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Guide to

Assessment of concrete strength in existing structures

Guide pour l'évaluation de la résistance du béton dans les constructions existantes

Leitfaden für die Beurteilung der Betonfestigkeit in vorhandenen Bauwerken

British Standards Institution

Contents

Foreword

The need to assess the strength of the concrete in an existing structure can arise from a variety of reasons, such as doubts following non-compliance of standard cube strength results or possible deterioration due to aggressive environments or a wish to check that the strength is acceptable for a particular loading system, especially when additional loading is being considered.

The drilling and testing of cores has been common practice for many years and several non-destructive tests have been available, well established test methods being described in BS 1881 and BS 4408.

This guide presents information on the standard method and on certain other methods that will assist in the selection of the method and testing programme most appropriate to the circumstances that prevail.

The interpretation of the test results and the factors that influence the relationship between the standard cube strength and the strength of the concrete in the structure are also discussed.

The recommendations in this standard are intended to provide guidance only; they are not intended to supplant engineering judgement or to inhibit the development and use of other test methods.

Numbers in parentheses in the text of the standard refer to the numbered references given in appendix A.

British Standard Guide to

Assessment of concrete strength in existing structures

1. Scope

This British Standard gives information on tests that are available to determine strength of concrete in a structure. Relative merits of these tests are indicated and methods of carrying out such tests are given.

This standard also contains guidelines to assist the engineer in interpreting results of tests, and outlines possible ways of comparing test results with the required strength for design purposes.

The information given in this standard amplifies sections of CP 110 : Part 1 : 1972 concerned with tests to measure and assess the strength of concrete in structures, including:

6.8.2.3 Action to be taken in the event of non-compliance with the testing plan.

9.2 Check tests on structural concrete.

2. References

The titles of the standards publications referred to in this standard are listed on the inside back cover.

A bibliography of some appropriate references is given in appendix A.

3. Definitions

For the purposes of this British Standard the following definitions apply.

3.1 standard cube strength. The measured compressive strength of a cube made, cured and tested in accordance with BS 1881 : Parts 1, 3 and 4.

3.2 cylinder strength. The compressive strength of a cylinder with a length/diameter ratio (λ) of 2 made and cured in accordance with clause **5** of BS 1881 : Part 3 : 1970, and tested in accordance with **3.2** of BS 1881 : Part 4 : 1970.

3.3 core strength. The compressive strength of a core, cut, prepared and tested in accordance with the requirements of BS 1881 : Part 4, for a stated length/diameter ratio.

3.4 estimated in-situ cube strength. The strength of concrete at a location in a structural member estimated from indirect means and expressed in terms of specimens of cubic shape.

NOTE. A direct measure of the in-situ cube strength cannot be obtained because it is not possible to produce a cast cubic specimen from that location. However, it is possible to obtain an estimated in-situ cube strength by using one or more of the methods described in clause **5**.

3.5 location. A region of concrete that, for practical purposes, is assumed to be of uniform quality.

3.6 characteristic cube strength. The value of the standard cube strength (which in CP 110 is measured at 28 days) below which 5 % of the population of all possible strength measurements are expected to fall.

3.7 design strength. The strength of concrete as used in calculations so that the allowable stress as defined by the relevant code of practice or other design basis employed is not exceeded under the loading conditions appropriate to that code or other design basis.

3.8 design load capability of a structural member. A level of loading that a structural member is designed to sustain with the appropriate partial safety factors against collapse, deflection or local damage.

NOTE. Direct measurement of capacity of a member to withstand such a load will not destroy the member under test unless this is inadequate for its envisaged purpose. (See **9.6** of CP 110 : Part 1 : 1972 for details of test loads and assessment of results.)

3.9 ultimate strength of a structural member. A measure of the maximum load that a member is capable of sustaining, the loading pattern being that applied in service.

NOTE. Direct measurement of the ultimate strength of a member results in destruction of that member, but in some cases it may be necessary to undertake such a test to assess the loadbearing capacity of similar members. (A suitable test method applicable to individual precast units is described in **9.5.3** of CP 110 : Part 1 : 1972.)

4. Planning an investigation

4.1 Information required from tests. A knowledge of in-situ strength of concrete in a structural member may be required for one or more of the following reasons.

(a) Doubt concerning the strength of concrete in the structure as a result of non-compliance of standard cube test results carried out in accordance with a specified compliance plan.

(b) Doubt concerning workmanship involved in batching, mixing, placing, compacting or curing of concrete.

(c) Deterioration of concrete due to:

overloading;
fatigue;
chemical action;
fire;
explosion;
weathering.

(d) To ascertain whether the in-situ strength of concrete is acceptable for:

the designed loading system;
the actual loading system;
a projected loading system for a new use.

Any structural investigation should be carefully planned and executed if the engineer is to obtain information which can be used to provide a reliable assessment of concrete strength in a structure. The detailed test programme will depend upon the reason for the investigation and whether:

(1) an estimate of the in-situ strength of concrete in a structural member is required;

(2) a comparison of the suspect concrete with satisfactory concrete in other parts of the structure is adequate;

(3) the investigation is required on the immediate surface, near to the surface, or in greater depth;

(4) additional information is required, e.g. uniformity and density of concrete and quality of materials used.

4.2 Acceptance of test data. Before any programme is commenced, it is desirable that there is complete agreement between the interested parties on the validity of the proposed testing procedure, the criteria for acceptance and the appointment of a person and/or laboratory to take responsibility for the testing.

4.3 Aspects of concrete strength. Table 1 provides a broad guide to various test methods to assess different aspects of the strength of concrete in the structure, or of a structural member.

4.4 Selecting a test programme

4.4.1 *General.* The test programme will be determined by the objectives of the investigation, the site conditions and economic factors, as outlined in **4.4.2** to **4.4.5**.

4.4.2 *Choice of test methods.* The relative merits and limitations of tests for various depths from the surface are summarized in table 2. The symbol **** indicates that the test compares well with other methods. The symbol * indicates that the test has disadvantages compared with others.

The particular test method used will depend upon the following.

(a) *Test location* (see also **3.5**). Factors to be considered include:

(1) position of suspect concrete in the member;

(2) position of highly stressed sections;

(3) variation of strength through depth of lift;

(4) position of reinforcement identified by the use of drawings or cover meter;

(5) need to avoid detrimental effect on reinforcement;

(6) presence of local defects that may influence test results.

(b) *Effect of damage.* The choice between destructive and non-destructive methods be influenced by the effect of:

(1) testing on the surface appearance of member;

(2) drilling of holes (e.g. in small columns or retaining walls);

(3) cutting of reinforcement.

(c) *Testing accuracy required.* This will depend upon the nature of the investigation and, often, upon the magnitude of the measured strength; if the measured strength is considerably higher than that required, precision may not be necessary. The level of accuracy that can be achieved will depend upon:

(1) test method;

(2) number of measurements;

(3) accuracy and reliability of available correlations (e.g. between pulse velocity and strength).

4.4.3 *Accuracy of estimates of in-situ strength.* Confidence with which it is possible to assess in-situ strength of concrete will increase with the number of assessments made. In the case of some tests (e.g. ultrasonic pulse velocity, surface hardness) little extra cost is incurred by obtaining a large number of test results. In other cases (e.g. core and gamma-ray testing) the cost of each test is appreciable. The decision on the number and type of tests to be made will, therefore, be based upon an assessment of the cost of obtaining a result of adequate reliability.

Benefit may be obtained by combining different testing techniques, e.g. combining pulse velocity measurements with core tests. Pulse velocity measurements on cores prior to crushing can increase the accuracy of strength estimates from pulse velocity measurements. The ease of taking a large number of pulse velocity measurements on structural components can provide a more comprehensive evaluation of the strength of a structure.

However, the most direct method of assessing in-situ strength of concrete in a structural element is by core tests.

Accuracy of estimates of in-situ strength, obtained from indirect non-destructive tests, will depend upon reliability of correlation between test method and core strengths. A combination of different test methods may be chosen for the following reasons:

(a) use of one method as a preliminary to another (e.g. use of ultrasonic methods to select areas from which to drill cores);

(b) use of a limited core investigation together with ultrasonic pulse velocity in order to establish a more accurate correlation for the particular site and permit a wider use of non-destructive methods;

(c) results from two or more different non-destructive methods can be used together to provide a more accurate assessment of strength;

(d) order of accuracy of different correlations between non-destructive tests and strength varies at different strength levels.

4.4.4 *Site conditions.* The site conditions that should be considered include:

(a) general site location, and ease of transport of test equipment;

(b) accessibility to suspect region on site;

(c) safety of personnel on site and general public, e.g. when gamma rays are used.

4.4.5 *Economics.* The test programme will be influenced by economic factors such as the value of the work and costs arising from:

(a) delays in construction whilst testing is conducted and decisions are made;

(b) delays in completion and hand-over;

(c) removal of defective concrete or strengthening of structure;

(d) different test methods;

(e) selection of an adequate number of tests for assessment.

5. Test methods

5.1 Core test

5.1.1 *General.* The most direct method of obtaining a value of the estimated cube strength is generally to drill cylindrical cores and test these in compression. Whenever possible, the cores should be drilled, prepared and tested in accordance with section 3 of BS 1881 : Part 4 : 1970, although this standard recommends alternative methods of treating the results. Detailed advice for core testing procedure is given in Technical Report No. 11 published by the Concrete Society (5).

5.1.2 *Selection of drilling points.* Each drilling point should be selected so that the core contains no steel parallel to its length and as little as possible perpendicular to its axis.

5.1.3 *Accuracy of test and number of cores.* The number of cores will depend upon the amount of information required, the required accuracy of strength estimates and the cost of drilling, preparing and testing the cores.

The accuracy of strength estimates depends upon the reproducibility of the test method and the number of cores tested. The strength estimated from a single core can be considered to lie (with 95 % confidence) within ± 12 % of the strength of the concrete at that location. The accuracy of the estimate is increased if more cores are taken at the same location. For n cores, the mean core strength can be considered to be accurate within $\pm 12/\sqrt{n}$ % of the strength at that location.

The degree of uncertainty that can be tolerated in the estimated in-situ strength will often depend upon the measured value of the in-situ strength when compared with the value that may be considered acceptable. If in-situ strength, based on the mean core strength, is found to be near the limit of acceptance, it may be necessary to drill further cores.

5.1.4 *Size of cores.* Before capping, a core should have a length at least 95 % of its diameter. When prepared for test, it should preferably have a length at least equal to its diameter and not exceeding 1.2 times its diameter. Cores of both 100 mm and 150 mm nominal diameter may be tested provided the nominal maximum aggregate size does not exceed 20 mm and 40 mm respectively. Whenever possible, however, 150 mm diameter cores should be drilled as less variability due to drilling and more reliable results are obtained, with the following exceptions:

(a) when reinforcement is congested, 100 mm diameter cores are less likely to contain pieces of steel;

(b) when it is necessary to restrict sampling to within a length of less than 150 mm.

It may sometimes be necessary to drill cores with a smaller diameter than 100 mm, e.g. if the section is less than 100 mm thick. Results of tests on such cores may be treated in the same way as those obtained on larger cores but the results may be less reliable, particularly if the maximum size of aggregate exceeds 30 % of the core diameter.

If circumstances dictate, a core may have a length of less than its diameter. Again, the result may be treated in a similar manner to results of tests on longer cores but the results may be less reliable; little reliance can be placed on results obtained on cores having a length/diameter ratio of less than 0.5.

5.1.5 *Core drilling.* Cores should be drilled by a skilled operator using well-maintained equipment complying with dimensional requirements of BS 4019 : Part 2.

While drilling work proceeds, a simple record of any observations likely to have a bearing on the validity in interpretation of core test results should be prepared.

5.1.6 *Treatment of cores prior to testing.* The laboratory should trim (see **3.1.5** of BS 1881 : Part 4 : 1970), examine and photograph each test core in accordance with instructions given by the engineer.

The ends of cores should preferably be ground to tolerances applicable to capped ends as given in BS 1881 : Part 3 or they may be capped with high-alumina cement mortar or a sulphur compound in accordance with **5.5.2** of the same British Standard.

5.1.7 *Core testing.* Each core should be measured in accordance with **3.1.4** of BS 1881 : Part 4 : 1970 to the nearest millimetre; its average cross-sectional area and its length/diameter ratio, λ, when prepared for test should be calculated.

The core should be tested in compression in accordance with **3.2** of BS 1881 : Part 4 : 1970, the mode of failure being noted and a sketch diagram made, if unusual. The maximum load sustained by the core should then be divided by its cross-sectional area to establish the *core strength* for the particular length/diameter ratio.

5.1.8 *Estimated in-situ cube strength*

(a) *Cores without steel.* The estimated cube strength can be obtained from the measured core strength by using the following equation (5):

$$\text{Estimated cube strength} = \frac{D}{1.5 + 1/\lambda} \times \text{core strength}$$

where

D = 2.5 for cores drilled horizontally (for precast units perpendicular to height when cast), or

D = 2.3 for cores drilled vertically (for precast units parallel to height when cast), and

λ is the length/diameter ratio

(b) *Cores with steel.* If in spite of efforts to obtain cores free of steel, they contain bars perpendicular to their axes, it becomes necessary to allow for the resulting reductions in core strength.

A convenient correction for the presence of a single bar can be made by multiplying the strength from the above formula by a factor of

$$1.0 + 1.5\, \phi_r d / \phi_c l$$

to give the estimated cubic strength

where

ϕ_r is the diameter of the reinforcement;

ϕ_c is the diameter of core;

d is the distance of axis of bar from nearer end of core;

l is the length of core

If the core contains two bars no further apart than the diameter of the larger bar, only the bar corresponding to the higher value of $\phi_r d$ need be considered. If the bars are further apart, their combined effect should be assessed by using the factor

$$1.0 + 1.5 \frac{\Sigma \phi_r d}{\phi_c l}$$

It should be noted that in-situ strengths estimated from the above formulae cannot be equated to standard cube strengths.

5.2 Ultrasonic pulse velocity test

5.2.1 *General.* Ultrasonic pulse velocity (UPV) test equipment measures the transit time of a pulse vibration through concrete. Provided the length of the pulse path between transducers of the equipment is known, the pulse velocity through the concrete can be established.

UPV tests do not provide a direct reading of concrete strength. It has been established however that pulse velocity bears a relationship to the quality of concrete. This relationship will vary according to details of the concrete mix, in particular the properties of aggregate.

The main virtue of the test, therefore, is that it provides a method of determining the variation in quality of concrete in different locations in one element, or in a series of elements, where the same mix has been used throughout.

Where the strength of concrete has been determined by other means and pulse velocities in the same samples have been determined, a correlation curve can be established for that particular mix. In these circumstances the ultrasonic pulse velocity test can be used to establish indirectly the strength of concrete, and particularly the variation in strength, throughout the elements under test.

For more detailed information see BS 4408 : Part 5.

5.2.2 *Selection of test location.* The direct transmission arrangement generally provides the most reliable measurement and should be used whenever possible. It is preferable to place transducers on smooth areas of the concrete surface, a moulded surface being generally more satisfactory than a floated or trowelled one.

It is preferable to choose locations so that the length of the pulse path is at least 150 mm. Considerably longer paths may be used but the longer the path the greater the possibility that small regions of suspect concrete will be undetected.

The presence of reinforcement can influence measurements since pulses travel faster through steel than through concrete. Measurements made on concrete containing steel will indicate higher velocities than in plain concrete since the pulses will be travelling partly in steel and partly in concrete. When the pulse runs in the same direction as the reinforcement, the pulse velocity is essentially that in the steel, which can be up to 50 % more than in concrete. BS 4408 : Part 5 shows how corrections can be made to allow for steel but these are approximate and the accuracy of the estimated pulse velocity of the concrete is reduced.

The effect of steel on the measurement of the pulse velocity is negligible if the pulse transmission is at right angles to the direction of the steel. Locations where reinforcement lies directly along or close to the pulse path should be avoided. To satisfy this, it may be necessary to choose some of the pulse paths using the semi-direct transmission measurement, where the transducers are placed on adjacent faces of concrete instead of the opposite faces used in the direct transmission measurement.

5.2.3 *Number of tests.* Ultrasonic test equipment permits transit times to be measured with considerable accuracy provided that the path length is not less than 150 mm and not so long that the transmitted pulse is unduly attenuated. Accuracy of the calculated pulse velocity also depends upon the accuracy with which the path length can be measured. There is little advantage in taking more than one reading at any single location (although this may usefully be checked) because accuracy of the pulse velocity will not be increased to any significant extent. The more effective procedure is to measure velocities at a number of locations over the member or structure to facilitate plotting of 'velocity contours'. The number of locations will depend upon the detail required but it will usually be best to test at least 40 locations on any one structural element, this being practicable because the test can be carried out rapidly and is non-destructive.

5.2.4 *Execution of tests.* Positions chosen for test locations should be marked out accurately on the surface of the concrete, which should be cleaned so as to be free from grit and dust. Path lengths should be determined to within an accuracy of ± 1 % and a suitable couplant should be applied to each of the test points.

Pulse transit times should be measured by a skilled operator using apparatus in accordance with BS 4408 : Part 5, which requires an accuracy of measurement of not less than ± 1 %. It is important that good acoustic coupling is established between transducers and concrete surface for each test.

Test results should be examined and any unusual reading should be repeated carefully to verify or amend the reading as necessary.

5.2.5 *Estimated in-situ cube strength.* A reliable estimate of in-situ strength can only be obtained if correlation between cube crushing strength and pulse velocity is known for the particular concrete mix used in the condition in which it exists in the structure. The correlation can be obtained from tests on works cubes or from suitable beams made from the same concrete mix. It is advisable to carry out tests on at least 30 cubes or beams over a wide range of strengths. A suitable range of strength may be obtained by varying the water/cement ratio of the mix or the age of test. The correlation is influenced by moisture conditions of the concrete and, if this is substantially different from that of the in-situ concrete, an appropriate allowance should be made.

Accuracy of values of estimated in-situ strength depends mainly upon the validity of an assumed correlation between in-situ strength and pulse velocity rather than the number of results. Accuracy of the estimated in-situ cube strength of a concrete at a single location can be of the order of ± 20 % but only if a correlation curve is available for that particular concrete.

If a correlation curve for the particular concrete is not available, a value of the estimated cube strength may be obtained by combining ultrasonic and core tests in order to obtain a correlation between core strength and pulse velocity in the cores. This correlation is likely to be based on only a few core test results with a limited strength range and accuracy of the estimated cube strength is reduced accordingly.

5.3 Gamma ray test. The method of testing concrete by means of gamma radiography (BS 4408 : Part 3) is not considered suitable for strength assessment. This method gives useful information on density variations and location of reinforcement as well as the efficiency with which ducts are grouted. As this test is not recommended for strength assessment, no further information is given in this standard.

5.4 Near-to-surface tests. In recent years, a number of tests have been developed that provide a measure of the in-situ strength of concrete near to the surface (4). The results of such tests should be viewed with caution for larger elements, or in circumstances where the compaction of the original mix was such as to produce a hard 'skin' on the surface of the element under consideration.
The methods include those outlined in **5.4.1** to **5.4.3**.

5.4.1 *Pull-out tests*

(a) Based on measurements of the force required to pull out special assemblies whose enlarged end has been cast into concrete. (See Malhotra and Carette (8); Kierkagaard-Hansen and Bickley (9).)

(b) Based on measurements of the force required to pull out bolts, fitted either with split-sleeve expanding assemblies or epoxy resin into holes drilled in hardened concrete. (See Chabowski and Bryden-Smith (1, 2); Maillhot et al (10).)

5.4.2 *Break-off test.* Based on direct measurements of the flexural strength of concrete in an annular cross section parallel to, and at a definite distance from, the concrete surface. (See Johansen (11).)

5.4.3 *Penetration test.* Based on measurements of the resistance of concrete to penetration by a hardened alloy probe fired into the surface.*

5.4.4 *Use of tests.* Experience with many of these methods so far is limited. Some of the tests have to be pre-planned with assemblies or disposable forms being placed in the formwork before casting. Others require more development to reduce the within-test variation to acceptable limits.

Whenever these or similar tests are used, it is recommended that the equipment, procedure and number of tests are fully described and the accuracy and reliability of the correlation between test measurement and in-situ cube strength clearly defined. This is demonstrated in **5.5** for the internal fracture test developed by the Building Research Establishment (1, 2) to assist in the structural appraisal of high-alumina cement concrete structures.

5.5 Internal fracture test

5.5.1 *General.* This test was introduced in 1976 and thus experience to date is small. The test is sometimes called 'pull-out' test but it is quite distinct from that described in references (3), (8) and (9).

It should be emphasized that the internal fracture test provides information on the strength of concrete at or near the surface of an element only

5.5.2 *Selection of test locations.* The test involves drilling holes 6 mm in diameter and 30 mm to 35 mm deep, in the surface of concrete. Conduct of the test may spall the concrete, leaving a shallow hole on the surface that can be some 50 mm across. Location of testing points should, therefore, be planned with an appreciation that the surface may be damaged. Holes should not be drilled at any point on the surface within 50 mm of an arris or any other discontinuity, or within 100 mm of another testing point or within 25 mm of reinforcement unless the cover is more than 25 mm.

Correlation between the test result and the strength of concrete may be influenced by compressive strain on the concrete and so it may be preferable to test concrete in regions where compressive stresses are low. Selected test locations should permit adequate access and space for purposes of conducting the test.

5.5.3 *Number of tests.* Six valid internal fracture tests are needed to obtain a mean value for one location. This mean value based upon six tests is likely to be accurate, with 95 % confidence, within ± 30 %.

5.5.4 *Testing procedure.* The method of test should be strictly in accordance with recommendations of the Building Research Establishment (1, 2). Each test result should be recorded as the maximum reading indicated on a torque meter.

5.5.5 *Estimated in-situ cube strength.* Data available suggests that the estimated cube strength, in N/mm², of concrete made with 20 mm maximum size gravel or limestone aggregate and ordinary Portland cement may be estimated by applying the following formula to the mean torque of six or more tests in one location.

$$\text{Estimated cube strength} = 3.74\,T^{1.55}\ \text{N/mm}^2$$

where T is the torque, in N m.

For other types of concrete (and, preferably, for those described above) it is recommended that, if possible, correlation between cube strength and torque should be established by tests on samples of the concrete being examined.

5.6 Surface hardness test

5.6.1 *General.* Surface hardness tests, which include rebound and indentation methods, provide only an approximate indication of strength and are discussed in detail in BS 4408 : Part 4. Their application is generally limited to tests on concrete with ages between about 3 days and 3 months. Concrete younger than 3 to 7 days may be damaged by what is essentially a non-destructive test while concrete older than 3 months is likely to have suffered carbonation at the surface. This can increase surface hardness unduly and give rise to considerable errors in assessing the estimated cube strength.

5.6.2 *Selection of test location.* Smooth and dry surfaces should be selected as test locations. Wherever possible surfaces to be selected should have been formed by shuttering. Free trowelled surfaces could however be used if necessary, although less reliance has to be placed on the results unless surfaces are ground before testing. Open-textured or honeycombed areas have to be avoided.

The points chosen for tests should be at least 20 mm away from an edge or sharp discontinuity and should be not less than 20 mm from each other.

Presence of reinforcement does not normally influence test results so that choice of test location should not be affected by the position of steel bars in concrete.

Usual directions of test are either horizontal or vertically down but any direction may be used provided this is measured and taken into account in interpreting test results.

*See ASTM C803-79 (12). The method is generally known as the Windsor probe test.

5.6.3 *Number of tests.* Surface hardness tests are similar to pulse velocity tests in that they are essentially non-destructive (although the concrete surface is marked) and accuracy of estimated in-situ cube strength depends upon the validity of the assumed correlation between in-situ strength and test results. Unlike the pulse velocity test, however, repeat tests within one location vary significantly with random high and low results. Provided at least 10 readings are taken in any one location (preferably an area not more than 300 mm square) the mean reading is likely to be accurate within $\pm 15/\sqrt{n}$ % with 95 % confidence, where n is the number of individual readings.

5.6.4 *Execution of tests.* Tests should be made with a suitable device (rebound hammer or indentation device of an appropriate size) and its correct functioning should be checked.

Tests should be made at each location in a systematic way by choosing points on the concrete surface at intersections of a regular grid of lines 20 mm to 50 mm apart.

The mean of all readings taken at each test location should be calculated using all readings (including abnormally high and low values).

5.6.5 *Estimated in-situ cube strength.* A reliable estimate of in-situ strength can only be obtained if correlation between hardness reading and cube strength is known for the particular concrete mix used. A correlation may be obtained on cubes (preferably 150 mm size) of the particular mix under test over a range of strengths. Details of the execution of correlation tests are given in BS 4408 : Part 4.

By using a correlation curve obtained in this way, it is possible to estimate the strength of concrete near the surface to an accuracy of within ± 20 % provided the concrete is not more than about 3 months old.

However, this degree of accuracy may be significantly reduced if the condition of in-situ concrete is different from that of concrete used for the correlation tests, since curing conditions and surface moisture conditions can influence correlation considerably.

6. Conducting an investigation

6.1 General. Having taken account of the various factors outlined in clause 4 in the determination and execution of a suitable test programme, the subsequent interpretation of test results and decisions regarding any future action will depend upon:

(a) the inherent variations in in-situ strength;

(b) the location and number of test results;

(c) interpretation of results;

(d) potential courses of action;

6.2 Inherent variations in in-situ strength. Tests on in-situ concrete (5, 6, 7) indicate the following.

(a) In-situ strength can vary within a structural member both randomly and, often, in an ordered fashion.

(b) The magnitude of variations of in-situ strength within structural members varies from one member to another in a random fashion.

(c) With height of a concrete lift, in-situ strength decreases towards the top of a lift, even for slabs, and can be 25 % less at the top than in the body of the concrete. Concrete of lower strength is often concentrated in the top 300 mm or 20 % of the depth, whichever is the less.

(d) At 28 days after casting, columns can have a mean in-situ strength of 65 % of the mean standard cube strength, with strength in the individual columns carrying from 50 % to 80 % (7). The little evidence available for floor slabs suggests that mean in-situ strength may only be 50 % of the mean standard cube strength.

(e) The gain in in-situ strength from 28 days onwards is not consistent. At 6 months, the increase in mean strength can vary from 0 to 25 % and at one year from 0 to 35 % of the 28 day strength.

Thus, the normal variation of an in-situ strength within and between structural members has to be borne in mind when evaluating in-situ results. Examination of individual test results will identify whether variations between results are excessive. Further tests may be required to establish whether certain results are rogue values or not.

6.3 Relationships between compressive strengths. Figure 1 illustrates numerical differences of the various strengths as defined. The strengths given are based on typical situations, using average constants and rounding to the nearest N/mm^2. The hatched areas show the surfaces through which the specimen is tested. A standard cube is tested on a surface obtained from a machined plate whereas, in the case of standard cylinders and cores, the specimen is tested on a bedded or ground surface.

The strength of this single batch of concrete as measured by a *standard cube strength* is 30 N/mm^2. If the strength is measured on a cylindrical test specimen the most likely value of the *cylinder strength* is 24 N/mm^2.

If this single batch of concrete is now cast into a structural member such as a column its strength will be less, owing to factors such as compaction and curing, and will vary depending on its position in the column (see **6.1**). For example, if cores were cut near the top and the base of the column, the *core strength* ($\lambda = 1$) could be 20 N/mm^2 and 23 N/mm^2 respectively. The same values of 20 N/mm^2 and 23 N/mm^2 would apply to the *estimated in-situ cube strengths.* If the length/diameter ratio differs from 1, the formulae in **5.1.8** should be used.

6.4 Location and number of test results

6.4.1 *Tests at a single location.* The in-situ cube strength at a single location may be estimated by calculating the average of a number of individual test results. Any variation between individual results has to be assumed to stem from testing errors rather than from variations in the quality of the concrete being tested. If results do not support this assumption, the situation should be reappraised and the results taken as coming from more than one location.

6.4.2 *Tests at a number of locations.* The number of measurements should be sufficient to enable variations in the quality of the concrete to be identified and defined. Once this has been done, it will often be necessary to conduct further tests on regions where the concrete strength is relatively low, possibly using a different type of test. The results of such further tests should be treated as being from a single location.

6.4.3 *Typical test programmes.* The object of most investigations will be to establish, for a particular structural element, the in-situ strength at:

(a) any critical design sections;

(b) the region having the lowest in-situ strength;

(c) any other location of interest.

These aims can be achieved by:

(1) making a visual survey;

(2) making a general scan of the structural element, using a non-destructive technique such as ultrasonic pulse or surface hardness tests (or preferably both);

(3) making a more detailed local survey, both at the critical section and at the location exhibiting the weakest concrete; this should involve non-destructive methods and in-situ strength tests such as cores, internal fracture, pull-out or break-off tests.

6.5 Interpretation of results

6.5.1 *General.* Since there are many different reasons for making an investigation into in-situ strength of concrete, it is possible to give only general guidance on interpretation of estimates of the in-situ strength of concrete in a structural element.

6.5.2 *Relationship between standard cube strength, design strength and estimated in-situ cube strength.* Design of reinforced and prestressed concrete structures is based on the commonly accepted principle that concrete can be considered as a randomly variable material, the test results of which follow a normal distribution. Inevitable differences between in-situ strength of concrete and that of standard cubes mean that there will be different distributions of results from large numbers of in-situ tests compared with standard cube tests on the same concrete. In design, these differences are taken into account by the introduction of the partial safety factor for strength γ_m.

Figure 2 shows the relationships between standard cube strength, design strength and estimated in-situ cube strength. The standard cube strength is obtained from specimens compacted, cured and tested in a standard way at one particular age.

An estimate of the characteristic strength f_{cu} can be determined from the distribution of a large number of standard cube results using the expression

$$f_{cu} = \text{mean concrete cube strength} - 1.64 \times \text{standard deviation}$$

or assumed to be equal to, or greater than, the specified strength grade, provided the test results comply with the appropriate compliance requirements as given in **6.8.2** of CP 110 : Part 1 : 1972 or **16.2** of BS 5328 : 1976.

For the analysis of sections, the design strength is given by f_{cu}/γ_m, where, for CP 110, $\gamma_m = 1.5$ for ultimate strength.

For any particular element in a structure the *design stress* may differ from the *design strength* depending on the design philosophy adopted (see also **3.7**).

The in-situ strength of concrete in a structural element has to be found from the in-situ test programme. Owing to the limitations of in-situ testing, an accurate estimate of the distribution of in-situ strengths is rarely possible. However, by identifying the critical design section and/or the location of the weakest concrete, it is possible to take measurements at these locations and, with appropriate correlation curves, obtain estimates of the corresponding mean estimated in-situ cube strengths at those locations. The accuracy of these estimates will depend upon the number of test measurements and the reproducibility of the test method (see **5.1.2**, **5.2.2**, **5.5.2** and **5.6.2**).

6.5.3 *Comparisons between estimated in-situ cube strength and design strength.* To ensure structural safety in accordance with design principles of section 2 of CP 110 : Part 1 : 1972, it is recommended that a check should be made to ensure that the estimated in-situ cube strength, obtained from methods described in clause **5**, is acceptable on the basis of comparisons with design strength at:

(a) the critical design sections;

(b) the locations identified with low strength concrete;

(c) any other location of interest.

The level of in-situ cube strength that may be considered acceptable in any particular case is a matter for engineering judgement but should not normally be less than 1.2 times the design strength.

The particular strength level selected should include an allowance for possible future deterioration of the strength of concrete that may result from chemical attack, weathering, vibration or some unforeseeable impact or other circumstances.

Thus in cases where the design strength is based on $\gamma_m = 1.5$, the following equation should assist in the use of the tables given in CP 110:

$$f_{cu} = 1.5\ \frac{\text{Estimated in-situ cube strength}}{\text{1.2 (or other appropriate factor considered suitable in particular circumstances)}}$$

6.6 Courses of action. Action to be taken in respect of a structural member in which the in-situ concrete is considered to fall below the level required has to be determined by the engineer. This may range from qualified acceptance in less severe cases to some form of remedial work, or to removal and replacement in the most severe cases. Alternatively, load tests may be carried out in accordance with **9.6** of CP 110 : Part 1 : 1972.

In determining the action to be taken, the engineer should have due regard to the technical and economic consequences of alternative remedial measures either to replace the substandard concrete or to ensure the integrity of the structural element from which it has been made. Other factors that should be taken into account include:

(a) the actual load on the structural element in comparison with the design strength and the appropriate partial safety factor;

(b) possible effects of any reduction in quality on the strength and durability of the particular structural element;

(c) the influence of age on the strength of the in-situ concrete.

Appendix A

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Table 1. Guide to tests for assessing aspects of concrete strength

Aspect of strength		Test method				
		Concrete			Structural member	
		Cast cube	Non-destructive test	Core	Load test	Ultimate load test
Concrete	Standard cube strength	Direct	Very indirect	Indirect	Very indirect	Very indirect
	In-situ strength	Indirect	Indirect	Fairly direct	Indirect	Indirect
Structural member	Design load capability	Very indirect	Very indirect	Indirect	Direct	Direct
	Ultimate strength	Very indirect	Very indirect	Indirect	Indirect	Direct

Table 2. Relative merits and limitations of various tests

Region tested	Test	Reference	Accuracy of strength estimate	Speed of test	Ease of test	Economy of test	Lack of damage to structure
In depth	Core test	BS 1881 : Part 4	****	**	**	*	*
	Ultrasonic pulse	BS 4408 : Part 5	**	***	***	***	****
	γ ray	BS 4408 : Part 3	See 5.3				
Near to surface	Internal fracture	(1, 2)	Insufficient experience available at present				
	Pull-out	(8, 9, 10)	Insufficient UK experience available at present. Some pull-out tests (e.g. reference (8) and (9)) generally not applicable unless bolt cast in at time of construction.				
	Break-off	(11)					
	Penetration resistance	(12)					
Immediate surface	Surface hardness	BS 4408 : Part 4	*	***	****	****	***

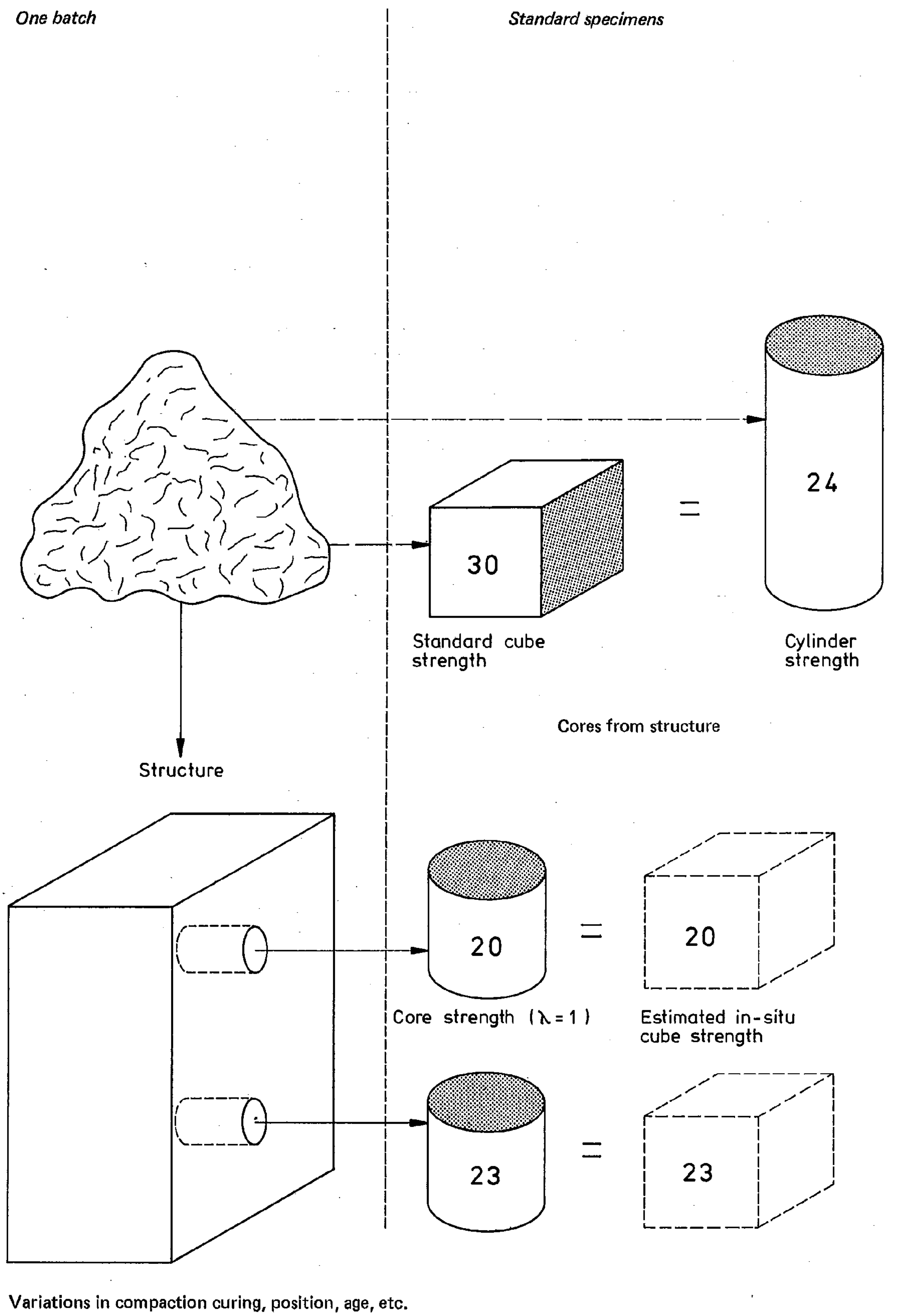

Figure 1. Illustration of approximate relationship of compressive strengths

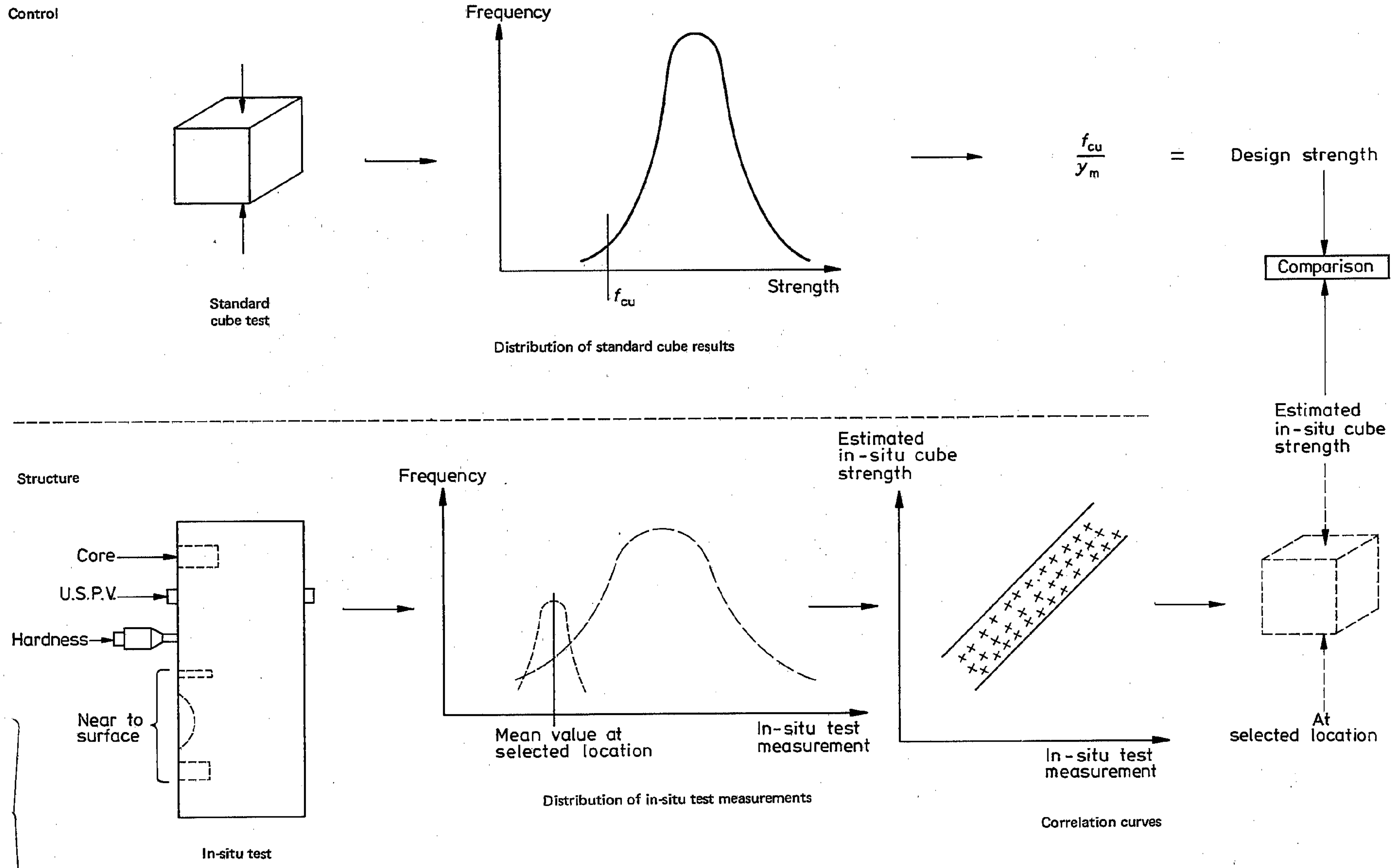

Figure 2. Comparisons between design strength and estimated in-situ cube strength

Standards publications referred to

BS 1881 Methods of testing concrete
Part 1 Methods of sampling fresh concrete
Part 3 Methods of making and curing test specimens
Part 4 Methods of testing concrete for strength
Part 5 Methods of testing hardened concrete for other than strength

BS 4019 Specification for core drilling equipment
Part 2 Concrete drilling equipment

BS 4408 Recommendations for non-destructive methods of test for concrete
Part 3 Gamma radiography of concrete
Part 4 Surface hardness methods
Part 5 Measurement of the velocity of ultrasonic pulses in concrete

CP 110 The structural use of concrete
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