6		◄	On standard form ►		
	1.7	Free-water/cement ratio	Table 10, Fig 4	$W/(C + 0.30F)$	=	
	1.8		Transferred to 3.8			
2	2.1 – 2.2		◄	On standard form ►		
	2.2a	Proportion of pfa	Specified		p =	.... %
	2.3	Free-water content	Table 9	.... –	=	kg/m^3
3	3.5	Portland cement	C6		C =	kg/m^3
	3.6	pfa content	C7		F =	kg/m^3
	3.1	Total	—		$(C + F)$ =	kg/m^3
	3.2 — 3.4		◄	On standard form ►		
	3.7	$W/(C + F)$	C8	.... ÷	=	....
	3.8 (1.8)	Maximum free-water/ cement ratio	Specified			....
4	4.1 – 4.2		◄	On standard form ►		
	4.3	Total aggregate content	C9	.... – .... –	=	kg/m^3
5	5.1 – 5.4		◄	On standard form ►		

Quantities		per m^3 (to the nearest 5 kg)	per trial mix of .... m^3
Cement	kg	....	....
pfa	kg	....	....
Water	kg	....	....
Fine aggregate	kg	....	....
Coarse aggregate:			
10 mm	kg	....	....
20 mm	kg	....	....
40 mm	kg	....	....

Note: Pulverised-fuel ash (pfa) to comply with BS 3892:Part 1.

Concrete strength is expressed in the units N/mm^2. 1 N/mm^2 = 1 MN/ m^2 = 1 MPa. (N = newton; Pa = pascal.)
The internationally known term 'relative density' used here is synonymous with 'specific gravity' and is the ratio of the mass of a given volume of substance to the mass of an equal volume of water.
SSD = based on the saturated surface-dry condition.