Concrete Society Technical Report No. 11
May 1976

Concrete core testing for strength

Report of a Concrete Society Working Party

Summary

This report provides recommended procedures for obtaining and the compressive testing of concrete cores and for the interpretation of the results. Evidence from practice and research is provided for the formulae and conversion factors recommended.

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5 November 1986

Dear Sir

'Concrete Core Testing for Strength'
Concrete Society Technical Report No. 11. No. 51.071.

With reference to your letter regarding the above publication, the copy you have at the moment is current. The Publication has not been revised since 1976.

Miss S Roach
Publications

With the compliments of the Communications Directorate

Inward No 2805
Date 14/11/86
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*The index on page 6 constitutes the detailed contents of Part 3.

Concrete core testing for strength

Part 1. Scope

The aim of this report is to recommend procedures to be followed when drilling and testing cores to assess the strength of concrete in pavements, in situ structures and precast units. The procedures are designed, on evidence from practice and research, primarily for concretes made with Portland cements and natural aggregates and for cores sampled, treated and tested to BS 1881 : Part 4 : 1970.

The conversion factors given in the report are considered to be applicable generally to concretes containing admixtures, but should be used with more caution for concretes which:

1 contain lightweight or artificial aggregates;
2 contain cements other than Portland; [illegible]
have extreme values for mix proportions;
4 are inadequately compacted;
have been subjected to unusual, variable or extreme conditions;
have deteriorated.

These cautions apply more to estimations of Potential Strength than to estimations of Actual Strength.

Definitions

The quality of concrete, as assessed by making and testing cubes in accordance with BS 1881, is different from that of concrete in an in situ element, a pavement or a precast unit. There are many reasons for this, among them being that the methods of compacting the cubes and storing them until they are tested differ from the treatment given to the remainder of the concrete.

In this report, the following terms are used for compressive strength relating to 'potential' or 'actual' quality of concrete. All except No. 4, Core Strength, are cube strengths or equivalent cube strengths.

1. *Standard Cube Strength*
   The compressive strength of a cube sampled, moulded and tested as defined in BS 1881 : 1970.

2. *Potential Strength*
   The notional strength of concrete considered as the average Standard Cube Strength at 28 days for a single batch of concrete moulded wholly as standard cubes.

3. *Estimated Potential Strength*
   An estimate of Potential Strength from a limited number of standard cubes or cores.

4. *Core Strength*
   The 'measured compressive strength' of a core as defined in BS 1881 : Part 4 : 1970, clause 3.3.

5. *Actual Strength*
   The notional strength of concrete at a single location, considered as the strength of a cube of the concrete as it exists in the structure.

6. *Estimated Actual Strength*
   An estimate of Actual Strength from the test of a core drilled from the structure.

Part 2. Introduction

The reasoning behind the procedures

The reasons for drilling cores for strength tests are commonly to assess one or a combination of the following.

(1) The quality of the concrete provided to the construction (Potential Strength).
(2) The quality of concrete in the construction (Actual Strength).
(3) The load factor of a structure to carry:
    (a) the actual loading system;
    (b) the designed loading system;
    (c) a projected loading system for a new use.
(4) Deterioration in the structure due to:
    (a) overloading;
    (b) fatigue;
    (c) chemical reaction;
    (d) fire or explosion;
    (e) weathering.

For purpose (3), an estimate of the Actual Strength provides a measure of strength of the concrete at a particular location which can be applied in structural calculations.

For purpose (4), values of Actual Strengths from cores drilled from affected and unaffected locations may enable assessments to be made of the degree and extent of deterioration.

For some of these purposes, the use of cores may not provide the most accurate means of assessing the quality concerned, but may be the most economic and practical method available. A simplified approach to the order of tests for different purposes is shown in Table 1.

It is obviously preferable to use a primary test, i.e. one correlating most directly with the strength aspect under review, whenever economic and practicable. It is unfortunate that, although an ultimate load test of a structure provides an accurate measurement of its strength, it also removes the structure, and proves an uneconomic method. On the other hand, the further removed the test method is from the property of interest, the less reliable the information will be. Thus, the standard cube, as a tertiary test, supplies relatively little information about the behaviour of the structural element.

Concrete cores, although a primary means for assessing concrete strength in the structure, are unfortunately relegated to a secondary position for assessing the strength of the standard moulded cube. However, when standard cube test results are not available or their validity is doubted, the core test may assist in finding answers to the two questions:

(a) is the structural element of adequate strength?
(b) was concrete complying with the specification supplied to the construction?

and may allow some distinctions to be made between effects of external conditions, site workmanship and the concrete supplied to the construction.

Non-destructive test methods

Two methods in general use, ultrasonic and rebound-hammer testing, can be useful in supplementing core testing by

(1) locating areas of potential weakness or variability;
(2) enabling areas between core locations to be surveyed, thus reducing the number of cores required for large areas or volumes of concrete.

The use of either method to assess strength, without specific correlation with relevant cube or core strengths, is deprecated. It can be seen from Table 1 that they are, at best, secondary or tertiary methods since they do not measure strength directly.

For assessment of deterioration, non-destructive tests can be used for detailed surveys or for continuous monitoring.

In addition, the covermeter is particularly useful for avoiding steel when coring. Gamma radiography, although not in general use, owing to the special safety requirements necessary, may be used to locate honeycombed areas and reinforcement at greater depths.

Background to the two procedures

Two procedures are provided in Part 3, one for estimating Actual Strength and one for Potential Strength. The appropriate locations for coring a structure will usually differ for the two purposes. For example, for Actual Strength it may

Table 1 Simplified order of test methods for different aspects of strength.

Aspect of strength	Test method Ultimate load test	Load test	Core	Moulded cube	Non-destructive test
Ultimate strength of structural member	Primary	Secondary	Secondary	Tertiary	Tertiary
Loading capacity of structural member	Primary	Primary	Secondary	Tertiary	Tertiary
Concrete strength in structural member	Secondary	Secondary	Primary	Secondary	Secondary
Standard moulded concrete cube strength	Tertiary	Tertiary	Secondary	Primary	Tertiary

be relevant to core at a location of poorly cured or compacted concrete, whereas for Potential Strength it is essential to core from concrete representative of a batch.

Although the separate procedures will produce the most reliable information for each purpose, this does not imply that it will always be necessary to cut cores for both purposes. For example, if Potential Strengths estimated by the recommended procedure pass the compliance requirements of the specification, it would usually be unnecessary to take further cores to check Actual Strength. Similarly, if Actual Strengths are acceptable to the engineer, it may be deemed unnecessary to pursue Potential Strength.

A single core provides a single estimate of Actual or Potential Strength only in the immediate vicinity of the core. A number of cores are needed to provide a reliable average value for assessing Potential or Actual Strength.

Obviously, a large number of cores taken for any situation will increase accuracy but in many instances, when delays are not critical, when there is no criticality of the structural element or when division of responsibility is not necessary, a small number may be accepted. If doubt persists, additional cores can be cut and tested within a few days.

The recommendations are based on the concept of compromise between reasonable accuracy and cost, for a wide spectrum of circumstances where the cost implications of acceptance of low strength or rejection of satisfactory strength in a structural element may be several orders of magnitude greater than the cost of core testing.

Conversion factors

The Core Strength and an estimate of Actual Strength at the age of extracting a core can be obtained with reasonable accuracy in many instances. Translation of a value forward or backward in time reduces the accuracy, because the Core Strength may vary with age owing to cement characteristics, maturity, moisture history, internal movements, stressing due to load and any aggressive environment, such that cores A, B, C and D in Figure 1 may have different strengths which bear no simple relation to each other. Potential Strength estimated back in time from core A will be more reliable than from core D and may be similar to Standard Cube Strength, provided allowance can be made for the factors which have affected the concrete in the structure differently from the same concrete in a standard cube.

To enable the most accurate values to be calculated for Actual and Potential Strengths, it is necessary to have either

(a) a range of conversion factors from which a selection can be made of the most appropriate ones for the particular circumstance; or

(b) average values for conversion factors which will suit most circumstances.

In some cases, where a significant influence can be readily quantified, e.g. the length/diameter ratio for a core, it is possible to provide a range of conversion factors. In other cases, where measurements are likely to be unavailable or difficult to assess, e.g. moisture history of concrete, method (b) has to be used. Both methods have been used for the procedures given in Part 3, and all factors are based on the comprehensive analysis of data from practice and research provided in Part 5.

It will be noted that the process of conversion in Part 3 differs from that given in BS 1881 by removing the unnecessary transition stage of first converting the Core Strength to a cylinder strength before conversion to a cube strength. The recommended procedure also allows for the influence of reinforcement, drilling damage, direction of drilling, curing and the age of testing in addition to influences of size and shape. Recommendations for drilling locations and sizes of cores are made to minimize the effects of variation due to some of these factors.

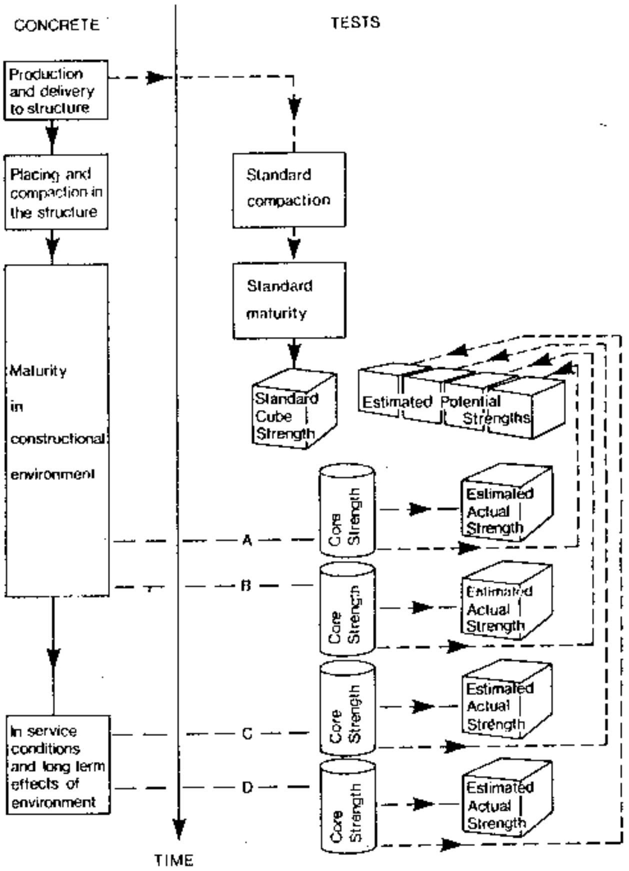


Figure 1: Illustration of the relationship in time between Standard Cube Strength, Core Strengths, Actual Strengths and Potential Strengths at a single location in a structure.

Use of estimated values

Figure 2 illustrates the procedures for a case where it has been necessary to cut cores in different locations to assess both structural integrity and compliance of the concrete with the specification, where CP 110 provides the criteria for judgement.

Estimated Actual Strengths can be compared, as an average or individually, with structural criteria and to assess effect of environment or workmanship. The average Estimated Potential Strength for the batch can be compared with specification compliance criteria for Standard Cube Strength.

A worked example, demonstrating the use of the procedures in a practical situation, is provided in Appendix 5 to Part 3.

Typically, Estimated Actual Strength is numerically less than the 'estimated cube strength' calculated to BS 1881 : 1970 from the Core Strength whereas the Estimated Potential Strength is higher.

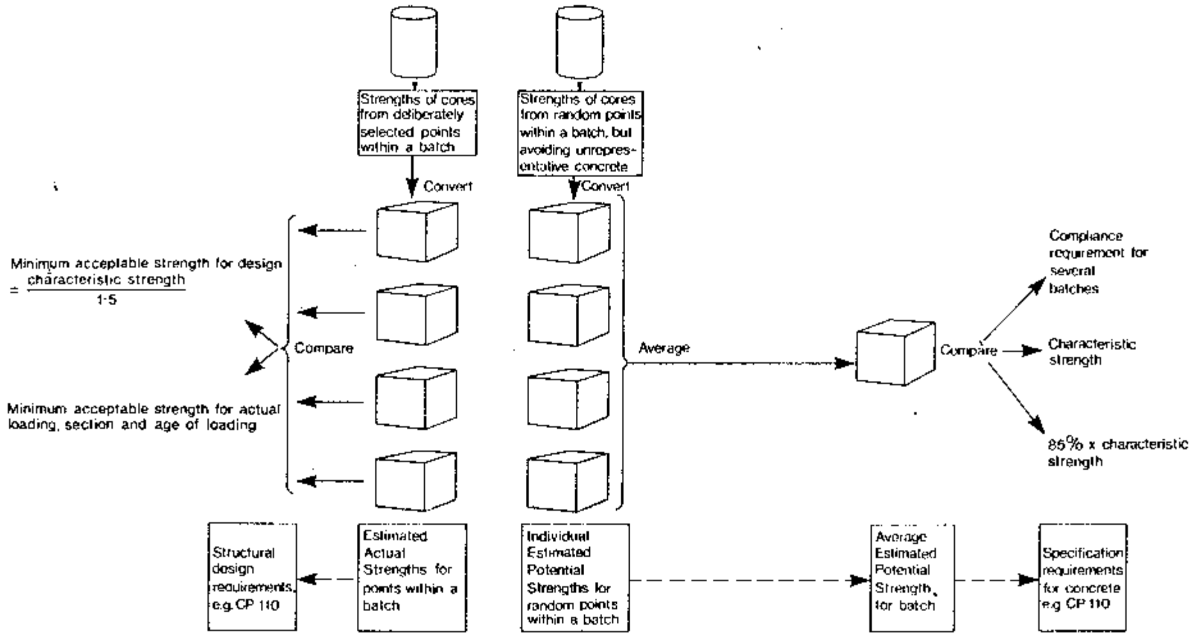


Figure 2: Illustration of the procedures for assessing Actual and Potential Strengths, where CP 110 provides the criteria for judgement.

BS 1881 : 1970

BS 1881 : 1970 provides a basis for core testing from the stage of receiving a core at the laboratory up to the determination of the Core Strength. However, it does not provide sufficient guidance on the location and extraction of cores or a sound basis for conversion to Actual or to Potential Strength.

The term 'estimated cube strength' in BS 1881 : 1970 is considered to be misleading and has been taken erroneously in practice to imply equivalence with the strength of a cube sampled, made, cured and tested to Parts 1, 3 and 4 of the Standard for moulded specimens.

It is recommended that measurement of concrete density and the restriction of the ratio of length to diameter of a core after capping to 1–1·2 should be made mandatory requirements for core testing in the next revision of BS 1881, and that sawing of plane ends before capping should be included as a recommended practice. Specific guidance, as supplied now for cube testing, is required in relation to mode of core failure in the strength test.

Other uses for cores

Although this report is concerned specifically with concrete core testing for strength, there are many other uses for cores. A list of such uses is provided in Part 4. Some of these other uses may aid interpretation of core strengths. It is possible that detailed guidance on them may be merited in the future.

Part 3. Procedures for obtaining and compressive testing of cores, and interpreting the results

Index

Clauses relating to Actual Strength only and to Potential Strength only are shown respectively on the left- and right-hand sides of a page and have the prefixes A/ and P/ respectively. All strengths in Part 3 are cube strengths or their equivalent, except for the measured Core Strength. Thus Actual Strength and Potential Strength are equivalent cube strengths.

To aid users of the Procedures, key aspects have been boxed or **printed in bolder type.**

3.1 Making the decision to drill cores

3.1.1 General

Before deciding to drill cores for compressive testing, it is essential that full consideration be given to the necessity for the test, its aims and the value of the results which will be obtained. The consideration will generally hinge on whether it is required to establish the serviceability of a structural element from an assessment of the strength of the concrete in it (Actual Strength), or to estimate the strength of the concrete provided for the manufacture of the element (Potential Strength) and normally expressed as the average strength of a number of cubes sampled, cast and tested in accordance with BS 1881.

Either situation may arise when a cube test result is deemed not to comply with a given specified value. CP 110 advises on the necessity of checking the validity of the result as the first action. Three possible situations then arise.

(1) Where, on investigation, all the parties having a direct professional or commercial interest in the matter (the Parties) are agreed that the test result is valid, further testing is not normally justified and subsequent action is best based on a consideration of the magnitude of the result.

(2) Where the Parties are agreed that some testing deficiency or deficiencies have been present, the test result should be rejected and further consideration of the true potential quality of that batch of concrete is not normally justified. If, however, the location of the concrete is judged critical by the engineer responsible for the performance of the structure, he may deem it necessary to obtain a valid assessment of the Actual or Potential Strength and will be obliged to resort to the interpretation of the results of some test or tests of the quality of the concrete in the work. The conclusions drawn in such cases should not, however, be regarded as proof of non-compliance on the part of the concrete producer.

(3) Where the Parties disagree regarding the validity of the cube test result, a proposal to make a second estimate of the Potential Strength of the concrete may be seen as an acceptable form of arbitration. In this situation, it is essential that the methods of test and interpretation of the results be agreed by the Parties *before* proceeding, otherwise the disagreement may become extended to the second estimate of Potential Strength and little has been gained.

In many cases the method used for estimating the Actual Strength or Potential Strength will be the core test. This part of the report recommends Procedures for the taking and testing of cores, and interpretation of the results such that the Actual Strength or the Potential Strength may be obtained with agreement, item by item, between the Parties.

It is seldom possible to obtain valid and fully appropriate estimates of both Actual and Potential Strengths from the same cores. Hence, the special conditions appropriate to the two approaches should be appraised by using the Procedure given in 3.1.2 before taking further action.

ACTUAL STRENGTH (Clauses A/...)

3.1.2 Procedure

A/3.1.2.1 Definition

Estimated Actual Strength is defined as the strength of concrete sampled from an element and tested in accordance with this Procedure such that the result, expressed as an equivalent cube strength, is an estimate of the concrete strength as it exists at the sampling location, without correction for the effect of curing history, age or degree of compaction.

POTENTIAL STRENGTH (Clauses P/...)

P/3.1.2.1 Definition

Estimated Potential Strength is defined as the strength of concrete sampled from an element and tested in accordance with this Procedure such that the result is an estimate of the strength of the concrete provided for the manufacture of the element expressed as the 28 day BS 1881 cube strength, allowance being made for differences in curing history, age and degree of compaction between core and BS 1881 cube.

A/3.1.2.2 General

The core test is used for the estimation of Actual Strength when the values obtained will enable the serviceability of the element sampled to be assessed and where other forms of test, which may be more convenient, comprehensive, faster, cheaper or less damaging to the appearance or performance, are deemed unacceptable for reasons of inaccuracy.

Reasons for requiring an estimate of Actual Strength may range from fire or other damage, to failure to test concrete in a critical location or the use of an unknown or suspect grade of concrete. Resolution of a dispute regarding the validity of cube test results, however, requires the estimation of Potential Strength.

The Actual Strength depends upon the quality of the concrete provided for the manufacture of the element plus the quality of workmanship and subsequent history.

Interpretation of the estimate, regarding serviceability of the element containing the concrete, will depend upon the design philosophy involved.

A/3.1.2.3 Preliminaries

If workmanship or subsequent history are suspect or if standard cube test results are not available, core testing for estimating Actual Strength of the concrete is appropriate. However, when the Standard Cube Strength is known for the batch or may be reasonably inferred, and if the workmanship and subsequent history are deemed acceptable, the element may be assessed by the following recommended procedure; on the basis of this assessment it may be deemed unnecessary to proceed with the estimation of Actual Strength from cores.

(1) Estimate the probable location of the suspect concrete in the element by observation, from records or by the use of non-destructive tests (e.g. ultrasonic or rebound-hammer tests), and ascertain that, with the exception of cube strength, the concrete is otherwise acceptable regarding compaction, finish, etc.

(2) Examine the design of the element to determine the part of the suspect concrete that will be most highly stressed in service.

(3) Calculate, according to the design method applicable to the element, the ratio *(A)*:

$$\frac{\text{Compressive strength required at most highly stressed location in \textit{suspect concrete}}}{\text{Compressive strength required at most highly stressed location in \textit{element as a whole}}}$$

or

$$\frac{\text{Design compressive stress (maximum for section) at most highly stressed location in \textit{suspect concrete}}}{\text{Design compressive stress (maximum for section) at most highly stressed location in \textit{element as a whole}}}$$

(4) Calculate the ratio *(B)*:

$$\frac{\text{Standard Cube Strength of \textit{suspect concrete}}}{\text{Minimum cube strength permissible by design method for the most highly stressed location in \textit{element} (less than or equal to the specified cube strength)}}$$

(5) If *(B)* is greater than *(A)*, the element may be regarded as having adequate strength (subject to comparable

P/3.1.2.2 General

The core test is used for the estimation of Potential Strength when the values obtained may assist in the resolution of a dispute (usually resulting from disagreement over the validity of test cubes) regarding the quality of concrete used in the manufacture of an element, where other forms of test, which may be more convenient, comprehensive, faster, cheaper or less damaging to the appearance or performance, are deemed unacceptable for reasons of inaccuracy.

The precision of an estimate of Potential Strength is such that it should not be regarded as an alternative to a valid BS 1881 cube test.

The Potential Strength is a measure of the quality of the concrete provided for the manufacture of the element *but is not* influenced by the quality of workmanship or the subsequent history.

Interpretation of the estimate, regarding specification compliance, will depend upon the wording of the specification involved.

P/3.1.2.3 Preliminaries

If concrete of suspected sub-specification quality exists in the element (by virtue of sub-specification but disputed cube test results), the Potential Strength of the batch may be judged from core tests. In addition, because of the possibility of intermixing of batches of fresh concrete during placing, assessment of Potential Strength may be appropriate for batches closely associated with the suspect batch.

checks on bond strength etc.) and proceeding with the estimation of Actual Strength from core tests may be judged unnecessary.

A/3.1.2.4 Restrictions

The estimation of Actual Strength from cores can be undertaken at any age, irrespective of the workmanship applied to the concrete (compaction, curing) and after chemical or physical deterioration; and for concrete made from any type of cement and aggregates.

P/3.1.2.4 Restrictions

The estimation of Potential Strength is restricted to concrete made from Portland cement and dense (normal-weight) aggregates. The concrete may not be younger than 28 days when tested, whilst interpretation becomes progressively less precise as the age increases beyond 28 days.

Restrictions are imposed by the Procedure on the locations within elements which may be drilled to provide test cores, and in some circumstances these may preclude the determination of Potential Strength from core tests.

Occasionally cores complying with the restrictions imposed by these Procedures will permit the estimation of both Potential Strength and the Actual Strength required for assessing element serviceability.

It may be appropriate to sample concrete containing a localized or untypical defect. In this event, the Actual Strength estimated should not be interpreted as typical for the element or for a batch. It would be most inappropriate to use such a sample for Potential Strength.

The estimation of Potential Strength from core test results must take into account factors likely to make the strength of the concrete in the core (Actual Strength) differ from that in the standard BS 1881 cube. These factors include the influence of voidage and curing differences, and both are functions of the nature of the concrete concerned. Curing differences (e.g. on-site curing compared with water curing) will, in particular, produce a strength difference (between Actual and Potential Strengths) which will depend upon

(a) the particular curing history of the concrete in the core and the age at test; and

(b) the strength-gain rate, which is a function of the chemical and physical properties of the cement and aggregates, and the composition of the cement.

The strength-gain rates of Portland cements are more variable at early ages than they are after 28 days. In particular, the gain in strength after 28 days of the site-cured concrete in cores may be very small for concretes made with Portland cement and dense aggregates, and hence the ratio of Actual Strength (at ages $>$ 28 days) to Potential Strength (28 day BS 1881 Standard Cube Strength) is nearly constant for a given curing history of the concrete in the core. Research data are available which allow an estimate of the ratio to be used for Portland cements, dense aggregates, curing histories typical of construction in the UK and ages after 28 days; this Procedure for the estimation of Potential Strength is restricted to such situations.

This Procedure cannot at present be used for concretes containing non-Portland and pozzolanic-mixture types of cement, because the ratio of Actual Strength : Potential Strength for these is not at present well enough known. Similarly, the influence of lightweight aggregates upon the ratio is not known adequately for lightweight concrete to be covered by this Procedure, although there is some reason to believe that the ratio Actual Strength : Potential Strength will increase with increasing aggregate absorptivity.

A/3.1.2.5 Precision of Estimated Actual Strength

P/3.1.2.5 Precision of Estimated Potential Strength

The core test is intrinsically more variable than the cube test, well cut and capped cores and well made cubes having typical coefficients of variation due to testing alone of 6 and 3% respectively.

Hence, the average estimate of the Actual Strength at a given sampling location derived from n cores is likely to lie (with 95% confidence) within $\pm 12\%/\sqrt{n}$ only of the true value of the concrete contained in the core samples.

It must therefore be appreciated that, when a comparison of the average estimate and a structurally required value is made, a risk of the comparison being inconclusive will exist which can only be reduced by increasing n and resolved by the application of engineering judgement.

In addition, the factors necessarily incorporated in an estimation of Potential Strength from core test results are such that little improvement in the reliability of the estimate is likely to be obtained with any increase in the number of cores beyond four per batch of suspect concrete.

Fewer than four cores per batch of suspect concrete are not permitted under this Procedure but even with four or more, the average estimate of the Potential Strength obtained is likely to lie at best within ±15% only of the true value for the batch, for sampling and testing reasons alone. In cases where the curing history of the element sampled is abnormal and not allowed for, the average estimate of Potential Strength can be further at error.

It must hence be appreciated that when a comparison of the average estimate and a specified value is made, a risk of the comparison being inconclusive will exist which cannot be reduced and can only be resolved by agreement.

3.2 Planning and preliminary work

3.2.1 General

The basis for the decision to drill cores for the estimation of Potential or Actual Strength should be communicated to the appropriate interested parties (i.e. those having professional or commercial interest in the concrete), and a planning meeting convened, preferably on site. In some cases, the complexity of the drilling locations may indicate that it is desirable to have a representative of the drilling contractor at the meeting.

3.2.2 Procedure

3.2.2.1 General

Planning and preliminary work should cover the following points.

(a) The necessity for the test and its aims.
(b) Evidence of the location of the suspect concrete from site records or non-destructive test survey results.
(c) Proposed drilling locations, number and size of test cores.
(d) Ancillary work, e.g. density tests and curing history.
(e) Strength levels required by the specification (Potential Strength) or design (Actual Strength) and action to be taken if the estimates obtained from cores are clearly greater, less or inconclusive.
(f) Responsibilities of individuals regarding execution of the work.

Detailed recommendations relevant to points (a) to (f) are given below, **and it is emphasized that the successful application of this Procedure in a core testing situation depends upon the comprehensiveness of the planning meeting and the degree of agreement reached between the interested parties before further action is taken.**

[redacted]

A full discussion of Actual Strength is given in section 3.1.2, but certain points should be appreciated.

(1) Actual Strength is the strength of the concrete as it exists in the element at the time of drilling.

(2) Actual Strength is the end result of the quality of the concrete used, the workmanship applied to it and all other

P/3.2.2.2 Necessity for the test and its aims

A full discussion of Potential Strength is given in section 3.1.2, but certain points should be appreciated.

(1) Potential Strength is the strength of the concrete as it would have been at 28 days after being made into cubes, cured and tested in accordance with BS 1881.

(2) Potential Strength relates to the quality of the con-

historical or environmental factors up to the time of drilling.

(3) An estimate of Actual Strength obtained from core results is of limited accuracy relative to the true Actual Strength of the concrete in the cores.

(4) An estimate of Actual Strength can be applied to a given design method to appraise the actual serviceability of the element sampled, without introducing the concept of a safety factor for strength (see BS Code of Practice CP 110) with virtually no restrictions on the nature of the concrete involved.

crete used, corrections being made to allow for the effect on core strength of the workmanship applied to the concrete and other historical and environmental factors up to the time of drilling.

(3) An estimate of Potential Strength obtained from core results is of very limited accuracy relative to the Standard Cube Strength of the batch of concrete sampled. Types of concrete which may be sampled are also restricted.

(4) An estimate of Potential Strength from cores can be compared with cube strengths required by a specification and, by introducing a safety factor for strength (see BS Code of Practice CP 110), can be used to assess the potential serviceability of the element sampled by assuming normal workmanship, curing etc. for the element.

(5) An estimate of Potential Strength from cores may help to resolve a dispute over the validity of suspect cube test results.

3.2.2.3 Determination of general drilling area and location of reinforcement

The location of the suspect concrete in the element should be determined by visual inspection or from records. If necessary, a non-destructive test should be used to determined its boundary with other concrete.

The probable location of steel within the expected depth of the core sampling should also be determined by using a covermeter (preferably) or from site records, and its position relative to the expected drilling surface marked on the element.

A set of cores for the estimation of Potential Strength must relate to a single suspect batch of concrete if comparison with disputed cube test results for that batch is to be made. The boundary of the suspect concrete should therefore be checked to confirm that the volume of concrete contained is not greater than the size of the suspect batch.

The section of core to be tested should not include the top 20% (to a limit of 300 mm) of the lift concerned. The top 50 mm should not be included in any case. In rare cases, these requirements may preclude the estimation of Potential Strength from cores. Where this upper concrete is present in the suspect batch, its location should be clearly marked.

Note. Most concrete will, when placed, display a degree of sedimentation (gravity drawing dense materials to the bottom of the lift and displacing the lighter air and water upwards). Hence, a little air and rather more water are likely to be trapped in the concrete towards the top of the lift, leading to a reduction in strength.

Research shows that, generally, the concrete weakened by sedimentation will be restricted to the upper 20% of the lift depth in shallow lifts ($<$ 1·5 m), and to the upper 300 mm in deep lifts ($>$ 1·5 m).

The Procedure requires, for estimation of Potential Strength, that the concrete in the test cores should not differ in composition from that which would have been sampled for making cubes to BS 1881, so that concrete from the upper 20% of the lift (or 300 mm for lifts deeper than 1·5 m) is regarded as unrepresentative of the concrete supplied to the construction and not appropriate for coring.

Research also shows that the strength of the top 50 mm layer of concrete in a lift is often significantly less than that of the mass of concrete below owing to the rapid drying it may receive or the vagaries of the weather and of site curing procedures. Since the corrections for the influence of curing upon the ratio Actual Strength : Potential Strength made later in this Procedure are only acceptably accurate for the mass of concrete below the surface layer, the depth of concrete which, owing to both curing and sedimentation problems, may not be included in test cores for the estimation of Potential Strength is: the upper 20% of the lift (minimum thickness 50 mm, maximum thickness 300 mm).

14,200

A/3.2.2.4 Number of cores

The number of [redacted] Actual Strength at a single sampling location is one. However, the Actual Strength estimated from a single core is likely to lie (with 95% confidence) within ±12% only of [redacted] Actual Strength of the concrete in that core.

If the number of cores taken from the sampling location is increased, the reliability of the average estimate of Actual Strength improves as follows.

Number of cores *(n)*	95% confidence limits on mean estimate of Actual Strength
1	±12%
4	± 6%
9	± 4%
16	± 3%

It may be of assistance, when considering the number of cores to be drilled, to bear in mind that, whilst it might be quite proper to deem a small sectioned column structurally inadequate from the result of a single core test, on the basis that one core represents a good sample of the quantity of concrete which could lead to failure, it would not be proper so to do if the single core had been taken from a large element.

Hence, it is recommended [redacted] the number of cores *(n)* drilled should reflect the volume of concrete truly liable to render the element structurally inadequate, and that the subsequent interpretation of the estimates of Actual Strength should accommodate a tolerance of $\pm 12\%/\sqrt{n}$ on their mean. Where the individual ultimately responsible for interpretation finds the potential region of 'not proven' of $\pm 12\%/\sqrt{n}$ for the initially proposed value of n too large, n should be increased to an acceptable value.

A/3.2.2.5 [redacted]

Cores may be drilled from any location within the suspect concrete, according to the purpose of the investigation, and preferably clear of reinforcement. In most cases, however, the serviceability of the element sampled can best be judged by drilling where the ratio

$$\frac{\text{Required compressive strength or design compressive stress}}{\text{Actual Strength of suspect concrete}}$$

is expected to be highest.

The Actual Strength is usually lowest in the top 20% ([redacted]inimum, [redacted]) of a [redacted] However, the applied compressive stress in service [redacted]

(i) a maximum [redacted] span in beams [redacted] slabs and near the [redacted] of the compression zo[redacted] of simple beams and slabs) and

(ii) near uniform with height and across the cross-section in walls and short columns.

Hence, cores from beams and slabs will generally be taken from that part of the suspect concrete nearest to mid-span and drilled from the compression (usually top) face, whereas those from walls and columns will generally be taken from the top of the suspect concrete in the lift and may be drilled from any surface.

P/3.2.2.4 Number of cores

The minimum number of cores required by the Procedure to provide an estimate of the Potential Strength of a batch of suspect concrete is four. These cores are required to be of uniformly and well compacted concrete and, where possible, free of embedded reinforcement.

If a poorly compacted layer of concrete or steel is found to be present in a core when it is extracted from an element, it will often be possible to trim the core length to remove these and still retain an adequate test length. In other cases, it may be necessary to make an on-the-spot decision to drill one or more extra cores. In exceptional cases, the location of steel in the element may make it impossible to obtain steel-free test cores. Where avoidance of steel does prove impossible, it must be understood that the subsequent interpretation of the test results is less reliable.

The mean estimate of Potential Strength obtained from four or more individual core test results (even with well compacted, uniform and steel-free cores) cannot be regarded as a reliable statement of the true 28 day BS 1881 cube strength to better than ±15%. Hence, a potential region of 'not proven' of ±15% must be anticipated when the subsequent comparison of the Estimated Potential Strength with some specified or required value is made, even after exercising great care in sampling the cores and allowing for exceptional curing and compaction or the presence of steel.

P/3.2.2.5 Location

Cores drilled for the estimation of Potential Strength should be taken such that each represents an approximately equal amount of the suspect concrete. However, in addition to the obvious need to avoid badly compacted concrete and reinforcement, this Procedure requires that the test length of core should not contain concrete from the top 20% (50 mm minimum, 300 mm maximum) of the lift which the suspect batch partly or wholly comprised.

Note. Where Potential Strength is to be estimated, the coring locations and the length of core subjected to compression testing must be carefully chosen so that the concrete sampled has been affected as little as possible by the effects of sedimentation during placing and uncertain curing. Sedimentation occurs with most types of concrete and placing techniques, whatever the depth of the lift may be (i.e. in slabs as well as columns), such that an excess of water and air may be trapped in the upper layers of the concrete rendering it untypical of that used to make the element and therefore unsuitable for coring for the estimation of Potential Strength.

Hence, avoidance of this upper layer of 'unrepresentative' (unacceptable for assessment of Potential Strength) concrete will generally dictate the drilling location and direction as follows.

(a) *Walls, columns and deep beams* will normally be drilled horizontally below the unrepresentative upper layer

Where the element is of such slender proportions that the removal of test cores could lead to doubts regarding future serviceability (even after making good), cores should be drilled from what is judged to be the nearest suspect concrete in an acceptably non-critical location.

Occasionally, the concrete may show, under visual or non-destructive examination, a region of apparently lower-than-average quality large enough to influence the serviceability of the whole element. In such cases, it may be appropriate to take cores from this concrete for the estimation of Actual Strength. Where, however, a localized or untypical defect is present in the drilled core, either by deliberate selection of the drilling location at an observed defect or by chance, it will be generally inappropriate to infer the serviceability of the element from any estimate of Actual Strength obtained from that core.

of the lift or element. If cores have to be drilled vertically from the top of the element, they should be of such length that the required test length (not less than one diameter) can be obtained after removal of the unrepresentative concrete.

(b) *Shallow beams and slabs* will normally be drilled vertically downwards through both unrepresentative and representative concrete, only the latter being used for the test length of core. Where feasible, however, drilling upwards may facilitate the avoidance of reinforcement and reduce the extent of the drilling required to obtain suitable test cores.

It should be noted that, in rare cases involving small batches or very large and deep lifts, the suspect concrete may lie totally within the unrepresentative upper layer of the lift. In such cases, Potential Strength cannot be determined satisfactorily and, should cores be taken from unrepresentative concrete, the estimated Potential Strength yielded by application of the formulae and factors given in this Procedure may be depressed (relative to the true Potential Strength) by 30% or more.

(c) *Pavements*, which are invariably drilled downwards from the surface, may be constructed in one layer or two. In the former case, the top 50 mm, or 20% of the slab depth if this is greater, should be regarded as unrepresentative concrete and should not be included in the test length.

If a slab has been laid in two courses, the upper will normally be about 50 mm in thickness and it will not be possible to obtain a core (even of unrepresentative concrete) from this course in accordance with this Procedure. The upper course should, however, have been compacted while the lower course was still plastic; if this was done, the slab can be considered as being of one 'lift' so that little, if any, of the lower course need be considered to be of unrepresentative concrete.

Pavements are usually compacted by the application of a vibrating beam to the upper surface. The effectiveness of the vibration tends to diminish with depth. Particular attention should, therefore, be paid to the examination of the cores extracted and their voidage before proceeding to estimate Potential Strength.

The face of the element from which cores will be drilled is usually fixed by the above and by practical considerations. However, it may be noted that drilling is usually easier and cheapest in the vertically downward direction and hardest and dearest in the vertically upward direction.

In some special cases, it must be anticipated that aesthetic considerations regarding the appearance of the element after coring may influence the selection of sampling locations. Also, whilst cores should never be cut from locations such that the coring itself renders the element unserviceable, there will invariably be a need to 'make good' after coring.

Note. Whilst making-good is not a topic which has been investigated in depth in the production of this document, it is suggested that restitution should be by either:

(1) ramming a dry (low-shrinkage) concrete of suitable potential strength; or

(2) pouring Portland cement grout or epoxy resin into the dry hole and inserting a cast cylinder (100 mm and 150 mm standard test cylinders should fit nominal 100 mm and 150 mm holes with a slight clearance) or an untested core of suitable length and quality of concrete, and using a 'pumping' or 'screwing' action to bed the cylinder in the grout or resin and force it out through the narrow annular gap.

Where the maintenance of appearance is critical, consideration might be given to sawing off and returning the outermost part of the core to its original position in the drilled hole, leaving only the internal portion and the annular gap to be filled with fresh material.

[redacted]:

Cores of both 100 and 150 mm nominal diameter are permitted under these Procedures, provided the nominal maximum aggregate size does not exceed 25 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 the reinforcement is congested and 100 mm diameter cores are therefore less likely to contain pieces of steel;

(b) when sampling deeper than 150 mm from the surface is not desired (e.g. when the compression concrete in a shallow beam or slab is less than 150 mm thick).

(b) when use of a 150 mm drill bit and rejection of unrepresentative concrete will not permit the production of a test core of adequate length.

Exception (b) above is based on the fact that test cores may not, under this Procedure, have a length less than one diameter nor greater than two diameters, when capped for test. In general, [redacted]er, sh[redacted] **preferred to long cores (length/diameter, λ = 1·0 to 1·2).**

Note. This preference is based on a consideration of several factors.

(1) Short cores have a geometry closer to that of cubes than long cores. Consequently, compressive testing machines which perform satisfactorily when testing cubes should also perform satisfactorily when testing short cores. Long cores, on the other hand, may be susceptible to a latent, and otherwise undetected, fault in the machine (possibly resulting from platen rotation under load) and fail under a combination of compression and bending, with a reduction in the subsequent estimate of Potential Strength.

(2) Long cores, particularly if extracted from slender sectioned elements, may vary in voidage along their length. Hence, whilst their failure load, and the subsequent estimate of Potential Strength which may be made, will be symptomatic of the section of core having the greatest voidage, any allowance made for the effect of voids will be based on the average (over-all) voidage of the core and, as a consequence, the estimate of Potential Strength will be depressed.

(3) The relation between cube and core strength is clearly dependent upon the differences in geometry of the two specimens and this fact is taken into account in the formulae given in clause 3.5.2.1. However, as is almost always the case when two different test variables are being compared, their relation to each other is not unique and may be influenced to some degree by many factors other than (in this case) geometry alone. For this reason, it is argued that the use of short cores (having geometry close to that of cubes) presents a correlation between the core and cube test least influenced by considerations of machine sensitivity (referred to in 1 above), aggregate type and size, cement type, workability level of the concrete when placed, Poisson's ratio and platen restraint, etc.

(4) From elements of small section, short cores are more readily obtained than long ones.

(5) The lower drilling costs associated with short cores are evidently desirable and ameliorate the unfortunate requirement in some cases for rejection of unrepresentative concrete from the test length.

(6) The weakening of the element, damage to reinforcement, and extent of making good are all minimized.

Choice	Dia. (mm)	Test length (mm)	Possible problems
First	150	150	May include steel bars in test length. May sample concrete to a greater depth than desired (as length increases).
	150	300	
	100	100	Not permitted if nominal aggregate size exceeds 25 mm. May sample concrete at lesser depth than desired (if short cores used). May produce less reliable results.
Last	100	200	

Choice	Dia. (mm)	Test length (mm)	Possible problems
First	150	150	May include steel bars in test length.
	150	300	Not permitted for sampling slabs thinner than 200 mm.*
	100	100	Not permitted if nominal aggregate size exceeds 25 mm, or for sampling slabs thinner than 150 mm.*
Last	100	200	May produce less reliable results.

*In all cases, the test length of core must not include unrepresentative concrete. Avoidance of this concrete when drilling into the sides or soffits of deep elements is generally easy, but when drilling downwards the depth of coring must allow for the subsequent rejection of unrepresentative concrete from the test length. Thus, if a slab is to be drilled from the upper surface, its depth will dictate the length of core drilled and tested.

Slab depth	Core dia.	Length of core		
		recovered*	rejected	tested
(mm)	(mm)	(mm)	(mm)	(mm)
300	150	210–300	60	150–240
	100	160–300	60	100–200
250	150	200–250	50	150–200
	100	150–250	50	100–200
200	150	200	50	150
	100	150–200	50	100–150
150	100	150	50	100

*When drilling less than the full thickness of an element, it is recommended to drill beyond the required distance to ensure that adequate length is recovered on extraction.

P/3.2.2.7 Ancillary data

The basic method of estimating Potential Strength given by this Procedure assumes that suspect concrete is well compacted and of normal curing history. It may be necessary to make special adjustments to Estimated Potential Strengths, however, for compaction or for curing if either has been abnormal. The following ancillary data should therefore be obtained in anticipation of need.

(a) *Potential Density of concrete*

The Potential Density of concrete (D_p) is the 28 day cube density, determined by displacement, which would have been obtained from well compacted cubes made and cured in accordance with BS 1881.

Where the 28 day densities of cubes taken from the suspect concrete are not in dispute, their average should be used as D_p.

Where valid cube densities for the suspect concrete are not available, however, D_p should be estimated from the mean density of 28 day cubes taken from the same mix (assuming these are valid), adjusted for any agreed deficiencies in the suspect concrete. As a working rule it may be assumed that, with the exception of concrete so grossly misbatched as to have been not recognizable as the specified grade or otherwise acceptable concrete (i.e. concrete which should not have been placed at all), agreed evidence of excessive workability or moderate misbatching can be regarded as reducing cube density by 1% (or 2% for both). In cases where even the mean density of 28 day cubes for the mix is not available (perhaps because the volumes of cubes have not been determined by water displacement), use may be made of the fact that the mean cube density for the mix should approximately equal the plastic density (where known) + the cement content of the mix (kg/m^3) divided by 20.

(b) *Curing history*

The curing history of the suspect concrete should be determined from site and meteorological records with regard to:

(1) ambient conditions when placed;
(2) protection and curing provided;
(3) age at removal of formwork;
(4) level of temperature and humidity over period between placing and coring.

3.2.2.8 Testing laboratory

The testing laboratory selected for the preparation and testing of cores should be appraised and agreed as acceptable to the interested parties regarding its capability for conducting the necessary examination, density tests, capping and compressive testing to the requirements of this Procedure. Particular attention should be paid to recent verifications of the performance of the compressive testing machine.

3.2.2.9 Required strength levels

The drilling and testing of cores should not proceed until an understanding has been reached regarding the levels required for estimates of Actual or Potential Strength, special attention being paid to corrections for the presence of steel or excessive voids in the cores, and abnormal curing (see section 3.5.2 and Appendixes to 4). A course of action in the event of an estimate being inconclusive should also be agreed.

3.2.2.10 Supervision

In addition to the provision of drilling equipment and services, the cutting of cores requires supervision by a responsible person acceptable to the interested parties.

The drilling supervisor should be capable of using his judgement to see that unnecessary damage to the structure is avoided and ensuring that each core is properly drilled, extracted and labelled. He should also provide a liaison between the various interested parties, the drilling contractor and the testing laboratory.

The brief to the drilling supervisor should cover the following:

(1) The exact location of the suspect concrete and any part of it deemed unsuitable for coring (i.e. unrepresentative concrete), and the probable location of steel likely to lie within the drilling depth.
(2) The diameter and number of test cores required and the corresponding drilling points on the surface of the suspect concrete.
(3) The depth of concrete to be extracted from each location, the part of that depth which is to be the test length and the procedure to be adopted if a core breaks off at less than the target length.
(4) Procedure to be adopted if inspection of the core reveals features which may invalidate the result or affect its interpretation, e.g. under-compaction; steel; cracks.
(5) Instructions to be given to the testing laboratory.

3.3 Obtaining the cores

3.3.1 General

Obtaining the cores involves the drilling, extraction, examination and identification of the cores, the recording of relevant data, designation of test lengths and despatch to the laboratory.

3.3.2 Procedure

3.3.2.1 Drilling and Extraction

Test cores should be drilled by a skilled operator using well maintained equipment complying with the dimensional requirements of BS 4019 : Part 2. Diamond-impregnated, water-cooled bits may be driven by electric or air-driven motors, but it should be noted that considerations of electrical safety will normally preclude the use of electric motors when drilling upwards.

The drill should be kept rigidly positioned during coring, by bracing or kentledge, otherwise badly ridged or curved cores may be obtained with possible reduction in measured strength.

Care must be taken to ensure that a suitable and uniform pressure is applied to the drill bit such that the optimum drilling rate for the concrete is achieved. Too little pressure will prevent the diamond cutting action, whereas too great a pressure will cause excessive diamond wear.

Before any core is broken out, it is necessary to ensure that the depth drilled is not less than that planned. If, unexpectedly, steel has been encountered (evidenced by change in drilling noise or speed, or colour of cooling effluent), the supervisor should make use of his brief to decide whether this is acceptable, whether to drill further in order to obtain a steel-free length, or whether to drill a replacement core.

Core removal is usually achieved satisfactorily by insertion of a cold chisel down the side of the core to cause breaking off at or close to the bottom of the drilled length, followed by extraction using the drill or tongs.

The supervisor should satisfy himself that the drilling methods being used are not causing signficant distortion or damage to the cores.

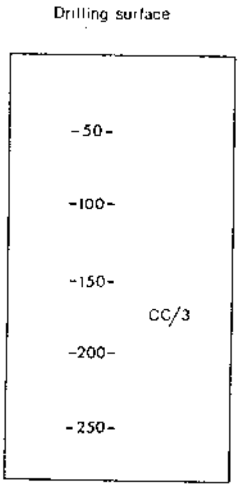
3.3.2.2 Examination

On extraction, each core should be examined by the supervisor to ensure that the required test length can be obtained (preferably steel-free; and, in the case of cores for Potential Strength determination, not containing poorly compacted concrete). If this is not the case, extra cores should be drilled from locations adjacent to those of the rejected cores.

The rejected cores may be required to be retained for further examination.

3.3.2.3 Core identification

Each core should be given a distinct, unique and indelible code number which is marked on the cut surface within the expected test length and cross-referenced on a simple sketch of the element drilled. Marks should also be made on the core to indicate distances in millimetres from the drilling surface so that the exact location in the element from which the test core came can be confirmed even when the ends have been trimmed.



Side view of drilled core, before trimming, showing marks at 50 mm spacing measured from drilling surface, and also code number for identification placed within length that is expected to be used as the test length.

3.3.2.4 Drilling report

The supervisor should prepare, while the drilling work proceeds, a simple record of any observations likely to have a bearing on the validity of interpretation of the core test results. This record, together with the drilling locations and core identification reference numbers, constitutes the drilling report.

3.3.2.5 Designation of test length and despatch to the laboratory

The supervisor should ensure that the cores are despatched to the testing laboratory without damage together with instructions as to which part of each (relative to the drilling depth marks) is to be capped, examined, photographed and tested.

In designating the test length of the as-drilled core, the supervisor should ensure compliance with the intentions of the interested parties and with the following rules, where possible (rule 1 being more important than rule 2 etc).

(1) The test length should be, after trimming and capping, not less than one nor more than two diameters, and preferably not more than 1·2 diameters.

(2) — (2) Sections showing poor compaction or other defects should not be included in the test length.

(3) — (3) Unrepresentative concrete (upper 20%, 50 mm minimum or 300 mm maximum) of the lift depth should not be included in the test length.

(4) Sections containing multiple or large pieces of steel should not be included in the test length.

(5) Sections containing one small bar should not be included in the test length.

3.4 Laboratory work

3.4.1 General

Laboratory work covers the trimming, capping and testing of each core, together with an examination (including assessment of voidage) and density determination.

3.4.2 Procedure

3.4.2.1 Trimming to test length

The laboratory should trim each core (see clause 3.1.5 of BS 1881 : Part 4) in accordance with instructions given by the drilling supervisor, ensuring that the trimmed length is not less than 95% of its diameter nor likely to exceed twice the diameter when capped. Trimming with a masonry or diamond saw is preferred, but careful hand trimming may be acceptable.

3.4.2.2 Examination

The laboratory should examine and photograph (see also Appendix 2) each test core in accordance with instructions given by the drilling supervisor. Notes will normally be required of the following.

(a) Any lack of homogeneity of the concrete within or between cores.

(b) The extent of voids visible on the drilled surface, particularly those which form honeycombing.

(c) The position of cracks, drilling damage or steel, defects and inclusions should be marked on the core, and sketch records made of their locations and size relative to the over-all geometry of the core.

(d) The approximate size of the aggregate and its type (bearing in mind that cut aggregate usually looks small and, in the case of gravels, more variable in type than might have been expected).

(e) Whether the aggregates seem continuously or gap graded, and any distinctive features of the fine aggregate.

Notes

BS 1881 : Part 4, clause 3.1.3, gives a method of classifying the extent of voids on the basis of their number and size distribution. This method does not, however, enable a direct estimate of the percentage of voids to be made. Appendix 2 to this Procedure gives a method of estimating voidage which may well, with experience in its use, find favour as a quantitative version of the BS 1881 classification and prove preferable to the determination of voidage from density tests.

Comments regarding the apparent cement content of the concrete and its original water content should only be made by an experienced concrete technologist and should always be viewed with caution.

Examination and photographing under different moisture conditions can assist in highlighting specific features, e.g. a wet surface is preferable for viewing the type, size and distribution of aggregate; a dry surface is preferable for viewing voids, cracks and drilling flaws.

3.4.2.3 [redacted]

Cores should be capped with high-alumina cement mortar or sulphur in accordance with clause 5.5.2 of BS 1881 : Part 3.

Notes

(1) **Other methods should not be used.** In particular, polyester resin and plaster-type materials are known to give unreliable results. Caps should be kept as thin as possible.

(2) With careful hand trimming of the core, the cap thickness should vary from a few millimetres to little more than the maximum aggregate size over the cross-sectional area, with an average thickness just over half the maximum aggregate size (e.g. about 10 to 15 mm thick for 20 mm aggregate) while still permitting avoidance of an undesirable degree of damage to coarse aggregate particles.

3.4.2.4 Density determination

The densities of cores provide generally useful information for interpretation of strength and in the case of estimation of Potential Strength provide vital quantitative and objective data for estimating voidage. **The measurement of Actual Density is therefore recommended in all cases,** using the following procedure.

(a) Immediately prior to capping, the trimmed core should be soaked in water for long enough (half an hour is usually sufficient) for an accurate and repeatable determination to be made of the core volume (V_u) by displacement in water using a method such as that given in Section 2 of BS 1881 : Part 5.

(b) The core should then be capped (after allowing it to dry if sulphur sand capping is to be used), particular care being taken to prevent air from being entrapped between the core and the capping material. If the density of the capping materials is not known from experience to better than ±1%, a specimen should be made and stored in water with the cores, and its density (D_c) determined prior to core testing.

(c) After storage in water, and immediately prior to compressive testing, the capped core should be weighed in air (in the soaked but surface-dry condition) and in water to determine its gross weight (W_t) and volume (V_t).

(d) The water-soaked density of the concrete in the uncapped core (D_a) may then be calculated from:

$$D_a = \frac{W_t - D_c(V_t - V_u)}{V_u}$$

Note. If the core contains steel, it should be extracted after the core compressive test and weighed (W_s). Its volume (V_s) may be determined by displacement of the meniscus in a measuring cylinder of water. Then:

$$D_a = \frac{W_t - D_c(V_t - V_u) - W_s}{V_u - V_s}$$

3.4.2.5 Testing the core

The core should be tested not less than 2 days after capping and immersing in water as required by BS 1881 : Part 3, clause 5.5.2 and Part 4, clause 3.2.2.

The average diameter of the core should be calculated in accordance with clause 3.1.4 of BS 1881 : Part 4 but to the nearest millimetre, and its average cross-sectional area calculated.

The length of the capped core should be measured to the nearest millimetre and the length/diameter ratio, λ, calculated.

The core should be tested in compression in accordance with clauses 3.2.1 to 3.2.4 of BS 1881 : Part 4, the mode of failure being noted and a sketch diagram made if this is unusual. The maximum load sustained by the core is then divided by its cross-sectional area to establish the Core Strength.

Note. Experience suggests that a satisfactory mode of core failure is one involving:

(a) no significant damage or cracking of the caps;
(b) no loss of bond between a cap and the core; and
(c) similar cracking visible all around the circumference of the core.

The occurrence of a prominent diagonal shear crack is thought to be satisfactory in long cores, but should be reported if associated with short cores ($\lambda < 1{\cdot}2$) or with reinforcement or honeycombing, to aid interpretation of the result.

3.5 Estimating Actual or Potential Strength

3.5.1 General

The Core Strength may now be converted to its equivalent estimate of Actual or Potential Strength in terms of cube strength.

In the case of Actual Strength the estimate obtained will be equivalent to the cube strength of the concrete represented by the core, no adjustment being required for location in the lift, degree of compaction or curing. The relevance of these variables to the estimates will have been considered in the original decision to investigate Actual Strength, the planning of the core sampling and the interpretation to be made.

3.5.2 Procedure

A/3.5.2.1 Estimation of Actual Strength

The estimation of Actual Strength from the Core Strength involves correction for the basic differences in shape between core and cube, and any possible difference in orientation (i.e. relative directions of casting and loading in the compressive test). These corrections are allowed for in the following equations.

Estimated Actual Strength

$$= \frac{2{\cdot}5}{1{\cdot}5 + 1/\lambda} \times \text{Core Strength}$$

for cores drilled in a horizontal direction

Estimated Actual Strength

$$= \frac{2{\cdot}3}{1{\cdot}5 + 1/\lambda} \times \text{Core Strength}$$

for cores drilled in a vertical direction.

In the case of Potential Strength the estimate obtained will be equivalent (subject to differences in test variability between cores and cubes) to the Standard Cube Strength at 28 days, by virtue of the special core sampling procedures used and the factors incorporated in the estimate to take account of differences in age, compaction and curing history, from those of the BS 1881 cube.

P/3.5.2.1 Estimation of Potential Strength

The estimation of Potential Strength from the Core Strength involves correction for the basic differences in shape between core and cube, and any possible difference in orientation (i.e. relative directions of casting and loading in the compressive test), as for the estimation of Actual Strength (see clause A/3.5.2.1, opposite). In addition, however, corrections for differences in composition, compaction and curing history between core and cube must be taken into account.

Before the estimation of Potential Strength, it is necessary to consider the data available on the composition, compaction and curing history of the suspect concrete contained in the core. If these are acceptably normal, simple equations given below provide the required estimate of Potential Strength; if not, more detailed calculations will be involved.

(a) *Composition.* Provided cores consist totally of representative concrete (i.e. do not include concrete from the upper 20%—minimum 50 mm, maximum 300 mm—of the lift), no allowance is required for difference in composition from that of a cube sampled in accordance with BS 1881.

Failure to exclude unrepresentative concrete from test cores can cause depression of the measured core strength (and hence estimated Potential Strength) by up to 30% (depending upon the abnormality of composition and curing history).

(b) *Compaction.* Provided the Estimated Excess Voidage of the core is zero (see Appendices 1 and 2), no correction for difference in compaction between core and cube is necessary. Where a significant Excess Voidage is estimated, however, a correction (Appendix 1) should be applied in the equations given below.

(c) *Curing history.* Provided the curing history is normal, no correction is necessary. The curing history, determined in accordance with clause P/3.2.2.7, can be regarded as normal if

(i) test cores have been cut from near a surface protected from drying by formwork for several days or from an upper surface with rejection of a length of not less than 50 mm adjacent to that surface, and that

(ii) ambient conditions have been typically (for the UK) variable in both temperature and humidity over the period since casting, without the suspect concrete being subjected to long periods during its early life of very high humidity (foggy, damp weather or direct rainfall) or drying weather (low humidity and winds in warm weather).

Where curing history and other relevant factors have been abnormal, a more reliable estimate of Potential Strength may be obtained by using the Procedure given in Appendix 3, which should be referred to in every case to confirm whether or not its use is indicated by the curing history of the suspect concrete.

Subject to the normality of the suspect concrete regarding composition, compaction and curing, the Potential Strength may be estimated from the following equations.

Estimated Potential Strength*

$$= \frac{3{\cdot}25}{1{\cdot}5 + 1/\lambda} \times \text{Core Strength}$$

for cores drilled in a horizontal direction

Estimated Potential Strength*

$$= \frac{3}{1{\cdot}5 + 1/\lambda} \times \text{Core Strength}$$

for cores drilled in a vertical direction.

***Note.** Because the strength of concrete in a structure increases in an uncertain way after 28 days and is unlikely in most structures to increase substantially over a period of several months, no age allowance is justifiable, except when knowledge exists for particular circumstances. To remove doubts, it is obviously preferable for the age of the core test to be as near 28 days as may be possible.

3.5.2.2 Correction of Estimated Actual or Potential Strength for the presence of steel in the test core

If, in spite of efforts to obtain test cores free of reinforcement, they do contain steel, it becomes necessary to allow for the resulting reduction in measured Core Strength (and hence the Actual or Potential Strength estimated according to clause 3.5.2.1) before interpretation of the results may take place. Appendix 4 gives guidance on the correction which may be made.

A/3.5.2.3 Significance of Estimated Actual Strength

An individual estimate of Actual Strength can be expected, with 95% confidence, to lie within ±12% of the true Actual Strength of the concrete in the core. Correspondingly, the mean Estimated Actual Strength obtained from n cores can be relied upon, with 95% confidence, as lying within $\pm 12\%/\sqrt{n}$ of the true average Actual Strength of the concrete in the cores.

P/3.5.2.3 Significance of Estimated Potential Strength

The individual estimates of Potential Strength provided by the four or more (n) cores required under this Procedure, are separated into the lowest and the remainder $(n - 1)$. The following is then calculated.

$$t = \frac{\text{Mean of remainder} - \text{Lowest}}{\dfrac{\text{Mean of remainder} \times 6}{100} \times \sqrt{1 + \dfrac{1}{n-1}}}$$

If t is greater than the value given by

n	t
4	2·9
5	2·4
6	2·1
7	2·0
8	1·9

the lowest result is probably (in statistical terms, $p > 0{\cdot}95$) significantly different from the others and should be rejected if there is evidence that the core concerned was abnormal in respect of location in the lift, steel content, voidage, lack of homogeneity, cracks or drilling damage when compared with the other cores.

If t is greater than the value given by:

n	t
4	4·3
5	3·2
6	2·8
7	2·6
8	2·5

the lowest result should be rejected irrespective of other considerations ($p > 0{\cdot}975$).

The estimate of Potential Strength required for further interpretation (see section 3.6) is the mean of the n individual estimates or the $n - 1$ individual estimates remaining after rejection of the lowest.

Note. The above procedure for rejecting an abnormally low result is necessitated by the fact that many unaccounted for phenomena or defects may occasionally produce an individual low and spurious result.

The occurrence of an abnormally high spurious result is much rarer. Where, however, there is good reason to doubt the validity of an individual high result, the procedure given above may be used (substituting 'highest' for 'lowest') to decide whether or not to reject it.

3.6 Interpretation of results

3.6.1 General

It is impossible for these Procedures to make comprehensive and exhaustive recommendations regarding the interpretation of estimates of Actual or Potential Strength because of the wide range of situations and specifications which may be concerned. A number of points are given, however, which in many cases may provide a basic Procedure for resolving an investigation. A worked example, demonstrating the use of the procedures in a practical situation, is provided in Appendix 5 (pages 29 to 31).

3.6.2 Procedure

A/3.6.2.1 Actual Strength

The individual or mean estimates of Actual Strength may be used in a number of ways depending upon the purpose of the investigation. Certain points should be borne in mind, however.

(1) Because this Procedure requires the test core to be soaked in water prior to test, a reduction (of up to about

P/3.6.2.1 Potential Strength

The mean Estimated Potential Strength yielded by the procedure given in clause P/3.5.2.3 can be used either for comparison with disputed cube results or directly with the specification for the concrete (and hence to assess the potential serviceability of the element).

(1) Where comparison with the specification is the prim-

15%) in observed strength relative to that in the (generally) drier structural location will occur. Also, the formulae used for estimating Actual Strength adjust for any orientation properties which the core may possess differing from those of a standard cast cube.

(2) For the reasons given above and because the estimate of Actual Strength is a (notional) cube strength, it should never be compared directly with a principal design stress. Instead, **the Estimated Actual Strength should be compared only with an appropriate fraction of the (true) cube strength required.**

If, for example, a structure has been designed to the British Standard Code of Practice CP 110 (or is otherwise to have its design compared with the requirements of that Code), the estimate of Actual Strength obtained from cores (subject to the tolerance of $\pm 12\%/\sqrt{n}$) could be required to equate with the 'design strength', equal to the 'characteristic strength (f_k) divided by the appropriate safety factor for strength (γ_m)'. The general value of γ_m is $1{\cdot}5$ and may be regarded as appropriate even for structures liable to contain saturated concrete. Hence, if the structure in question can be relied upon to remain dry under load, the Estimated Actual Strength could be compared with $f_k/(1{\cdot}5 \times 1{\cdot}1)$ or $f_k/1{\cdot}65$ (the value of $1{\cdot}1$ being a 'safe' allowance for the difference in strength between wet and dry concrete).

If the Estimated Actual Strength $-12\%/\sqrt{n}$ is higher than $f_k/1{\cdot}5$ or $f_k/1{\cdot}65$ (as appropriate) the element may be deemed safe irrespective of the location of the concrete in it.

If lower, it will become necessary to compare the Estimated Actual Strength and its tolerance of $\pm 12\%/\sqrt{n}$ with the value of $f_k/1{\cdot}5$ or $f_k/1{\cdot}65$ scaled down according to the reduction in stress level expected for the suspect concrete relative to the maximum for the element (i.e. ratio *A* given in clause A/3.1.2.3).

ary purpose, the mean Estimated Potential Strength (*P*) plus its tolerance of ±15% should first be compared with the minimum cube strength permitted by the specification.

For example, CP 110 permits a minimum cube strength of 85% of the specified characteristic value (*C*). Then,

(a) if $P > C$, there is little doubt that the concrete provided for the manufacture of the element complied with the specification minimum cube strength.

(b) if $P < 0{\cdot}74C$, there is little doubt that the concrete provided for the manufacture of the element did not comply with the specification minimum cube strength,

Note. $0{\cdot}74 = \dfrac{0{\cdot}85}{1{\cdot}15}$

(c) if $C > P > 0{\cdot}74C$, the case is 'not proven'.

In situation (a), there is now no reason to suspect the potential quality of the concrete and further interest, if any, would be focused on Actual Strength.

In situation (b), the non-compliance of the Potential Strength of the concrete is established. However, it is still possible that, even though the element contains sub-specification concrete, it may be found to have an acceptable potential serviceability by applying the procedure given in Clause A/3.1.2.3, $P \pm 15\%$ being given the role, in ratio (*B*), of 'cube strength (proven) of suspect concrete'. Alternatively, where the cores drilled for the determination of Potential Strength are deemed appropriate to the estimation of Actual Strength by the procedure given in clause A/3.5.2.1, the results obtained may be used according to clause A/3.6.2.1 to establish the actual serviceability of the element.

In situation (c), engineering judgement must be applied to determine a course of action between that for situations (a) and (b) according to the value of *P* relative to *C* and $0{\cdot}74C$.

(2) Where comparison with a disputed cube result is the primary purpose, the mean Estimated Potential Strength (*P*) plus its tolerance should first be compared with the disputed cube test result (*T*) and its testing tolerance of about ±5%.

Then

(a) if $P > 1{\cdot}24T$, there is little doubt that the cube result was invalid.

Note. $1{\cdot}24 = \dfrac{1{\cdot}05}{0{\cdot}85}$

(b) if $P < 0{\cdot}83T$, there is little doubt that the cube result was not depressed by failure to test to BS 1881.

Note. $0{\cdot}83 = \dfrac{0{\cdot}95}{1{\cdot}15}$

(c) if $1{\cdot}24T > P > 0{\cdot}83T$, the case is 'not proven'.

In situation (a), there is now no reason to suspect the potential quality of the concrete and further interest, if any, would be focused on the cube testing procedures and, possibly, Actual Strength.

In situation (b), the non-compliance of the Potential Strength of the concrete can be confirmed by comparison of $T \pm 5\%$ with the minimum permitted by the specification, without further utilization of the less reliable estimate obtained from cores (*P*). However, it is still possible that, even though the element contains sub-specification concrete, it may be found to have an acceptable potential serviceability by applying the procedure given in clause

A/3.1.2.3, $T \pm 5\%$ being given the role, in ratio *(B)*, of 'cube strength (proven) of suspect concrete'. Alternatively, where the cores drilled for the determination of Potential Strength are deemed appropriate to the estimation of Actual Strength by the procedure given in clause A/3.5.2.1, the results obtained may be used according to clause A/3.6.2.1 (and clause A/3.1.2.3) to establish the actual serviceability of the element.

In situation (c), engineering judgement must be applied to determine a course of action between that for situations (a) and (b) according to the value of P relative to $1{\cdot}24T$ and $0{\cdot}83T$.

Appendix 1 to Part 3: Correcting core strength for the influence of Excess Voidage

The Excess Voidage of a core is that amount by which the Actual Voidage exceeds the voidage of a well made cube of the same concrete (the Potential Voidage). Since the Potential Voidage is never known in practical situations, its value is assumed where necessary to be 0·5%.

Excess Voidage cannot easily be determined with precision, but two independent methods of estimating it are recommended.

(1) *By visual means (see Appendix 2)*

This method is subjective but independent of information other than that evidenced by the core itself and the assumption that the Potential Voidage is 0·5%.

(2) *From density test results*

This method is objective but dependent upon the precision with which the Potential Density of the concrete has been established and upon the degree of water saturation of the voids.

In the density test method, the Excess Voidage of a core is given by the expression:

$$\frac{D_p - D_a}{D_p - k \times 1000} \times 100\%$$

where (D_p) is the Potential Density (clause P/3.2.2.7); (D_a) is the Actual Density of the core water-soaked (clause 3.4.2.4); 1000 is the density of water (all three density values being expressed in kg/m³); and k is the fraction of the voids in the core resulting from imperfect compaction and filled with water when D_a is measured.

The value of k is assumed to be 0·5 unless there are agreed reasons for adopting another value, so that

$$\text{Estimated Excess Voidage} = \frac{D_p - D_a}{D_p - 500} \times 100\%$$

Note. Although the capillaries in the cement matrix of concrete lose water to the atmosphere while the concrete is in the structure, the soaking of cores for 2 days replaces this lost water. However, only a fraction of the much larger (and usually discrete) air voids resulting from imperfect compaction will be filled with water by the time D_a is measured. This fraction *(k)* has been shown by research to range over all the possible values (from 0 to 1·0) and, in any given situation, will be a function of the materials and mix proportions of the concrete, the magnitude and form of the core voidage, the curing conditions in the structure, the duration of soaking in the laboratory and the geometry of the core. In addition, the exposure of voids on the drilled surface of the core can lead to errors in the validity of the value of D_a determined in the laboratory (particularly where honeycombing is present).

It is recommended that the Excess Voidage of each core be estimated by both these methods to the nearest 0·5%. These two estimates should then be compared and a single value agreed to the nearest 0·5%.

The multiplying factor required for correcting the measured core strength for the influence of Excess Voidage before proceeding to the estimation of Potential Strength is given in the table below. Normal compaction is generally expected to yield values for the Excess Voidage of about 0·5 to

2·5%, but the table shows correction factors for values up to 5% for use in special circumstances. Because of their increasing unreliability, cores having Excess Voidages greater than 5% should never be used to estimate Potential Strength.

Excess Voidage (%)	Strength multiplying factor
0	1·00
0·5	1·04
1·0	1·08
1·5	1·13
2·0	1·18
2·5	1·23
3·0	1·28
3·5	1·33
4·0	1·39
4·5	1·45
5·0	1·51

Appendix 2 to Part 3: A method of estimating Excess Voidage by visual means

On the assumption that the Potential Voidage is 0·5%, it is possible to estimate the Excess Voidage of the core by comparing the number and size of the voids exposed on the drilled surface of the air-dry core with those displayed in Figures 3a to 3e. These are 125 x 80 mm life-size photographs of the surface of the cores having known Actual Voidages, and hence inferrable Excess Voidages, as follows.

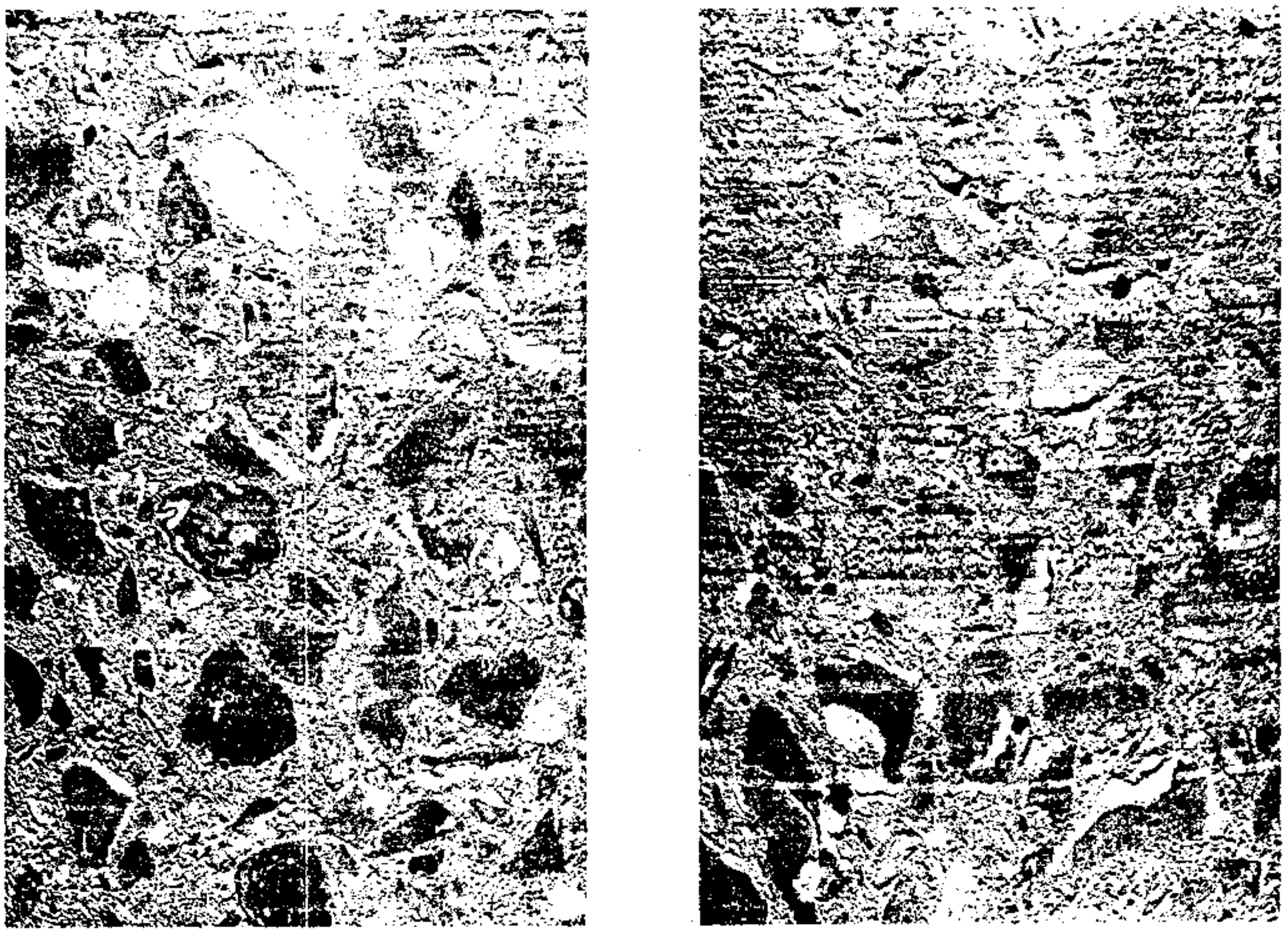
Figure No.	Excess Voidage (%)
3a	0
3b	0·5
3c	1·5
3d	3·0
3e	13·0

The comparison of the surface voids of a given core with those shown in Figure 3 should always be made by two observers, in order to avoid extremes of subjective bias, care being taken to ensure that the voids are viewed in strong light angled so as to highlight them with shadows (as in Figure 3). The recommended procedure for the comparison is as follows.

(1) Cut a 125 x 80 mm rectangular aperture in a piece of thin card.
(2) Place the card on the core with elastic bands.
(3) Assess the Excess Voidage of the area of core in view by comparing it with Figure 3 and record the assessment.
(4) Move the card to other areas and repeat the assessment until the cylindrical face of the core has been surveyed representatively.
(5) Average the individual assessments and record the result to the nearest multiple of 0·5%.

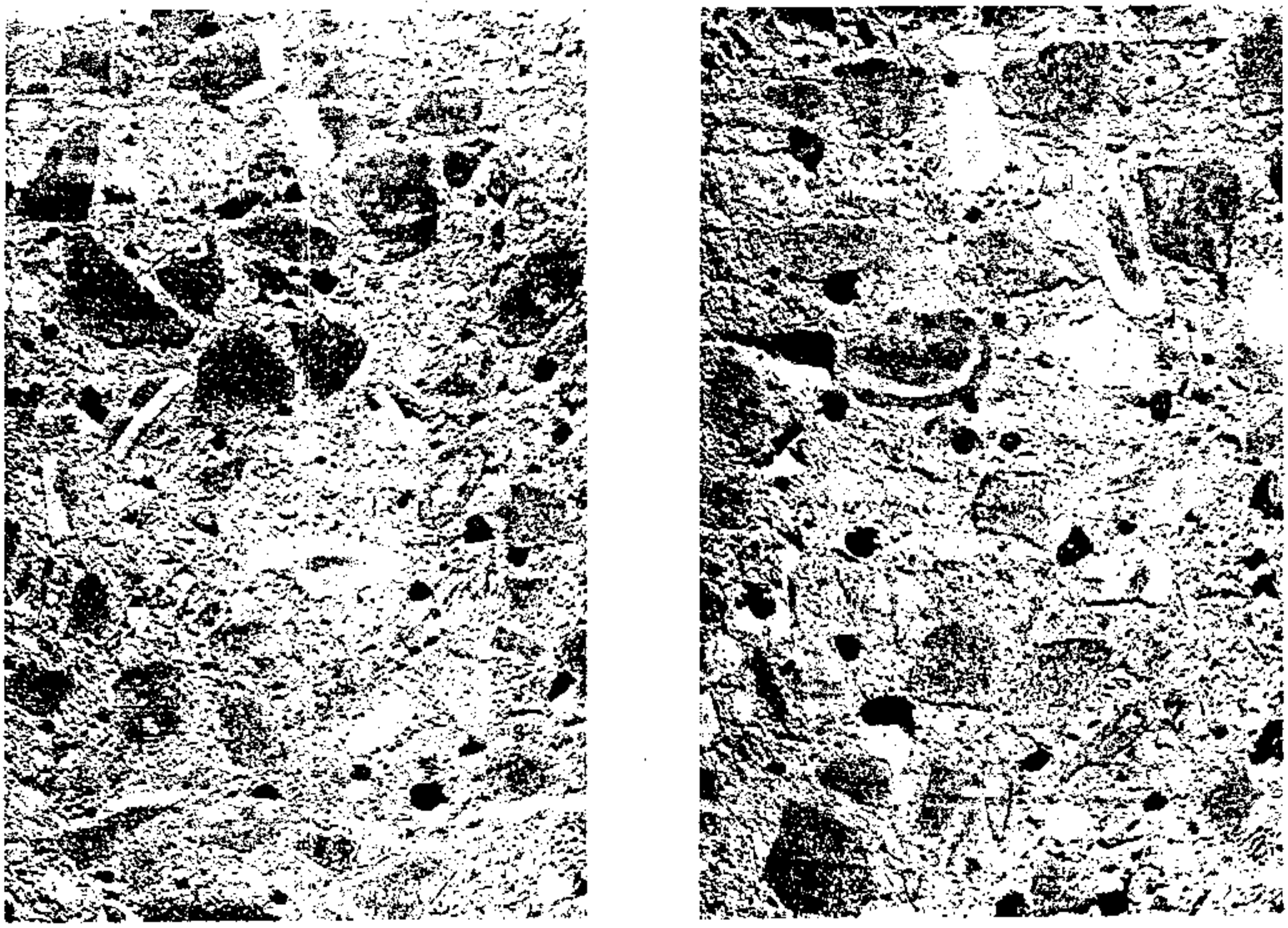
Notes

(1) Where the relative frequencies of small and large voids on the test core differ from those shown in Figure 3, estimation of the Excess Voidage may be facilitated by remembering that a void of a given diameter (or linear dimension) is equal in volume to eight voids having only half that diameter (or linear dimension).
(2) Where a photographic record of the air-dry core is required, the centre of the photograph should include that 125 x 80 mm area having an Estimated Excess Voidage nearest to the average for the whole core. The lighting should also be such that a photograph comparable in quality to Figure 3 is obtained, and the photograph should be reproduced to life size.
(3) In making a void count to BS 1881 (see clause 3.4.2.2 (b) of the Procedures), it should be noted that the number and size of the voids is to be expressed as 'per 100 000 mm^2 of cut face', which is 10 times the area of each individual area surveyed by using the method described in this Appendix.



(a) Excess voidage = 0

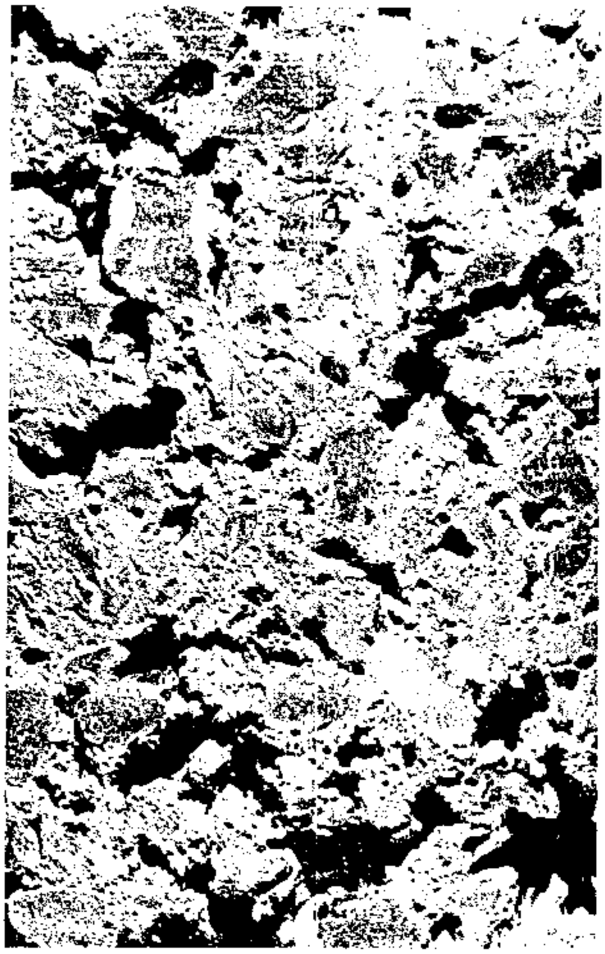
(b) Excess voidage = 0·5%



(c) Excess voidage = 1·5%

(d) Excess voidage = 3·0%

Figure 3: Actual-size photographs of cores of different voidages masked to give a standard area of 125 x 80 mm in each case.



(e) Excess voidage = 13·0%

Figure 3 continued

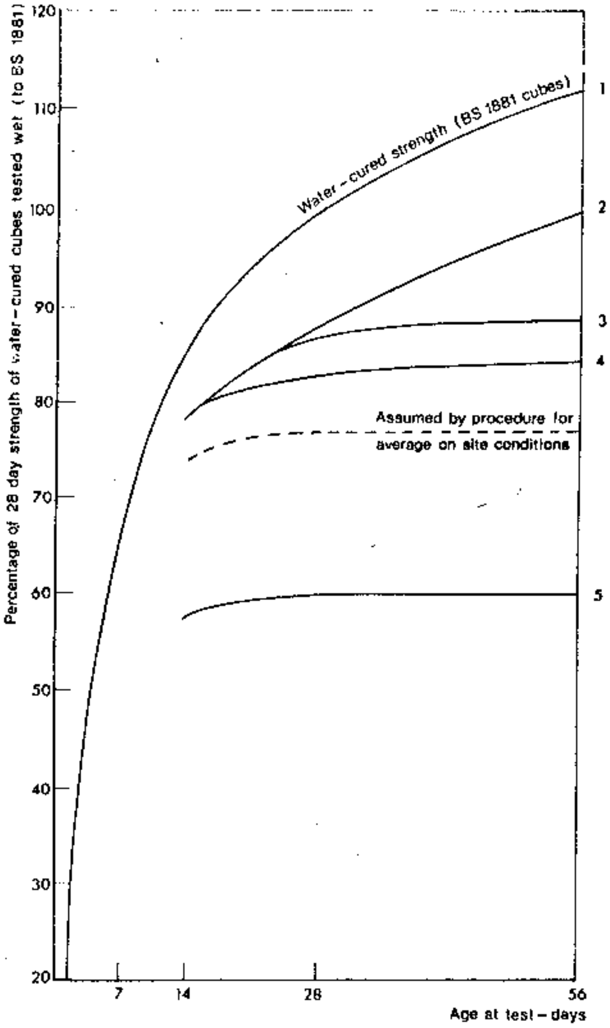


Figure 4: Effect of curing upon strength (determined after soaking for 2 days in water).

Appendix 3 to Part 3: The influence of curing history upon core strength

Research on cores shows that on average, if complying with the physical requirements for estimating Potential Strength (e.g. exclusion of unrepresentative concrete, etc.), they yield estimates of Actual Strength which are only 77% of the true cube strength (and, hence, of the Potential Strength). This reduction in strength is attributable to differences in curing between the elements sampled and water-cured cubes; differences in compaction can be assumed to be insignificant.

The equations given by the Procedures for the estimation of Actual and Potential Strengths would, if applied to the measured strength of cores complying with the physical requirements for estimating Potential Strength, show that at 28 days:

$$\frac{\text{Actual Strength}}{\text{Potential Strength}} = 0{\cdot}77$$

In addition, research shows that increase in measured core strength with age is usually very small after 28 days, so that no correction for age is justified when Potential Strength is being calculated.

In some exceptional cases the reduction, at 28 days, to 77% of the water-cured strength may not be appropriate to the concrete in an element cored in accordance with these Procedures. This applies, for example to:

(a) elements cast and cured under water;
(b) cores taken from deep within massive elements;
(c) surface concrete (the first 50 mm depth, or so) drying continuously.

Figure 4 shows strength-gain curves for typical Portland cement concrete made with dense aggregates, for various conditions, all test specimens having been soaked in water for 2 days prior to test. The curves correspond to the following curing conditions.

(1) water curing (BS 1881 cube curing regime);
(2) concrete protected from all water loss;
(3) concrete protected from water loss for 12 days, then allowed to dry to air;
(4) concrete protected from water loss for 5 days, then allowed to dry to air;
(5) concrete allowed to dry continuously to air.

Comparing the specimen situations (a) to (c) with conditions (1) to (5), it is probable that:

situation (a) corresponds to condition (1);
situation (b) corresponds to condition (2), (3) or (4) depending upon the depth in the structure;
situation (c) corresponds to condition (5).

If, from a consideration of the curing history of concrete cored for the estimation of Potential Strength (see clauses P/3.2.2.7 and P/3.5.2.1), it is found that the concrete in the test cores has received curing abnormal to that assumed by the Procedures for average on-site conditions (indicated by the broken line on Figure 4), an appropriate percentage should be selected from Figure 4 to replace the assumed value of 77%.

The Estimated Potential Strength for abnormally cured concrete may be calculated by first estimating the Actual Strength from the measured strength of cores complying with the requirements for Potential Strength determination, using the equations given in clause A/3.5.2.1, and then dividing this estimate of Actual Strength by the percentage value established from Figure 4.

Appendix 4 to Part 3: Correcting Core Strength for the influence of included steel

Cores used to measure the strength of concrete should not contain steel. Where this simply cannot be avoided, it must be expected that a reduction in measured strength will occur for a core containing steel (other than along its axis). The extent of this reduction depends upon many variables, and may range from zero to 20% (when large-diameter or multiple bars are present). When there *is* steel in the core, a factor should be used to multiply the Core Strength, or Estimated Actual or Potential Strengths, to correct for the presence of steel.

Allowing for a single bar

For a core containing a bar perpendicular to the axis of the core, the estimated Actual or Potential Strength should be corrected for the presence of steel by multiplying by the factor

$$1{\cdot}0 + 1{\cdot}5\left(\frac{\varphi_r}{\varphi_c} \times \frac{h}{L}\right)$$

where φ_r = diameter of bar;
φ_c = diameter of core;
h = distance of axis of bar from nearer end of core;
L = length of core.

Allowing for multiple bars

For multiple bars, their effect should be allowed for by using the factor

$$1{\cdot}0 + 1{\cdot}5\,\frac{\Sigma(\varphi_r \times h)}{\varphi_c \times L}$$

Note. For two bars which are no further apart at their closest point than the diameter of the larger bar, only the bar corresponding to the higher value of ($\varphi_r \times h$) needs to be included.

Appendix 5 to Part 3: A worked example using the recommended Procedures

This example from practice* illustrates how the Procedures have been used for the estimation of Potential Strength, with agreement between the interested parties, to resolve a problem in which the validity of cube strength data was in doubt.

The initial information

Specification
Specified strength: 20 N/mm²
No cube result below 17 N/mm² allowed at 28 days.

Construction
In situ reinforced concrete suspended floor slab and beams for a large multi-storey car park.

Interested parties
Specifying authority, contractor, ready-mixed concrete supplier and independent testing laboratory.

Concrete design and supplier's test data
A cement content agreed before the commencement of supply to this section of the contract formed the main criterion of design. The expected average strength of 31 N/mm² was in excess of that of 29 N/mm² required for the strength aspects of the specification.

Over a four-month period, test results for cubes made on site by the supplier averaged 32 N/mm², but during two of those months (the period in dispute) few tests were made on that site. Test results from other sites by the supplier, however, confirmed that the mix design remained satisfactory over that two-month period.

The situation
During the two-month period, 40 cube results at 28 days were obtained by the contractor using an independent testing laboratory for the later curing and crushing of the cubes. Ten (25%) of the results were below the characteristic strength of 20 N/mm² and two (5%) were below 17 N/mm².

The average strength was 22·5 N/mm².

No significant faults could be attributed to the manufacture of the cubes or their early curing.

Some cubes from the period in the waste heap at the testing laboratory had unusual modes of cube failure (unreported) and the gain in strength recorded generally from 7 to 28 days was unusually low. A cube test verification against a reference machine showed that the test laboratory machine was producing correct results currently, but a fault in the spherical seating existed which might have led to low results on occasions.

Planning and preliminary work	*Relevant clause in Part 3 Procedures*
In the light of this situation, the specifying authority required cores to be taken and convened a meeting of all four parties.	P/3.2.1
The prime *purpose* of the core tests was stated as estimation of Potential Strength for comparison with compliance requirements.	3.1.1, *Item 3* P/3.1.2.1
No *restrictions* applied. The concrete was made with Portland cement and natural aggregate and was between one and two months old.	P/3.1.2.4

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*Based on the use of a preliminary draft of Part 3. Minor adjustments have been made to the worked example to conform to the final recommendations, but these have not materially affected the estimates of Potential Strength or the conclusions.

P/3.2.2.4 The initial *number of cores* selected for test was 15, aimed at surveying all the suspect concrete, not any one particular batch.

P/3.2.2.5 The *location* was confined to slab areas which were to be drilled vertically downwards, avoiding reinforcement where possible, and only the lower half of each core was to be used as the test length.

P/3.2.2.6 The *size of core* selected was 100 mm diameter to minimize problems with reinforcement and to allow a test length of 100 mm before capping.

P/3.2.2.7 (a) The *Potential Density* of the concrete was agreed from the supplier's data at 2350 kg/m^3.

P/3.2.2.7 (b) The *curing history* for the slab was agreed as normal for the type of construction, and the weather had been generally moderate over the two-month period.

3.2.2.8 The preparation and testing was split between two testing *laboratories*.

3.2.2.9 The principle was agreed that correction for excessive voidage would be made before results were compared with *required strength levels* and that no extra factor was necessary for abnormal curing.

3.2.2.10 A site representative of the specifying authority present at the meeting was named as responsible for drilling *supervision*.

Obtaining the cores

3.3.2.2 On *examination* after drilling: only four cores contained steel, but outside the test length; none were honeycombed or bowed; and all had sufficient depth to enable the top 20% of the slab depth to be removed before capping.

Laboratory work

3.4.2.1 Each core was *trimmed to a test length* of about 100 to 110 mm (before capping) by using a masonry saw.

3.4.2.2 The cores were subjected to a visual *examination* as required by BS 1881 and a detailed report was prepared for each core.

3.4.2.3 High-alumina cement mortar *capping* was used and the resulting λ ratio ranged from 1·2 to 1·3.

3.4.2.4 A *density determination* was made on each core, the average saturated core density (D_a) 2315 kg/m^3 being 35 kg/m^3 below that of 2350 (D_p), the agreed Potential Density. Individual values ranged from 15 to 50 kg/m^3 below D_p.

3.4.2.5 *Testing of the cores* for strength was done to BS 1881, and measured core strengths were obtained ranging from 15·5 to 24·5 N/mm^2.

Estimating Potential Strength

P/3.5.2.1 (a) No allowance was necessary for unrepresentative concrete, the *composition* of each core being wholly from below the top 20% of the depth of the section.

P/3.5.2.1 (b) and Appendixes 1 and 2 Visual estimates of *Excess Voidage* ranged from 0·5 to 2%, averaging 1%.

The average Excess Voidage was estimated from core densities to be

$$\frac{35 \times 100}{2350 - 500} = 2\%$$

The agreed value for Estimated Excess Voidage was 1·5% to be used for all cores and required a correction factor for strength of 1·13.

The *curing history*, being typical, did not require an extra correction factor for abnormal curing. P/3.5.2.1 (c)

The cores were drilled vertically so that the appropriate formula for *estimation of Potential Strength* was P/3.5.2.1

$$1{\cdot}13 \times \frac{3}{1{\cdot}5 + 1/\lambda} \times \text{Core Strength}$$

Use of this formula yielded estimates of Potential Strength ranging from 23·0 to 36·5 N/mm^2 for the 15 cores, with an average value of 30 N/mm^2.

No *correction for presence of steel* in the cores was necessary. 3.5.2.2

Interpretation of results

At this stage, a comparison of the Estimated Potential Strengths from cores with specification requirements, supplier's results and independent test results indicated that: 3.6

(1) all estimates from cores exceeded the specified strength, 20 N/mm^2;

(2) the average estimate from cores of 30 N/mm^2 was not significantly different from that expected by the supplier from design (31 N/mm^2) or from results over the four-month period (32 N/mm^2);

(3) there was a large discrepancy between the average estimate from cores (30 N/mm^2) and that for cubes from the independent testing laboratory (22·5 N/mm^2).

Conclusions

It was concluded that concrete complying with the specification had been supplied and that the low cube test results reported by the independent testing laboratory were probably caused by a fault in the testing machine or in its operation, which had since been rectified (or had rectified itself). Further consideration of the concrete was probably unnecessary.

Note. As this was one of the first attempts to use the recommendations, the specifying authority, quite rightly, pursued the testing of additional cores (already drilled) which further confirmed the conclusions. A satisfactory load test was also made on an area of slab for which the lowest cube results had been obtained.

Consideration of *Actual Strength* was not necessary but use of the formula A/3.5.2.1 and A/3.6.2.1

$$\frac{2{\cdot}3}{1{\cdot}5 + 1/\lambda} \times \text{Core Strength}$$

would yield values ranging from 15·5 to 24·5 N/mm^2, all in excess of (Specified Strength)/1·5, i.e. 13·3 N/mm^2.

Use of non-destructive testing

A survey of the undersides of slabs and beams was made using Rebound Hammer tests as additional confirmation of the general quality and to reduce the number of cores taken.

Use of BS 1881 : Part 4:1970

Calculation of 'estimated cube strengths' as required by BS 1881 yielded values ranging from 18·5 to 28·5 N/mm^2, and averaging 23·5 N/mm^2. Use of these values as 'valid' estimates of Potential Strength might have led unnecessarily to prolonged discussion, mistrust of the supplier's information, acceptance of results from the independent testing laboratory and possibly to removal and replacement of some of the concrete.

Part 4. Other uses for cores

Cores may be required to be taken for a variety of purposes other than to assess strength. Some of these purposes provide additional information which can aid judgement of the validity of strength data, particularly in isolating causes of strength differences and in distinguishing effects due to the concrete itself, to workmanship and to the environment.

Some of the tests listed in Table 2 can be done, or are required to be done by the procedures of Part 3 of this report or by BS 1881, as part of the core test before crushing, e.g. assessment of voidage, without detriment to the strength determination. Some can be made on the crushed core but others need to be made on independent specimens to ensure accuracy, e.g. chemical analysis for water/cement ratio.

Table 2 Tests other than compressive strength, which may be made on cores to provide information to assist interpretation of strength data and for other purposes.

Non-destructive	Direct visual examination of core before trimming and capping (by naked eye or possibly hand lens)	Coarse aggregate	Nominal maximum size* Grading—continuous or discontinuous Particle shape* Mineralogy. Group Classification* Relative proportions, distribution in concrete*
		Fine aggregate	Nominal maximum size Grading—fine or coarse Type—natural, crushed or mixture Particle shape Relative proportion, distribution Mineralogy
		Cement	Colour of matrix of concrete
		Concrete	Compaction*, segregation*, porosity*, honeycombing* General composition, apparent coarse aggregate to mortar proportions Depth of carbonation Evidence of bleeding Evidence of plastic settlement, loss of bond Presence of entrained air Applied finishes, depth and other visible features Abrasion resistance Crack depth, width, other features Concrete depth, thickness Inclusions, particularly impurities Cold joints
		Reinforcement	Type (round, square, twisted, deformed) Size*, number, depth*/cover*
		Core drilling faults	Bowing Ridges
	Indirect visual examination of core before trimming and capping (by microscopic or petrographic techniques)		Mineralogy Air/sand content, bubble/void, size/spacing Microcracking Surface texture of coarse aggregates Fine aggregate particle shape, maximum size, grading Degradation
	Routine physical tests of cores before capping		Density Water absorption Ultrasonic-pulse velocity
Special physical tests of companion cores			Indirect tensile strength Abrasion resistance (surface only) Frost resistance Movement characteristics
Routine chemical tests of cores after crushing for strength			Aggregate/cement ratio Type of cement Aggregate grading (recovered) Sulphates Chlorides Contaminants Admixtures
Routine chemical tests of companion core (not to be used for compressive strength)			Water/cement ratio
Special tests on core after crushing for strength			Sulphate attack Cement and other minerals and mineral phases, and molecular groupings such as NaCl, CaCl$_2$, SO$_3$, C$_3$A etc. Contaminants Chloride attack High alumina conversion Aggregate reactivity

*Required by BS 1881 for the core test.

Part 5. Evidence from research and practice

Introduction

The procedures for estimating Actual and Potential Strength recommended in Part 3 are based upon information gained from practice and research. The object of this Part is to summarize the available knowledge, so enabling the validity and limitations of the recommendations to be assessed, and indicating aspects of the subject which would merit further investigation.

Relationship between Core Strength and Actual Strength

The main factors which need to be considered when relating the Core Strength to the Actual Strength are:

(1) diameter of core;
(2) length/diameter ratio of core;
(3) direction of drilling;
(4) shape of specimen;
(5) method of capping;
(6) effect of drilling operation;
(7) reinforcement;
(8) curing of core;
(9) moisture condition of core;
(10) flaws in core.

[redacted]

British Standard 1881[1] states that **cores shall have a diameter of either** [redacted] This standard does not relate the permissible diameter of the core to the maximum aggregate size, but standards[2-4] of other countries state **that the diameter of the** [redacted]es **the nominal maximum size** [redacted] **the aggregate.**

Several investigators[5-11] have examined the results of drilling cores with a diameter of less than three times the nominal maximum size of the aggregate. For example, cores having a diameter of 50 mm have been taken from concrete made with aggregate of 20 mm maximum size[6]. For a given height/diameter ratio, little, if any, difference was noted between the mean strengths yielded by cores of 50 and 100 mm diameters, but [redacted] **cores tended to** [redacted]**riable** results. Similar results were obtained during an investigation on the strengths of cores of 50, 100 and 150 mm diameter drilled from concrete with a maximum aggregate size of 30 mm[9]. In this case, it was shown that the testing error associated with 50 mm diameter cores was about twice that associated with 150 mm cores. This implies that, to obtain a similar degree of accuracy, more cores should be drilled if these are of small diameter.

Evidence is also available on the strengths of cores having a diameter equal to the maximum size of aggregate in the concrete. Cores of 150, 200 and 250 mm diameters were cut from concrete with aggregate of 150 mm maximum size; all yielded similar mean strengths[10]. The testing error again increased as the diameter of the cores was reduced.

Another investigation[11] involved the testing of cores of 35, 50, 75 and 100 mm diameter with mixes having maximum aggregate sizes of 4, 8 and 16 mm. It was found that it was difficult to obtain reliable results from the cores of 35 mm diameter.

The use of cores of 50 mm diameter to assess the compressive strength of concrete with aggregate of 30 mm maximum size is permitted by the relevant Swiss standard[12].

Table 3 Relative strength of cores of different diameters.

Reference	Number of cores	Strength of 100 mm dia. cores / Strength of 150 mm dia. cores
6	50	0·98
9	716	1·04
28	48	0·80*
31	—	1·00
36	128	1·05

*Several investigators have commented upon this result but there seems to be no explanation for its contrasting with other evidence.

Apart from tests on cores having a diameter less than three times the maximum aggregate size, the effect of size upon the compressive strength of different types of specimen, including cores, cylinders and cubes, has been studied by many investigators[6,8,9,11,13-38]. It is generally accepted that the strength tends to increase with decreasing size of specimen, there being several influencing factors which are discussed by various authors[8,17,28,37-41]. Any difference between the compressive strengths of 100 mm and 150 mm cubes is, however, so small that both RILEM[42] and CEB[43] suggest that it is of no significance.

Results of substantial programmes of tests on cores of 100 and 150 mm diameter, given in Table 3, indicate that, generally, the diameter has little, if any, effect upon the measured strength.

2

Length/diameter ratio of cores

The measured strength of a core decreases as the ratio of its length to its diameter, λ, increases. This report recommends that, when capped ready for test, a core should have a length/diameter ratio of between 1·0 and 1·2. It is, therefore, convenient to correct the measured strength of any core to obtain the strength which would have been obtained had the core a length/diameter ratio of 1·0.

The effect of the length/diameter ratio upon the strength of a cast cylinder or a core has been studied by many investigators[13,19,20,27,29,35,36,38,40,44-49]; the results of the tests are summarized in Table 4, all the data being based upon a specimen having a length/diameter ratio of 1·0. It is evident that there is a considerable range in the findings; it seems clear, however, that the relationship given in BS 1881[1] underestimates the difference in measured strength associated with a change in length/diameter ratio.

A detailed study of the results obtained in the various investigations suggests that the strength, f_1, of a core having a length/diameter ratio of 1, can be estimated from the strength, f_λ, of a core having a length/diameter ratio of λ, by the formula:

$$f_1 = \frac{2{\cdot}5 f_\lambda}{1{\cdot}5 + 1/\lambda}$$

It follows from this formula that the strength, f_2, of a core having a length/diameter ratio of 2, is yielded by the formula:

$$f_2 = \frac{2 f_\lambda}{1{\cdot}5 + 1/\lambda}$$

Table 4 Relative strength of cores of different length/diameter ratios.

λ	Relative strength										
	Cylinders						Cores				
0·5	1·53	1·62	1·33	1·30	1·52	—	1·39	—	1·37	—	—
1·0	1·00	1·00	1·00	1·00	1·00	1·00	1·00	1·00	1·00	1·00	1·00
1·5	0·88	0·88	0·89	0·90	—	0·87	0·83	0·82	0·88	0·84	0·95
2·0	0·85	0·86	0·83	0·87	0·86	0·84	0·84	0·75	0·81	0·82	0·92
3·0	—	0·81	0·78	—	0·84	—	—	—	—	0·80	—
Reference	44	13	20	46	47	29	46	48	36	38	BS 1881

3 *Direction of drilling*

Any heterogeneity in the concrete which is related to the direction of casting may have a different effect upon the strength of the core, depending upon the direction of drilling. Evidence regarding the effect is conflicting. The results of an investigation(29,50) on cores drilled from columns indicated that the strength was about 12% less if the cores were tested at right-angles to the direction of placing. More extensive tests by the same author(32) indicated a difference of only 3%, which is not statistically significant.

Johnson(45) found that cylinders cast with their axes horizontal had a compressive strength about 5% less than that of cylinders cast in the normal manner; Bloem(51) found the difference to average 15%. Other results(15,52-54) indicate that the compressive strength of cubes tested in the direction of casting may be similar to that of cubes tested at right-angles to the direction of casting or up to 20% higher.

Recognizing the discrepancies between results reported by the various investigators, Johnston(55) cast prisms from a range of 23 mixes. The findings from this carefully controlled programme indicated that the strength of prisms was 8% higher if these were tested in the same orientation as cast. The magnitude of this difference was similar for all normal-weight structural concrete.

This finding was in accord with results obtained by the Bureau of Reclamation(56,57) from a total of 237 cores drilled vertically and horizontally from two dams. These two investigations indicated that, on average, vertically drilled cores were stronger than horizontally drilled cores by 7 and 9% respectively.

4 *Shape of specimen*

Most of the available information relating the strengths of cylindrical and cubical test specimens is based upon tests on cast specimens rather than samples cut from a larger concrete mass. The measurements are usually made on standard test cubes and cylinders and so any observed relationship includes the orientation effect.

The considerable volume of information(5,15,20,30,36,48-50,58-71) indicates that the relationship between cylinder and cube strengths is not unique but depends upon factors such as the concrete mix and the precise methods of test. A summary paper produced by RILEM(19) shows that the ratio between the strengths of cubes and of cylinders with a length/diameter ratio of 2 has been found to vary from 0·9 and 1·5. A study of the information suggests that it is difficult to be more precise than to assume that the strength of a cube is 1·25 times that of a cylinder having a length/diameter ratio of 2. This value is in accord with the recommendations made by RILEM(42) and CEB(43) and is specified in BS 1881 for converting a corrected cylinder strength, obtained from a core test, to the equivalent cube strength.

5 *Method of capping*

Before being tested in accordance with BS 1881, the two ends of a core must be capped with a high-alumina-cement mortar, a sulphur–sand mixture or by other suitable means. The thickness and composition of the caps have some influence upon the strength of a core, as evidenced by several authors(15,16,27,32,49,71-84) but the effect is generally of no practical significance, provided that the capping material is not inherently weaker than the concrete and that the caps are sound and flat and perpendicular to the axis of the core, within the tolerances quoted in BS 1881. This conclusion is in agreement with the finding(74,85) that the same compressive strength is yielded by cylinders capped with neat cement or a mixture of sulphur and fire clay as is obtained from cylinders having ground end faces. It has been reported(83), however, that filled polyester resins are not suitable for capping, as they reduce the strength by up to 20%. It has also been found(32) that the use of filled polyester resins increases the variation in measured strengths.

6 *Effect of drilling operation*

It has been suggested that the operation of drilling can damage a core and hence reduce its compressive strength. Such damage is sometimes apparent when drilling immature or inherently weak concrete, but normally it is not possible to see any deleterious effects on the cut surface of a core.

A core may be inherently weaker than a cylinder because the surface of a core includes cut pieces of aggregate, many of which will only be retained in the specimen by adhesion to the matrix. Such particles are likely to contribute little to the strength of the core.

In the course of two investigations, sleeved cylinders have been cast within concrete slabs. Campbell and Tobin(28) cast 150 mm diameter metal sleeves in each of four 300 mm thick slabs. At ages of 28, 56 and 91 days, the strengths of pairs of these cylinders were compared with the strengths of pairs of cores of the same size and shape. On average, the cylinders had a strength 5% greater than the strength of the cores.

Similar tests are described by Bloem(86). Pairs of slabs were cast from each of three concrete mixes, one being well cured and one poorly cured. Each slab was provided with 36 plastics inserts to enable cylinders to be abstracted for test at six ages. The results were compared with those of 36 corresponding cores taken from each slab. The correlation between the strengths of the push-out cylinders and the cores was good and indicated that the compressive strength of the cylinders was 7% greater than the strength of the corresponding cores.

7 *Reinforcement*

The effect of reinforcing bars upon the strength of cylinders has been studied in the United States(87). A total of 66 cylinders was cast, some unreinforced, some with one bar perpendicular to the axis and others with two mutually perpendicular bars, both perpendicular to the axis. The particular location of the bars was found to have little effect upon the strength of the cylinders. The average reductions in strength are given in Table 5.

Similar tests(69,71) have been conducted on 170 cylinders, 300 mm long x 150 mm diameter, some of which contained single bars of 10 or 20 mm diameter, set at various depths and distances from the axis. The cylinders were tested after being stored for 26 days in air followed by 2 days in water. The average percentage reductions in strength are given in Table 6.

A series of tests conducted in Germany(88) involved the testing of more than 300 cores, 151 mm high and 99 mm in diameter, cut in a vertical direction from slabs. Variables included the percentage reinforcement, the number of bars, the positions of the bars and the strength of the concrete. The results indicated that as much as 3·4% by volume of reinforcement (two 18 mm bars) had little effect upon the measured strength, the maximum reduction being 3%.

Table 5 Average reduction in strength due to presence of one or two bars.(87)

Diameter of bar (mm)	Number of bars	Reduction in strength (%)
12	1	8
	2	11
25	1	9
	2	13

Table 6 Average reduction in strength due to presence of bars at different positions.(69,71)

Diameter of bar (mm)	Distance from axis (mm)	Reduction in strength (%) at distance from top of cylinder of 50 mm	150 mm	250 mm
10	0	1·5	2·6	3·8
	50	3·3	1·6	−0·4
20	0	3·5	11·6	−0·1
	50	10·4	8·6	5·4

8 *Curing of core*

Once a core has been cut, the method of curing, and hence the rate of strength development, will differ from that of the parent concrete. The difference in strength at the time of test will depend upon the maturity of the concrete when the core was drilled and upon the subsequent moisture and temperature history of both the parent concrete and the core. The concrete is usually mature at the time of drilling and any difference in the subsequent hydration of the specimen and the parent concrete is likely to be small; in any case, it will be very difficult to make a realistic allowance for the effect any difference may have upon the relative strengths of the core and of the concrete it represents.

9 *Moisture condition of core*

The measured strength of a core is dependent upon its moisture condition(86). BS 1881 requires that a core shall be immersed for a period of at least 48 h prior to test and that it shall still be wet when tested; this requirement is similar to that which applies to compressive tests on other concrete specimens including cubes. In principle, the effect of the moisture content at the time of test is not considered to be a characteristic of the concrete affecting its inherent strength but to be a parameter associated with the testing technique. Thus, it is akin to the rate of loading, which similarly affects the measured strength and is, therefore, also standardized. Provided a core is tested wet, therefore, it is not necessary to allow for the difference in moisture content when inferring the strength of the parent concrete.

Some authorities(3,4,33,35,89) do not share this opinion and advocate that the core at the time of test should be dry or have a moisture condition similar to that of the parent concrete in the structure. Account must be taken of the moisture condition at the time of test when reviewing results quoted by various investigators.

10 *Flaws in core*

There are many faults which can occur in a core; these include cracks due to a variety of causes, voids due to water gain beneath horizontal reinforcement and voids left upon removal of an immersion vibrator from a mix of low workability. The information gained upon examining such a core can be of considerable value, but the measured strength of the core is likely to be low and not indicative of the Actual Strength of the concrete.

Estimation of Actual Strength

The definition of the Actual Strength of the concrete within an element must be related to a specific test method. It would be possible to base the strength upon tests on a core of a given length/diameter ratio or on a sawn cube. The results of tests on the latter type of specimen would not, however, be directly comparable with strengths measured on cast cubes. Differences between Actual and Potential Strength would reflect both real differences between the two materials and effects of the different specimens. The latter effect can only be eliminated by expressing the Actual Strength in terms of tests on cast cubes, although these are hypothetical test specimens in that they cannot be produced from the concrete in the element.

The Actual Strength can be assessed from the Core Strength by considering the six specimens illustrated in Figure 5. These are:

1(a) core drilled horizontally*, length/diameter = λ
1(b) core drilled vertically, length/diameter = λ
1(c) core drilled vertically, length/diameter = 2
2(a) cylinder with top layer removed, length/diameter = 2
2(b) cylinder as cast, length/diameter = 2
3(a) cube tested on side.

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*The direction of drilling relates to the concrete at the time of casting.

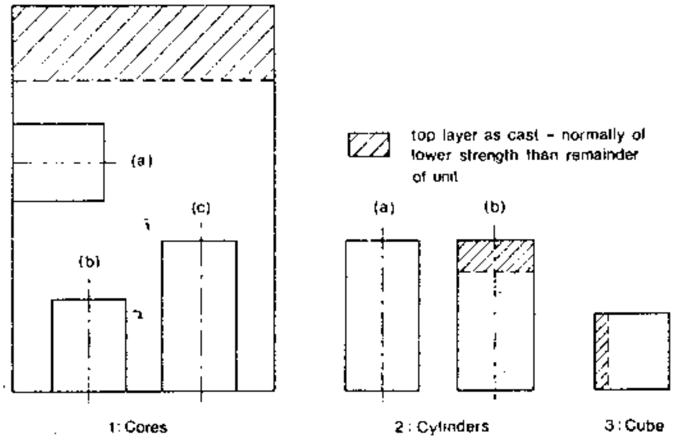

Figure 5: Types of specimen used in relating Core Strength and Actual Cube Strength.

The conversion process is as follows.

1(a) to 1(b) The difference between the strengths of these specimens is associated with the direction of drilling. On average, the strength of a core drilled vertically is about 8% greater than that of a core drilled horizontally. If the strength of 1(a) is p, the estimated strength of 1(b) is $1\cdot 08p$.

1(b) to 1(c) The effect of the length/diameter ratio upon core strength is such that

$$\text{the strength of 1(c)} = \frac{2}{1\cdot 5 + 1/\lambda} \times \text{the strength of 1(b)}$$

$$= \frac{2\cdot 16p}{1\cdot 5 + 1/\lambda}$$

1(c) to 2(a) The difference between the strengths of these specimens is associated with the fact that the cylinder has a cast, rather than a cut, surface. Experiments have indicated that a specimen with a cast surface has a strength about 6% greater than the core. Therefore,

$$\text{the strength of 2(a)} = 1\cdot 06 \times \text{the strength of 1(c)}$$

$$= \frac{2\cdot 29p}{1\cdot 5 + 1/\lambda}$$

2(a) to 2(b) The strength of the latter is lower because of the presence of the weaker material near the top. There is little direct evidence on the magnitude of this decrease but a general examination of the reduction in strength towards the top of a layer of concrete, the strengths of cores drilled from cubes and the relationship between actual and potential strength suggests that a value of 15% will yield results consistent with the available evidence. On this basis, it can be estimated that

$$\text{the strength of 2(b)} = \text{the strength of 2(a)} \times \frac{1}{1\cdot 15}$$

$$= \frac{2p}{1\cdot 5 + 1/\lambda}$$

2(b) to 3(a) There is a considerable volume of data on the relationship between the strength of a cube, tested on its side, and a cylinder. The best average estimate is that the cube strength is 25% greater than the cylinder strength. Hence

$$\text{the strength of 3(a)} = 1\cdot 25 \times \text{the strength of 2(b)}$$

$$= \frac{2\cdot 5p}{1\cdot 5 + 1/\lambda}$$

It may be noted that if $\lambda = 1$, the strength of 3(a) $= p$. This means that the strength of a core of length/diameter ratio 1, drilled horizontally, is similar to that of a cube; this is in line with evidence provided by tests made upon cores drilled from cubes. This is summarized in Table 7.

The Estimated Actual Strength, f_{act} is, therefore, yielded by the equations:

$$f_{act} = \frac{2\cdot 5f_\lambda}{1\cdot 5 + 1/\lambda}$$

if cores are drilled in a horizontal direction;

$$f_{act} = \frac{2\cdot 3f_\lambda}{1\cdot 5 + 1/\lambda}$$

if cores are drilled in a vertical direction.

Table 7 Evidence on relationship between core strength and cube strength.

Ref.	Cube size (mm)	Core diameter (mm)	*L/D* of cores. λ	$\frac{\text{Core strength}}{\text{Cube strength}}$	Approximate cube strength (N/mm²)
5	200	50	1·12	1·04*	10 to 50
30	150 and 200	100 and 150	1	1·02 to 1·05 0·86 to 1·16	31 68 and 80†
49	150	100	1	1·03 0·97	60 30
36	200	100 150	1	1·05 1·00	12 to 70 12 to 70
32 and 35	150	70 and 100	1	1·04	25 and 60

*Corrected to equivalent value for $\lambda = 1$
†Measured on 200 and 150 mm cubes respectively

Relationship between Actual and Potential Strength

The main factors which need to be considered when relating the Actual and Potential Strength are:

(1) differences in constituents;
(2) differences in mix proportions;
(3) differences in compaction;
(4) differences in curing.

1 *Differences in constituents*

It is possible for the actual quality to be reduced by the introduction of impurities to the concrete during the course of transporting and placing.

2 *Differences in mix proportions*

The mix proportions in a core may differ from those of a representative sample of the freshly mixed concrete because of incomplete mixing, the inadvertent or purposeful addition of water or the loss of materials by leakage, evaporation or transfer to surfaces with which the concrete comes into contact.

The most common reason for the mix proportions within part of a structural element being different from those of the freshly mixed concrete is, however, segregation. In particular, segregation in the form of bleeding, or water gain, is encouraged by the compaction process which causes a greater concentration of the lighter constituents towards the upper surface of the concrete. Many investigators(6,9,31,32,35,49,50,68,70,71,81,90-107) have noted that the concrete towards the top of a wall or column is weaker than the material elsewhere in the element.

The variation in strength over the depth of a well-cured slab has been studied by Meininger(6). The results indicated that any vertically drilled core containing material from the top 25% of the slab—whether the length of the core was 25%, 50% or 75% of the slab depth—had a strength about 8% less than cores not including material from the top 25% of the depth. Sherriff(70,71) cut 18 cores from a well cured slab; six were cut through the full depth of the slab whilst the others represented 50% and 75% of the full depth, from both upper and lower surfaces. The results indicate that a core including material from near the top of the slab has a strength about 11% less than that of other cores.

Henzel and Grube(102) tested over 200 cores from a well cured foundation slab having a depth of from 0·8 to 2 m. In this case, the strength of cores from the top 200 mm of the slab was only 4% less than the strength of cores cut from material at greater depth.

The available evidence indicates that the reduction in strength towards the top of a wall or column may be between 0 and 30% but gives little indication of the factors governing the magnitude of this decrease. Petersons(50) suggests, however, that the reduction in strength increases with the strength of the concrete, typical values being given in Table 8.

It is clear that the concrete towards the top of a lift, or near the upper surface of a slab, is not typical of the material as a whole and should, therefore, preferably be avoided when taking cores to assess Potential Strength. The study of the literature suggests that this unrepresentative material can be assumed to extend some 300 mm from the upper surface in deep lifts; if the depth of the concrete is less than 1·5 m, it can be taken that weaker concrete near the upper surface is confined to less than 20% of the full depth. Some of the literature(31,68,107), however, indicates that the variation can extend through the full depth of a wall.

Table 8 Reduction in strength at top of lift for different cube strengths according to Petersons.(50)

Cube strength (N/mm^2)	Reduction in strength at top of lift (%)
20	5 to 10
40	15 to 20
60	25 to 30

Table 9 Reduction in strength due to presence of entrapped air.

Aggregate	Free water/cement ratio	Reduction in strength (%)
Uncrushed gravel	⩽ 0·40	5
	0·41 to 0·54	6
	0·55 to 0·62	7
	⩾ 0·63	8
Crushed rock	⩽ 0·49	7
	0·50 to 0·58	8
	0·59 to 0·65	9
	⩾ 0·66	10

3 *Differences in compaction*

It is often considered that, for air contents up to about 10%, each 1% of entrapped air causes a reduction in compressive strength of some 5 to 6%. This is in general accord with the results of tests(108) but more recent evidence(109) indicates that the effect of the entrapped air upon the strength depends upon the nature of the coarse aggregate and the water/cement ratio of the concrete. Warren(110) has examined the results and concluded that each 1% of entrapped air reduces the compressive strength, on a compound basis, by the amount indicated in Table 9*.

The effect of a particular air void content upon the compressive strength of a core will be greater if the voids are unevenly distributed.

4 *Differences in curing*

An important factor affecting the relationship between the Actual Strength and the Potential Strength of concrete of the same age is the difference in the curing history between the concrete in a core and that in a cube representing the same batch of concrete. The difference in the curing may be occasioned by a difference in thermal history or in available moisture for hydration.

The thermal history of a concrete element of simple shape can be forecast(111) and used to estimate the equivalent age under the curing conditions applied to standard cubes(112). If the concrete is more than 28 days old, the difference in strength represented by the difference in equivalent age is likely to be low. In view of the imprecision

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*For example, if 1% of entrapped air reduces strength by 8%, 3% of entrapped air will reduce strength by $100(1 - 0{\cdot}92^3)\% = 22\%$.

of the estimates and assumptions involved, it is probably best to assume that any difference in strength caused by differences in thermal history can be ignored.

The possibility of the Actual Strength of the concrete being adversely affected by loss of moisture will depend upon circumstances. Evidence(113) suggests that it is essential to protect slabs but, in temperate climates, it is not normally necessary to cure formed surfaces after they have been struck.

The effect of curing upon the relationship between Actual and Potential Strength has, therefore, two distinct aspects:

the loss of moisture from the surface;
the general difference in curing conditions between the concrete in the structure and the test cube.

Loss of moisture from the surface. The evidence suggests that forms are likely to prevent serious loss of moisture, so that this is only likely to occur from a surface which is exposed from the time of casting. Such surfaces are obviously at the top of a lift and, hence, composed of concrete which is normally unrepresentative due to segregation; any reduction in strength caused by poor curing must be additional to the effect of segregation.

The effect of poor curing probably only extends to a depth of some 50 mm from the upper surface and so is seldom relevant to cores drilled horizontally. The little evidence available, therefore, is based upon cores drilled vertically into pairs of slabs, one of each pair being well cured and one poorly cured. Data available are summarized in Table 10.

General difference in curing conditions between the concrete in the structure and the test cube. Many investigators(6,8,10,28,31,32,35,48-50,67,70,74,81,86,90,92,102-104,114-121) have made direct observations on the relative strengths of specimens cut from walls, columns and slabs and of cast specimens of the same shape. Results have conflicted but, in general, it has been found that the strengths of cores taken from structures are lower than those of cast specimens tested at an age of 28 days, the reduction being up to about 30%. The cores, however, often included unrepresentative concrete near the top of a lift of a slab and many of the test methods differed considerably from procedures currently used in the United Kingdom; much of the earlier work was also conducted on cores drilled before diamond cutting was employed.

Some of the more reliable information is given in Table 11. Unless otherwise stated, the cores had a length/diameter ratio of 2; all cubes and cylinders were tested when the concrete was about 28 days old and unrepresentative concrete towards the top of a lift was not included in the cores. The use of parentheses indicates that the value concerned has been calculated on the basis that the cube strength is 1·25 times the cylinder strength.

Table 10 Reduction in strength due to poor curing according to various authors.

Reference	Reduction in core strength associated with poor curing (%)
70	11
81	14
86	25
114	25

Petersons(49) reviews the relationship between the core strength and the cylinder strength as evaluated by various authors. In a later paper(35) he suggests that the mean values of the strength in a finished structure are approximately related to the strengths of standard specimens as indicated in Table 12.

Upon reviewing all the available evidence, it is difficult to detect any consistent effect of either the strength level or the efficiency of curing upon the relationship between the strength of cores and of standard cubes. An assessment of all the results, with due regard to the degree to which the various results would seem to be reliable, suggests that it might be assumed that the following relationship is approximately true for cores taken from concrete cast on site and drilled vertically:

$$\text{Core Strength } (\lambda = 2) = 0{\cdot}67 \times \text{Potential Strength}$$

i.e.

$$\text{Potential Strength} = 1{\cdot}5 f_2$$

Estimation of Potential Strength

The Potential Strength can be assessed from the Core Strength by considering the three cores illustrated in Figure 5. As discussed earlier, if the strength of 1(a) is p, the strength of 1(c) is $2{\cdot}16p/(1{\cdot}5 + 1/\lambda)$. It has been shown that, in general, the Potential Strength is approximately 1·5 times the strength of a core of length/diameter ratio 2 drilled in a vertical direction. This only applies if the core is free of reinforcement, is well compacted and does not include the weaker material near the top of a lift.

The Estimated Potential Strength, f_{pot}, is therefore given by the equations:

$$f_{\text{pot}} = \frac{3{\cdot}25 f_\lambda}{1{\cdot}5 + 1/\lambda}$$

if cores are drilled in a horizontal direction;

$$f_{\text{pot}} = \frac{3 f_\lambda}{1{\cdot}5 + 1/\lambda}$$

if cores are drilled in a vertical direction.

Table 13 compares the values of Potential Strength yielded by the above formulae with values yielded by use of the data in BS 1881. The formulae yield higher strengths because BS 1881 takes no account of the direction of drilling or differences in curing; the increase is greater when the length/diameter ratio is high because BS 1881 underestimates the influence of length/diamter ratio upon core strength.

Difference between Actual and Potential Strength

The formulae for converting core strength to cube strength indicate that, if the concrete in the structure is fully compacted and normally cured, the Actual Strength is about 77% of the Potential Strength.

The relative strength of structural concrete and standard-cured cubes has been studied by non-destructive techniques(104,106,107). Results(107) obtained on four sites are summarized in Table 14.

The tests indicated a greater difference between Actual and Potential Strengths than given by the formulae. One reason for this is that the concrete tested included the weaker material towards the tops of lifts in walls and columns and near the upper surface of slabs.

Table 11 Relative strength of cores from structures and test cubes.

Direction of drilling	Core strength / Cylinder strength	Core strength / Cube strength	28 day cube strength (N/mm²)	Age of cores (days)	Ref.
Vertical	0·89	(0·71)	16 to 39	28	10
	0·94	0·89	16	28	48(1,2)
	0·84	0·74	31		
	0·75	0·64	49		
	0·91	(0·73)	44	93	81
	0·79	(0·63)			
	0·81	(0·65)	28	90	102(3)
	0·63	(0·50)	47	30	86(1)
	0·70	(0·56)	36		
	0·77	(0·62)	32		
	0·82	(0·66)	27	93	6
	0·88	(0·70)	44	91	114(1)
	(0·88)	0·71	35	34	70(4)
Horizontal	0·85	(0·68)	37	93	81
	0·81	(0·65)			
	0·73	(0·58)	27	93	6
	(1·13)	0·91	68	40	104(5)
	(1·10)	0·88	52		
	(0·89)	0·71	45 to 75	28	32(6)
	0·85	(0·68)	37	91	114
Both	(0·85)	0·68	—	28	121(7)

Notes

(1) Cores taken from full depth of slab
(2) Cores tested in moist condition
(3) Core strengths corrected from results of tests on cores with λ = 1·0
(4) Core strengths corrected from results of tests on cores with λ = 1·1
(5) Core strengths corrected from results of tests on cores with λ = 3·0
(6) Cores tested in dry condition
(7) Results based upon tests on 24 sites

Table 12 Relative strength of standard cylinders and cores from structures.(49)

Strength of standard cylinders (N/mm²)	Strength of cores (N/mm²)	Reduction in strength (%)
20	19	5
30	27	10
40	36*	15*
50	42·5	15

*Figures mathematically inconsistent

Table 14 Relative strength of concrete from actual structures and in cubes.(107)

Element	Number of sites	Mean ratio of Actual Strength to Potential Strength
Columns	3	0·68
Walls	2	0·59
Slabs	2	0·45

Table 13 Comparison of strength values yielded by use of formulae recommended here for Potential Strength and by use of data in BS 1881.

Method	Direction of drilling					
	Horizontal			Vertical		
	λ = 1*	λ = 1·2*	λ = 2	λ = 1*	λ = 1·2*	λ = 2
A: Formulae	$1{\cdot}30f_\lambda$	$1{\cdot}39f_\lambda$	$1{\cdot}62f_\lambda$	$1{\cdot}20f_\lambda$	$1{\cdot}29f_\lambda$	$1{\cdot}50f_\lambda$
B: BS 1881	$1{\cdot}15f_\lambda$	$1{\cdot}17f_\lambda$	$1{\cdot}25f_\lambda$	$1{\cdot}15f_\lambda$	$1{\cdot}17f_\lambda$	$1{\cdot}25f_\lambda$
$\frac{A-B}{B}$	13%	18%	30%	4%	10%	20%

*Limits recommended in Part 3

Effect of age upon Core Strength

Cores are often used to obtain an estimate of the Potential Strength prior to the time at which the cores are tested; it is, for example, often wished to obtain an estimate of the Potential Strength at 28 days from the results of core tests conducted at later ages. This necessitates some knowledge of the rate at which the concrete will gain strength.

Most of the available data on the increase in the strength of concrete with time have been obtained from tests on various types of standard specimen cured at a constant temperature while immersed in water. The results of these tests cannot be applied directly to elements of concrete within a larger mass because of differences in the temperature history and in the availability of moisture for hydration. Any allowance for the effect of age upon the strength of concrete must, therefore, be based upon data obtained on testing concrete cast as part of a larger mass or on specimens cured under similar conditions to concrete within a larger mass. It is doubtful whether the guidance on rate of gain of strength given in the Department of the Environment Specification for Road and Bridge Works(122) and in the Code of Practice for Structural Concrete(123) was obtained in this way.

The rate at which concrete gains strength also depends upon the characteristics of the cement, being influenced not only by the type of cement but by variations between different cements of the same type. The characteristics of cement have changed and differ between one country and another, so that any data which may be available may not be representative of current concrete produced in Britain.

Campbell and Tobin(28) conducted tests on cores drilled from well cured slabs cast in a laboratory; the slabs were made with Type 1 cement, the American equivalent of ordinary Portland cement. The results of the tests on concrete made with aggregates of normal density indicated an increase of strength of between 3 and 13% between the ages of 28 and 84 days.

Bloem(86) conducted similar tests which indicated a gain of 11% between 28 and 91 days, when Type 1 cement was used, and between 4 and 13% when using cement of Type III, which is the American equivalent of rapid-hardening Portland cement. These results were obtained from cores taken from slabs which were well cured; cores taken from poorly cured slabs had 91 day strengths of between 92 and 102% of the 28 day value. Bloem's results also indicated a strength reduction between 28 days and a year of between 1 and 8% for the well cured slabs and between 10 and 17% for the poorly cured elements. No explanation is offered for the reduction in strength with increasing age.

Higginson and Townsend(124) provide information on the strengths of 900 mm long x 450 mm diameter cores drilled from 13 mass concrete dams constructed over a period of 30 years. The mixes were made with sulphate-resisting cements, of Types II and IV, and most mixes included pozzolanic materials and/or air-entraining agents. Understandably, the results showed considerable variations between one site and another but they did indicate a consistent increase in strength with the increasing ages of test of 28, 90, 180 and 365 days. Other tests conducted by the Bureau of Reclamation(56,57,124-126) show that the strength of mass concrete consistently increases over a period of 22 years.

Ultrasonic-pulse-velocity tests(107) made on sites in the United Kingdom indicated an increase in strength of approximately 30% from 28 days to 6 months and about 3% from 6 months to 1 year. The results of a more recent analysis of these, and later, results(127) are summarized in Table 15.

Table 15 Increase in strength with age from ultrasonic-pulse-velocity tests.(127)

Site	Number of members tested	Mean increase in strength between ages of 28 days and 6 months (%)
A	16	22
B	4	35
D	19	30
X	47	20
Y	11	24

Table 16 Increase of Actual Strength with age.

Age	Actual Strength as found in reference			Inferred range
(days)	28	84	105	
28	100	100	100	100
91	103 to 113	111	—	100 to 120
182	—	—	130	100 to 130
364	—	101 to 108	134	100 to 135

The tests on the 97 members showed a mean increase of 23%, the increase being similar for columns, walls and slabs. It was not possible to identify the factors responsible for difference in the gain in strength between one site and another.

Two of the authors of this Report have independently conducted compressive tests on cubes cured by various regimes but all immersed in water for at least two days before test. The results suggest that concrete gains little, if any, strength after 28 days if the method of curing is such as to reduce the strength to less than 80% of the Potential Strength. Such a method of curing applies in structures, the formulae developed in this Report indicating that the Actual Strength is, on average, about 77% of the Potential Strength.

The relative strengths at different ages of cores taken from properly cured concrete, made with ordinary Portland cement and no admixture, are summarized in Table 16.

Variability of results

There is a considerable amount of information(6,8-11,29,33,86) on the variability of cores cut from slabs and walls. This indicates that there is a tendency for the variability to be greater when the cores are of small diameter, although some investigations indicate that the size of core has no significant effect.

It is difficult to summarize the available information; in some cases, the variation is high, probably because it reflects the heterogeneity of the parent concrete, whilst in others low values have been recorded, often on the basis of a small number of results. Table 17 gives an indication of the coefficients of variation which might be expected from cores drilled vertically from slabs cast in a laboratory and horizontally from the lower parts of walls cast in a

Table 17 Typical coefficients of variation for the strengths of cores drilled from concrete cast in a laboratory.

Direction of drilling	Coefficient of variation for cores of diameter		
	50 mm	100 mm	150 mm
Vertically from slab	7%	5%	3%
Horizontally from wall	10%	8%	6%

laboratory. These figures may be compared with a coefficient of variation of about 3% which can be achieved when testing cubes[128].

In practical situations, the variability of the Core Strengths is, to some extent, indicative of the variation in Actual Strength in a structure. It is, however, little guide to the precision with which the Potential Strength may be estimated as this depends, to a very large extent, upon the validity of the various conversion factors employed.

Further research

It is clear that there is no simple relationship between the mean strength of a set of cores and the Potential Strength of the concrete; any estimate of Potential Strength will, therefore, be subject to considerable error. This error is related both to the inherent variability in the strengths of individual cores from one batch of concrete and the reliability of the conversion factors applied. There is, therefore, a limit to the additional precision which can be achieved by testing a larger number of cores. It may be possible to develop improved formulae to convert Core Strength to Potential Strength but it will always be necessary to accept a substantial measure of approximation. A major improvement in the reliability of the assessed values of Potential Strength might be achieved if more information were to be obtained on the difference between the actual and potential qualities. This would enable a more realistic method of converting Core Strength to Potential Strength to be developed; this might take specific account of some of the influencing factors such as the thermal history and moisture condition of the concrete. The precision with which the Potential Strength could be assessed would also be improved if a more accurate method of assessing the reduction in Core Strength caused by the presence of voids could be developed; more knowledge on the effect of age upon the strength of in situ concrete could also be of considerable value.

The estimate of Actual Strength is likely to be more reliable than an assessment of Potential Strength because it is not necessary to use so many conversion factors. Again, it is possible that the recommended equations may have a consistent tendency to give either high or low results. A better estimate might be achieved if more data relative to the various conversion factors were to be obtained. The main problem in assessing Actual Strength is, however, likely to lie in the interpretation of the result rather than in its derivation.

References

1. BRITISH STANDARDS INSTITUTION. BS 1881:1970. *Methods of testing concrete. Part 4: Methods of testing concrete for strength.* London. pp. 25.
2. AMERICAN SOCIETY FOR TESTING AND MATERIALS. C42–68. *Standard method of obtaining and testing drilled cores and sawed beams of concrete.* Philadelphia. Part 14. pp. 32–36.
3. DEUTSCHEN NORMENAUSSCHUSS. DIN 1048: Part 2: 1972. *Prüfverfahren für Beton: Bestimmung der Druckfestigkeit von Festbeton fertiger Bauwerke und Bauglieder.* (Testing methods for concrete: compressive strength of concrete in structures and members.) Berlin. p. 1.
4. STANDARDS ASSOCIATION OF AUSTRALIA. AS 1012. Part 14: 1973. *Method for securing and testing cores from hardened concrete for compressive strength or indirect tensile strength.* Sydney. pp. 12.
5. JOOSTING, R. Le prélèvement et l'examen de petites carottes de béton. (Drilling and examining of small concrete cores.) *RILEM symposium on the experimental research of field testing of concrete. 5th–7th October 1964.* Trondheim. pp. 376–382.
6. MEININGER, R. C. Effect of core diameter on measured concrete strength. *Journal of Materials.* Vol. 3. No. 2. June 1968. pp. 320–336.
7. MAURER, A. Carottes de petit diamètre. (Cores of small diameter.) *Bulletin du Ciment.* Vol. 38. No. 3. March 1970. pp. 1–4.
8. LEWIS, R. K. *The compressive strength of concrete cores.* Melbourne, Commonwealth Scientific and Industrial Research Organisation, 1972. pp. 15. Report L.18.
9. HENZEL, J. and FREITAG, W. Zur Ermittlung der Betondruckfestigkeit im Bauwerk mit Hilfe von Bohrkernen kleineren Durchmessers. (The determination of the compressive strength of concrete in a structure with the aid of test cores of small diameter.) *Beton.* Vol. 19. No. 4. April 1969. pp. 151–155.
10. MATHER, B. and TYNES, W. O. Investigation of compressive strength of molded cylinders and drilled cores of concrete. *Journal of the American Concrete Institute. Proceedings* Vol. 57. No. 7. January 1961. pp. 767–778.
11. POIJÄRVI, H. and SYRJÄLÄ. *Ohuiden rakenteiden betonin lujuuden määritys porausnäytteiden avulla.* (Evaluation of concrete strength in thin walled structures by means of cores.) Helsinki. The State Institute for Technical Research. 1969. pp. 31. Series 3.
12. SCHWEIZERISCHER INGENIEUR UND ARCHITEKTEN VEREIN. *Norm für die Berechnung, Konstruktion und Ausführung von Bauwerken aus Beton, Stahlbeton und Spannbeton.* (Standard for the design, construction and performance of plain, reinforced and prestressed concrete structures.) Zurich. Schweizerischer Ingenieur und Architekten Verein. 1968. pp. 80. Technische Norm 162.
13. GONNERMAN, H. F. *Effect of size and shape of test specimens on compressive strength of concrete.* Chicago, Lewis Institute, Structural Research Laboratory, 1925. pp. 16. Bulletin No. 16.
14. BLANKS, R. F. and McNAMARA, C. C. Mass concrete tests in large cylinders. *Journal of the American Concrete Institute. Proceedings* Vol. 31, No. 3. January–February 1935. pp. 280–303.
15. L'HERMITE, R. Recent research on concrete. *Annales des Travaux Publics de Belgique.* Vol. 50. No. 5. October 1949. pp. 481–510. (Translated from the French.) London, Cement and Concrete Association. 1951. pp. 31. 61.024.
16. PRICE, W. H. Factors influencing concrete strength. *Journal of the American Concrete Institute. Proceedings* Vol. 47. No. 6. February 1951. pp. 417–432.
17. NEVILLE, A. M. The influence of size of concrete test cubes on mean strength and standard deviation. *Magazine of Concrete Research.* Vol. 8. No. 23. August 1956. pp. 101–110.
18. Discussion on reference 17. *Magazine of Concrete Research.* Vol. 9, No. 25. March 1957. pp. 52–55.