Some trends in concrete specification and control

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Abstract

The aims of concrete specification and control are described and an assessment of possible future developments is made. The consideration of concrete specifications includes mix proportions, strengths, and water–cement ratios. Sampling and testing are discussed, including the relation between acceptance and performance tests, and statistical control. Among future trends considered are the specification of two distinct classes of concrete, production control, design stresses and testing methods.

THE Symposium on Mix Design and Quality Control[1], organized by the Cement and Concrete Association in 1954, introduced a more scientific approach to the production and control of concrete on the site. The principles then laid down have since become accepted and adopted throughout the construction industry. A more recent development has been to examine the many factors which influence the quality of concrete from the production of raw materials[2,3] to the inspection of the finished structure. The topics discussed at the Symposium on Concrete Quality in 1964[4] included the variability of raw materials, methods of specification, the significance and limitations of existing test methods and problems of workmanship and inspection.

The most significant trends, however, are to be seen in the new approach to the specification and testing of concrete introduced in the Code of Practice for precast concrete CP 116[5,6] and discussed in a noteworthy paper by Teychenne[7]. In the light of this changing attitude to concrete, the opportunity is taken here to reconsider the aims of concrete specification and control and to anticipate possible future developments.

Concrete properties and specifications

The primary concern of the design engineer is that concrete in the hardened state should have sufficient strength and elasticity to support the applied loads, without undue deflection, and sufficient durability not to deteriorate under the expected conditions of exposure. Any properties he may specify in the fresh state are mainly to ensure proper compaction and removal of air voids so that the desired strength and durability can be realized.

Since suitably strong dense inert aggregates are readily available in Great Britain, the properties of hardened concrete are determined almost entirely by the properties of the cement-paste binder. The adoption of a sufficiently low water–cement ratio, together with proper hydration, produces dense hardened cement paste having high strength, high elastic modulus, low creep and shrinkage, and low permeability to water and aggressive liquids and consequently a high resistance to weathering and chemical attack.

The basic aim of specifications for structural concrete, therefore, is to control the water–cement ratio at different levels to produce concrete of different qualities. Unfortunately there is still no quick reliable direct method of

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measuring the water–cement ratio. As a result, two independent indirect methods have become established, as outlined in Table 1. Water–cement ratio can be controlled either by controlling the proportions and workability in the fresh state or by controlling the strength of concrete in the hardened state.

Mix proportions specifications

When considering the properties of fresh concrete made with aggregate from one source, the water–cement ratio is dependent upon five other independent variables, namely, cement content, aggregate content, grading and maximum size of aggregate, and the required workability. Once a mix has been designed, the water–cement ratio will be automatically controlled if all the other variables are kept within close limits. In fact, for concretes of medium consistence (that is 2 in. to 4 in. slump), an experienced concrete-mixer operator, controlling workability by eye alone, can be relied upon to produce concrete of uniform quality as long as the proportions and aggregate grading are controlled as well[8].

Specifications of proportions have undergone a much needed revision over the years. Early specifications defined the mix proportions in bulk-volume terms, that is 1 part of cement : n parts of sand : $2n$ parts of coarse aggregate. The large variety of shapes and gradings of aggregates available in this country means that, with these nominal mixes, a considerable range of water–cement ratios, with corresponding variation in strength, is required to produce concrete of medium consistence. Accordingly, limitations were applied, in turn, to the cube-strength and the grading and shape of the aggregate, both of which led to uneconomical and restrictive specifications.

In 1957, CP 114[9] partially overcame this problem by allowing the originally constant value of 2 for the bulk-volume ratio of coarse aggregate to sand to vary from 1½ to 3. However, now that concrete mixes are almost universally batched by weight rather than by volume, bulk-volume proportioning is not only irrational but inexact owing to the large variations which can occur in the aggregate bulk-density test. The logical development is the introduction of standard mixes based on dry weights, and these have been included in the 1965 revision to CP 114 and CP 116. These standard mixes specify the proportions more precisely for different types, gradings and maximum sizes of aggregate, workability and degrees of quality control.

A modification to the standard mixes by weight is to specify the proportions in terms of the cement content per cubic yard of fully compacted concrete[10]. This method is common practice within the ready-mixed concrete industry, and enables lightweight aggregate and natural aggregate mixes to be specified in the same way. Such a specification, while not defining exactly the amount of aggregate, effectively restricts this to within certain limits. However, as with all specifications of proportions, it is necessary to apply limits to the aggregate grading if the water–cement ratio is to be controlled by controlling workability.

One limitation of the standard-proportions-and-workability type of specification is the large variations in water–cement ratio which can occur, for a given workability, owing to the inherent variations in the quality and grading of the aggregates used throughout Great Britain. Consequently, to ensure sufficient strength and durability, standard mixes have higher cement contents than the corresponding mixes properly designed for the available materials. Their use, however, can produce considerable savings on small and medium works where designed mixes and expensive control methods are unwarranted[11].

Strength specifications

The standard cube-crushing strength is one of the most sensitive and unambiguous measures of water–cement ratio, being far less dependent on proportions than other testing methods such as density, ultra-sonic pulse velocity and resonant frequency[8]. For this reason the cube test has become established as a measure of the properties of hardened concrete and the basis for design stresses. The control of the water–cement ratio through strength enables the designer to choose the most economical proportions with the available materials.

In specifications of strength, it is necessary to ensure that the strengths obtained are associated with a suitably low water–cement ratio and are not the result of special aggregate characteristics or intense compaction of mixes of low workability. Conversely, excessively rich mixes must be avoided since these may produce severe shrinkage cracking due to drying or cooling effects. Thus, in specifications of strength, upper and lower limits to the cement content should be specified, these being 900 and 400 lb. per cu. yd respectively in CP 116.

The introduction of limits on workability in a specification of strength is, for a given type and grading of aggregate, more a control on the cement content than on the water–cement ratio. Such a limitation is generally superfluous, except perhaps to define an upper limit, for example, 5-in. slump, above which there is no advantage in going.

Water–cement ratio specifications

In principle the water–cement ratio of a concrete mix can be controlled directly by accurate measurement of any water in the aggregate and the water added at the mixer. In practice, the excessive time involved in performing any standard moisture-content test makes successive measurements on each batch during normal production virtually impossible. Moisture meters, based on the electrical resistance of the damp material, have been developed to measure the moisture content of the batch of aggregate immediately above the discharge gates of the storage bins. Although these devices require frequent recalibration and the probes are subject to damage by abrasion, they have been used with considerable success on ready-mixed concrete plants[12]. Further development of such devices should prove advantageous.

Sampling and testing

The basic tests which are, or will shortly be, generally used are the slump, compacting factor and vebe tests for fresh concrete, and the cube, cylinder splitting and flexural beam tests for hardened concrete. When considering the numbers of tests to be performed and the method of taking samples, it is important to differentiate between acceptance or performance tests, which indicate whether or not the specific requirements are being met, and control tests, which provide a measure of the uniformity of the concrete produced[13].

Acceptance or performance tests

These tests are carried out on the constituent cement and aggregates and the fresh and hardened concrete to confirm that the chosen materials and proportions adequately satisfy the specification. Such tests are sometimes restricted to preliminary tests on laboratory trial mixes, whereas final acceptance of the proportions must await results from full-scale trial mixes on the site.

Strictly, with proportions specifications, the acceptance tests should actually check whether the concrete contains the requisite amount of cement, sand and coarse aggre-

TABLE I   METHODS OF SPECIFYING, CONTROLLING AND TESTING CONCRETE MIXES

SPECIFIED CHARACTERISTIC	CONTROLLING FACTORS	LIMITS APPLIED TO			TESTS	
		PROPORTIONS	GRADING	WORKABILITY	ACCEPTANCE	CONTROL
PROPORTIONS (a) Bulk volume (b) Weight (c) Cement content per cu. yd	Proportions Workability Grading	(a) Specified (b) Specified (c) Specified	(a) Specified (b) Specified (c) Maximum size, grading envelope	Upper and lower limits only	(i) Wet analysis (ii) Batching checks and workability (iii) Cube test	Cube test
STRENGTH	Strength	Upper and lower limits to cement content	Maximum size only	Upper limit only	(i) Cube test (ii) Wet analysis (iii) Batching checks and workability	Cube test
WATER–CEMENT RATIO	Moisture in aggregates Mixing water Cement content	Upper and lower limits of cement content	Maximum size only	Upper limit only	(i) Wet analysis (ii) Batching checks, moisture tests and workability (iii) Cube tests	Cube test

gate. At the moment, analysis of freshly-mixed concrete in the manner described in Part 4 of BS 1881[14] is the only direct way of checking the proportions. This method and subsequent developments of it are rather slow, require special apparatus and are not particularly sensitive to variations in the proportions. Thus, satisfactory results of works-cube strength tests have come to be accepted as the standard of acceptance for both proportions and strength specifications. Nevertheless, it is just as important with proportions specifications to make frequent checks on the actual amounts of materials being batched, on the accuracy of the weighing equipment and on the workability, as it is to make cube tests.

Control tests for uniformity

When assessing the results of cube tests from samples of concrete taken on the site, it is useful to separate the inherent random variations as follows.

Testing variations due to the process of sampling, making, curing and testing of cubes.

Within-batch variations due to non-uniform mixing caused by poor sequence of loading materials, insufficient mixing time, wear of blades or poor discharge procedure.

Batch-to-batch variations due to variations in the quality of raw materials or in the batched proportions of cement, aggregates and water. This constitutes the main variation and its assessment is the prime aim of quality-control tests on the site.

The method of taking a concrete sample and the number of specimens made from it will depend on which variation is being measured and the desired reliability of the estimate of the average. To assess testing variations, it is necessary to test a number of specimens from a composite sample taken from one batch in the manner described in Part 1, BS 1881. To measure within-batch variations, a number of specimens must be tested from samples taken from different parts of one batch. To assess the batch-to-batch variation it is necessary to test specimens from composite samples taken from random batches.

Even in a laboratory, using one brand or blend of cement and weighing out dry materials, it is difficult to reduce the coefficient of variation for testing much below 5 per cent[7, 13]. Variations between batches are much greater than either within-batch or testing variations, and, for good control, a 15 per cent overall coefficient of variation must be expected. It can be shown that, to provide a reliable estimate of the true average (namely, the error of the average should not exceed 5 per cent for 90 per cent of the time), only three cubes from one batch are required to assess the testing variations, whereas one specimen from each of twenty-five batches is required to establish the average strength of that number of batches[13]. More than one cube per batch in the latter case would not significantly increase the accuracy of the average.

The original test procedure in CP 114, that is testing three cubes from one sample taken once every week, is more of a check on testing variations than variations from batch to batch. As Teychenne[7] has pointed out, this method of infrequent sampling often leads to considerable bias due either to the sampling of the wetter mixes delivered by ready-mixed concrete suppliers or the extra care taken by site staff when they know cubes are to be taken. An accurate estimate of the true variation of the quality of concrete can only be obtained from a large number

of random sampled tests. The introduction of such an approach in CP 116 marks a significant change in attitude in this country to the assessment of variability.

Statistical control and rejection of concrete

The variability of concrete has led to the use of statistical methods[15] to analyse cube results on the basis that these follow the pattern of the normal frequency distribution curve. The main questions to be answered when applying these methods to concrete quality control are: How can certain site-control measures be defined quantitatively in terms of values of standard deviation or coefficient of variation? Does standard deviation or coefficient of variation remain constant for a certain degree of control? How many results should be permitted to fall below the specified strength? What should be done when the specified requirements are not met?

These topics have been discussed in detail by Teychenne[7]. He presents further evidence in support of the conclusions of Erntroy[16] and Murdock[17] that, for a constant degree of control on the site, the coefficient of variation remains constant up to average cube-strengths of about 3,000 lb. per sq. in., above which strength the standard deviation tends towards a constant value. It is still very difficult, however, without previous experience, to relate quality control measures on the site with specific values of coefficient of variation or standard deviation.

It is only in recent years that engineers have begun to appreciate the full implications of the statistical approach, namely, that the specified strength of a randomly variable material like concrete cannot be an absolute minimum since there is always a chance that a certain number of specimens will fall below the specified strength. BS 1926[18] and CP 116 permit 2½ per cent of the test results to fall below the specified strength, whereas the CEB recommendations[19] allow 5 per cent. The implementation of such specifications requires a certain minimum number of test results if a reasonable estimate of the true variation is to be obtained. It is important, especially at the beginning of a job, to ensure that a sufficiently large number of randomly-sampled specimens are tested. CP 116 is the first code of practice to demand such a procedure.

It is doubtful whether sampling and testing of a truly random nature has yet been carried out in this country. When such results become available, it may have to be accepted that, even with good production control, standard deviations of 1,000 lb. per sq. in. and over are the rule rather than the exception owing to the considerable variations in the quality of the raw materials.

Although an indication of the variability can be obtained from a small number of samples by applying various statistical checks[5, 18], these can lead to a greatly increased error of the estimate. Those given in CP 116 have been severely criticized[20] and are undoubtedly much more restrictive than the corresponding checks in the ACI Building Code[21]. Obviously there is still considerable room for improvement in the mathematical treatment of data in the British codes of practice.

Probably the most controversial issue in concrete practice today is whether the concrete in a structure should be cut out if the results of some cube tests fall below the specified strength. The kind of questions which arise, especially when samples are taken very infrequently, include: How much concrete on site is represented by the low-strength cubes? How far were the results below the specified strength? Could the sub-standard cubes have reached the specified minimum with a further period of

curing? What decrease in concrete strength can be tolerated before the strength of the structural element is seriously affected? It must be admitted that, in practice, very little concrete is ever replaced due to low results of cube tests. Any reparations on the site are almost invariably the result of bad compaction, honeycombing, segregation, and similar defects.

Once again, CP 116 has taken a realistic approach to this problem. For when more than the permitted number of results fall below the specified strength, it is the proportions of subsequent batches of concrete which have to be modified, and not the concrete in the structural element. Excessively low strengths, however, cannot be tolerated and, if any cube result is less than 80 per cent of the specified strength, CP 116 stipulates that units made with the corresponding batch of concrete should be subjected to individual inspection and testing. For such testing, the Code is the first to recognize the usefulness, as qualitative checks, of such non-destructive methods as the ultra-sonic pulse velocity, gamma-radiography and Schmidt hammer.

Future trends

These few observations indicate that there is still considerable room for improvement in many aspects of the specification control and testing of concrete. Indeed, it might be argued that, over the last sixty years, little appears to have changed basically in the production methods of normal structural concrete. After all, the 'new approach' in CP 116 is really only an acceptance and rationalization of what has been common practice for so many years!

In comparison with other materials today, concrete must be regarded as a low-grade low-strength material. Yet its low cost, durability and ease of manufacture has enabled it to cope easily with competition from other more sophisticated materials. Consequently concrete, in its present form, should comprise a considerable proportion of concrete production in the foreseeable future.

Nevertheless, the design engineer is being called upon to subject concrete to ever-increasing stresses, ranges of temperature and patterns of loading. The special requirements of nuclear-reactor pressure-vessels and industrialized methods of production have emphasized the great lack of knowledge of the fundamental properties of fresh and hardened concrete. In addition, the application of the new design methods based on probability theory, as outlined in the recommendations of CEB[19, 22], as well as the higher design stresses recommended in CP 114 and CP 116, require a more accurate assessment of the quality of concrete and its variability.

It seems probable that these differing requirements will be met in the future by two distinct grades or classes of concrete involving different methods of specification, control and testing and different permissible design stresses. The two separate classes might be termed *standard-grade* and *special-grade* concretes.

Standard-grade concrete

Standard-grade concrete would comprise the long accepted range of concretes for general use in mass and reinforced concrete structures where there are no special requirements of strength, durability, or the like. On small jobs, where comprehensive mix design and quality control methods would be uneconomical, the standard grade concrete will be specified in terms of proportions by weight and workability. When efficient production control methods are used, as on large sites, precast concrete products works and ready-mixed concrete plants, more economical

concretes will result by specifying the mixes by strength.

For standard-grade run-of-the-plant concrete to remain an inexpensive material, it must be made from correspondingly low-cost raw materials whose quality is inherently variable. Considerable variation in the quality of standard-grade concrete must be accepted, therefore, even with good production control.

Special-grade concrete

Special-grade concrete would include all those types of concrete where improved or special qualities are required, for example high strength, low shrinkage or creep, special thermal or acoustic properties, increased resistance to physical deterioration or chemical attack. Laboratory tests have shown that concretes with many different properties are technically possible. For example, cube strengths of 15,000 lb. per sq. in. and over can be achieved with specially-selected and graded aggregates, problems of drying shrinkage can be overcome by using expanding cements or high-pressure steam curing, and a considerable increase in tensile strength can be produced by the introduction of fine wire or fibres into the concrete.

The high-strength concretes already specified for pre-stressing could be considered as the fore-runners of a whole range of special-grade concretes. The manufacture of such materials will demand efficient procedures of production control more suited to the precast concrete factory or ready-mixed concrete plant. Since specially prepared cements and aggregates of higher quality and uniformity may also be required, special-grade concretes are certain to be much more expensive than standard grades.

Production control and design stresses

For standard-grade concrete, the permissible compressive stress in bending would be unlikely to exceed 1,500 to 2,000 lb. per sq. in. and would be based on a relatively high safety factor in comparison with the specified works-cube strength. There would be certain minimum requirements for the control of concrete quality, similar to those outlined in CP 116 (Clause 212 and Appendix B4) with a regular, although perhaps limited, amount of testing of randomly-sampled cubes.

Due to their nature, considerably higher design stresses would be allowed for special-grade concretes. However, increased stresses could be permitted also with standard grade concretes if a complete statistical quality-control system, including extensive random sampling and testing, was being adopted.

Testing methods

There is a real need for a more rapid and reliable assessment of the properties of concrete for the purposes of both acceptance and quality control. For fresh concrete, the mechanical wet-analysis method[14] is not capable of much further development, and other techniques may prove more suitable. There are various methods by which the consistence of concrete in the mixing drum can be measured[12]. It is possible to determine the water content in fresh concrete by means of neutron moderation, and the cement content by the methods of heavy-media separation, radio-active tracers or electromagnetic radiation[23].

For hardened concrete, Grant[24] has demonstrated forcibly how a simple accelerated cube-test can be used in the production control of ready-mixed concrete. A more widespread use of such a test is long overdue. More

detailed specifications for compressive testing machines and methods of testing are required since work by Cole[25] and Sigvaldason[26] has shown that the standard cube test is not nearly as uniform or reproducible as was supposed.

Further development of non-destructive testing methods is also necessary since they can provide a measure of the quality of concrete in the structure.

Need for more education and training

Special grade concretes may never comprise a very high proportion of the total production, but their acceptance and inclusion in future codes of practice would proclaim a significant change in the attitude to the use of concrete as a structural material. However, the widespread manufacture of high-grade concrete demands a much higher standard of training of those involved than exists today. There is a great need for education in the basic principles of concrete technology at all levels from the senior engineer writing the specification to the man on the mixer. There are many training facilities available including the City & Guilds of London Institute Concrete Practice and Concrete Technology Certificate Courses and those organized by the Cement and Concrete Association. Specifications can play an important part in ensuring that staff attend these courses. CP 116 takes the lead again here by requiring the design and manufacture of precast concrete units to be supervised and controlled by an engineer experienced in concrete technology and a supervisor who has reached the level of the CGLI Concrete Technology Certificate.

Acknowledgement

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