BS 6089:2010





BSI Standards Publication

Assessment of in-situ compressive strength in structures and precast concrete components – Complementary guidance to that given in BS EN 13791

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Contents

Summary of pages
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Foreword

Publishing information

This British Standard is published by BSI and came into effect on 30 April 2010. It was prepared by Technical Committee B/517, *Concrete*. A list of organizations represented on this committee can be obtained on request to its secretary.

Supersession

This British Standard supersedes BS 6089:1981, which is withdrawn.

Information about this document

This is a full revision of the standard and introduces the following principal changes:

- this Standard has been completely re-structured as complementary guidance to BS EN 13791;
- techniques used in the assessment of the strength of structures, but not included in BS EN 13791, are described;
- flowcharts are included to help users find the appropriate information for their needs.

Use of this document

As a guide, this British Standard takes the form of guidance and recommendations. It should not be quoted as if it were a specification or a code of practice and claims of compliance cannot be made to it.

Contractual and legal considerations

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

Compliance with a British Standard cannot confer immunity from legal obligations.

Introduction

BS EN 13791 contains some methods for assessing the strength of structures, but there are other techniques that are useful for this purpose. As these techniques are not defined in the European standard, it is permitted to describe these techniques in a complementary British Standard. BS EN 13791 also permits the method for calculating the in-situ characteristic strength of existing structures about which there is no prior knowledge from core data to be defined in the place of use. Due to the uncertainties associated with investigating unknown structures, the committee wished to define a slightly more conservative system based on established statistical principles. This system is defined in this British Standard.

The publication of BS EN 13791 superseded part of BS 6089:1981. The information that was not superseded is still regarded as being useful and worthy of inclusion in a complementary British Standard to BS EN 13791. In addition, Concrete Society Technical Report (CSTR) 11 [1] is no longer regarded as best practice and is superseded in part by BS EN 13791. In places it also conflicts with BS EN 13791. Consequently, aspects of the CSTR 11 approach have been adopted within the overall system described in this British Standard and the Concrete Society's contribution to this British Standard is acknowledged.

BS EN 12504-1 describes the method for taking and reporting core tests, which is a building block for BS EN 13791 and this British Standard. BS EN 12504-1 describes how the core strength is measured and reported. To use such data in structural assessment, it is necessary to correct core test data for the length:diameter ratio and transverse reinforcement. The values for such corrections are given in the UK National Annex (NA) to BS EN 12504-1, and there is a recommendation in the UK NA to report both the measured strength and the corrected strength. In addition, it is useful and sometimes essential to know the voidage of the cores for the interpretation of the information. The UK NA to BS EN 12504-1 recommends the excess voidage be measured and reported. It ought to be noted that the corrected core strength does not include a correction for voidage as such a correction is inappropriate when determining characteristic in-situ strength.

The assessment of compressive strength in old structures is an area where fixed rules do not apply. The guidance supplied in this British Standard needs to be considered in the light of the specific situation and engineering judgement applied to the specific case.

In general, when dealing with disputes over concrete quality, an assessment with respect to structural adequacy gives the same outcome as an assessment of whether the concrete conforms to its specification. However, there will be a few situations where the concrete will be shown to conform to its specification, yet from a structural viewpoint be inadequate. BS 6089 provides no guidance on what should be done in such a situation. The relevant CEN Technical Committees have been made aware of this issue.

1 Scope

This British Standard complements BS EN 13791, which gives methods for determining the characteristic in-situ compressive strength in concrete structures and precast concrete components based on:

a) core testing;

b) rebound hammer, ultrasonic pulse velocity and pull-out force measurements after a relationship with core strength has been determined for the particular concrete under investigation.

This British Standard provides additional guidance on:

- planning an investigation (see Clause **5**);
- selection of test methods (see **5.4**);
- selection of the test locations (see **5.5** and **5.6**);
- assessment of individual core results within a group (see **6.1**);
- assessment where the strength of concrete based on test specimens is in doubt (see Clause **7**).

In addition, this British Standard provides guidance on the following cases not covered by BS EN 13791:

- assessment of an unknown structure using a margin based on the t-statistic (see **6.2**);
- use of indirect methods without correlation to core strength (see **6.3**);
- relative testing, i.e. comparison of a volume of concrete under investigation with concrete in similar elements that has been accepted (see **6.4**);
- action when the producer has declared nonconformity (see Clause **8**).

This British Standard does not provide guidance on:

- the use of cores with a diameter of less than 50 mm or the use of microcores;
- whether a structure has adequate durability;
- the use of in-situ testing as an alternative to conformity testing based on test specimens.

  NOTE For completeness, Figure 1 and Figure 2 identify such a procedure but this British Standard does not attempt to provide any of the necessary detail.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

BS 1881-201, *Testing concrete – Part 201: Guide to the use of non-destructive methods of test for hardened concrete*

BS EN 206-1:2000, *Concrete – Part 1: Specification, performance, production and conformity*

BS EN 12390 (all parts), *Testing hardened concrete*

BS EN 12504-1, *Testing concrete in structures – Part 1: Cored specimens – Taking, examining and testing in compression* (including National Annex)

BS EN 12504-2, *Testing concrete in structures – Part 2: Non-destructive testing – Determination of rebound number*

BS EN 12504-3, *Testing concrete in structures – Part 3: Determination of pull-out force*

BS EN 12504-4, *Testing concrete in structures – Part 4: Determination of ultrasonic pulse velocity*

BS EN 13791:2007, *Assessment of in-situ compressive strength in structures and precast concrete components*

PD 6687, *Background paper to the UK National Annexes to BS EN 1992-1*

AINSWORTH, P. R. and HOPKINS, C. J. *Action in the case of nonconformity of concrete structures, C519.* CIRIA, 2000. ISBN 978 0 86017 519 3 [1)]

3 Terms and definitions, symbols and subscripts

3.1 Terms and definitions

For the purposes of this standard, the terms and definitions given in BS EN 13791, BS EN 12504-1 and the following apply.

3.1.1 corrected core strength
core compressive strength modified to a given length:diameter ratio, usually 1:1 or 2:1 and adjusted to take account of transverse reinforcement, if any

NOTE See UK National Annex to BS EN 12504-1.

3.1.2 estimated potential strength
estimate of the 28-day cube/cylinder strength of the concrete supplied to the works under investigation based on a measured in-situ core strength

*NOTE See **3.1.5**.*

3.1.3 excess voidage
voidage in excess of that achieved in standard test specimens or in the case of air-entrained concrete, voidage in excess of the upper limit on air content

*NOTE See BS EN 206-1:2000, **5.4.3**.*

3.1.4 maturity
function of age and temperature such that for a given concrete, any batch with the same maturity will have the same compressive strength

NOTE General current practice is to express maturity as equivalent age in days at 20 °C.

1) Available from Construction Industry Research and Information Association (CIRIA) at www.ciria.org.uk.

3.1.5 potential strength

notional compressive strength of concrete in the volume represented by the core if it had been wholly moulded as standard specimens and tested at 28 days in accordance with the relevant parts of BS EN 12390

3.2 Symbols and subscripts

For the purposes of this standard, the symbols and subscripts in Table 1, Table 2 and Table 3 apply.

Table 1 **Symbols**

Symbol	Explanation
K_v	correction factor for excess voidage
n	number of results
R_t	ratio used when testing for statistical outliers
s	sample standard deviation
s_r	sample standard deviation of reference element
s_s	sample standard deviation of element under investigation
$t_{0.05}$	t-value used in the determination of characteristic strength
v	degrees of freedom
$\overline{X_r}$	mean ultrasonic pulse velocity (UPV)/rebound number of the reference element
$\overline{X_s}$	mean UPV/rebound number of the element under investigation
γ_m/η	partial safety factor for difference in strength between test specimens and the structure
σ_{is}	estimated population standard deviation of in-situ strength measurements

Table 2 **Subscripts used in the relationships between different expressions of strength when the compressive strength of the structure is to be assessed using equivalent cubes**

Subscript	Explanation
f_{is}	*Core compressive strength.* Compressive strength of a core, tested in accordance with BS EN 12504-1.
$f_{is, cube}$	*Core compressive strength expressed as the strength of an equivalent cube.* Compressive strength of a core, tested in accordance with BS EN 12504-1 when the length:diameter ratio is 1:1. *NOTE Whenever practical, the Engineer ought to specify that cores to be tested have a length:diameter ratio of 1:1. In this case* f_{is} *is equal to* $f_{is, cube}$.
$f_{is, cube, corrected}$	*Corrected core strength expressed as the strength of an equivalent cube.* Core compressive strength after correction for any transverse reinforcement and the length:diameter ratio using the factors given in the UK National Annex to BS EN 12504-1, $f_{is, cube, corrected} = K_{is, cube} K_s f_{is}$. *NOTE If the core has a length:diameter ratio of 1:1 and no transverse reinforcement,* $f_{is} = f_{is, cube} = f_{is, cube, corrected}$. *These are the individual core data that are used for the assessment of structural adequacy.*
$f_{is, cube, location}$	*Average in-situ core strength at a single location.* Mean strength of two or more corrected core strengths taken at a single location.
$f_{is, lowest}$	*Lowest core strength expressed as the strength of an equivalent cube.* Lowest value of $f_{is, cube, corrected}$ for a set of "n" results.
$f_{m(n), is}$	*Mean core strength expressed as the strength of an equivalent cube.* Mean of "n" values of $f_{is, cube, corrected}$.
$f_{ck, is, cube}$	*Characteristic in-situ strength expressed as the strength of an equivalent cube.* Characteristic in-situ cube strength determined from the set of "n" values of $f_{is, cube, corrected}$ or $f_{is, cube, location}$ and determined in accordance with the requirements of BS EN 13791 and this British Standard. *NOTE Prior to taking the cores, it ought to be agreed if the individual corrected core results or the average core strength at each location are to be used to determine the in-situ characteristic strength.*
f_{ck}	*Characteristic strength.* Estimated characteristic cube strength used in structural assessment, determined from $f_{ck, is, cube}/0.85$.
$f_{ck, spec}$	*Specified characteristic strength.* The minimum characteristic strength associated with the specified compressive strength class; see BS EN 206-1:2000, Table 7 and Table 8.
$f_{is, cube, corrected, compacted}$	*Corrected core strength if fully compacted.* Corrected core strength adjusted for excess voidage in accordance with **A.3**, expressed as the strength of an equivalent cube. *NOTE This is only used in the determination of potential strength.*
$f_{pot, cube}$	*Potential strength.* Potential strength expressed in terms of cube strength; see **3.1.5**.

NOTE The terms f_{is}, $f_{is, lowest}$, $f_{m(n), is}$ *and* f_{ck} *are also used when the adequacy of a structure is to be determined using equivalent cylinders, but the derivation and numerical values are different; see Table 3.*

Table 3 **Subscripts used in the relationships between different expressions of strength when the compressive strength of the structure is to be assessed using equivalent cylinders**

Subscript	Explanation
f_{is}	*Core compressive strength.* Compressive strength of a core, tested in accordance with BS EN 12504-1.
$f_{is, cyl}$	*Core compressive strength expressed as the strength of an equivalent cylinder.* Compressive strength of a core, tested in accordance with BS EN 12504-1 when the length:diameter ratio is 2:1. *NOTE Whenever practical, the Engineer ought to specify that cores to be tested have a length:diameter ratio of 2:1. In this case f_{is} is equal to $f_{is, cyl}$.*
$f_{is, cyl, corrected}$	*Corrected core strength expressed as the strength of an equivalent cylinder.* Core compressive strength after correction for any transverse reinforcement and the length:diameter ratio using the factors given in the UK National Annex to BS EN 12504-1, $f_{is, cyl, corrected} = K_{is, cyl} K_s f_{is}$. *NOTE If the core has a length:diameter ratio of 2:1 and no transverse reinforcement, $f_{is} = f_{is, cyl} = f_{is, cyl, corrected}$. These are the individual core data that are used for the assessment of structural adequacy.*
$f_{is, cyl, location}$	*Average in-situ cylinder strength at a single location.* The average strength of two or more corrected core strengths taken at a single location.
$f_{is, lowest}$	*Lowest core strength expressed as the strength of an equivalent cylinder.* Lowest value of $f_{is, cyl, corrected}$ for a set of "n" results.
$f_{m(n), is}$	*Mean core strength expressed as the strength of an equivalent cylinder.* Mean of "n" values of $f_{is, cyl, corrected}$.
$f_{ck, is, cyl}$	*Characteristic in-situ strength expressed as the strength of an equivalent cylinder.* Characteristic in-situ cylinder strength determined from the set of "n" values of $f_{is, cyl, corrected}$ or $f_{is, cyl, location}$ and determined in accordance with BS EN 13791 and this British Standard. *NOTE Prior to taking the cores, it ought to be agreed if the individual corrected core results or the average core strength at each location are to be used to determine the in-situ characteristic strength.*
f_{ck}	*Characteristic strength.* Estimated characteristic cylinder strength used in structural assessment, determined from $f_{ck, is, cyl}/0.85$.
$f_{ck, spec}$	*Specified characteristic strength.* The minimum characteristic strength associated with the specified compressive strength class; see BS EN 206-1:2000, Table 7 and Table 8.
$f_{is, cyl, corrected, compacted}$	*Corrected core strength if fully compacted.* Corrected core strength adjusted for excess voidage in accordance with **A.3** expressed as the strength of an equivalent cylinder. *NOTE This is only used in the determination of potential strength.*
$f_{pot, cyl}$	*Potential strength.* Potential strength expressed in terms of cylinder strength; see **3.1.5**.

NOTE The terms f_{is}, $f_{is, lowest}$, $f_{m(n), is}$ and f_{ck} are also used when the adequacy of a structure is to be determined using equivalent cubes, but the derivation and numerical values are different; see Table 2.

Throughout BS EN 13791, where the term f_{is} is used, this should be taken as meaning $f_{is, cube, corrected}$, or $f_{is, cyl, corrected}$, depending upon whether the strength is to be assessed using equivalent cubes or equivalent cylinders. By agreement prior to testing, it can also mean $f_{is, cube or cyl, location}$.

4 Relationship between standard specimen 28-day strength and in-situ strength

NOTE 1 The ratio of characteristic in-situ compressive strength to characteristic compressive strength of standard specimens is based on comparing cores and standard specimens with exactly the same maturity and it is not valid when the maturity is different.

*In BS EN 13791:2007, Clause **6**, the compressive strength class is determined from characteristic in-situ strength divided by 0.85 with some rounding to give whole numbers.*

The characteristic strength (f_{ck}) can be used directly for checking structural adequacy without converting it into a compressive strength class.

The characteristic strength $f_{ck} = f_{ck, is, cube}/0.85$ or $f_{ck, is, cyl}/0.85$ depending on whether the characteristic strength is to be expressed in terms of cube strength or 2:1 cylinder strength. If structural adequacy is being checked using British Standards of national origin, e.g. BS 8110, the characteristic strength should be in terms of cube strength. However, if it is being checked using BS EN 1992-1-1 or other European design codes, the characteristic strength should be in terms of cylinder strength. While it is possible to estimate the characteristic strength expressed in terms of cubes or 2:1 cylinders from any set of core length:diameter ratios, the conversion factors introduce additional uncertainty into the estimated characteristic strength, which can be avoided by specifying that the cores be tested at the appropriate length:diameter ratio (1:1 for cubes and 2:1 for 2:1 cylinders). Where correction factors are needed, these are given in the UK National Annex to BS EN 12504-1.

The calculated compressive strength class is a function of the maturity of the cores at testing. In normal situations, concrete gains strength with increasing maturity provided that there is water for continued hydration and so any estimate based on cores taken at an earlier age will give conservative (safe) estimates of the compressive strength class. When testing structures with a maturity greater than 28 days at 20 °C, it is not necessary to take maturity into account except when estimating potential strength.

The procedure in BS EN 13791:2007, **7.1**, for curing cores should be followed. However, if it is necessary to test saturated cores, the strength may be enhanced to take this difference in testing into account; see **5.4** for a recommended value.

*NOTE 2 According to BS EN 13791:2007, **7.1**, the cores are normally tested after three days of storage in laboratory air and this gives a higher strength than if they had been tested in a saturated condition (see BS EN 13791:2007, **A.2.1**). The factor of 0.85 in BS EN 13791 is compatible with previous UK practice, which used a factor of 0.77 for Portland cement (CEMI) concrete and water cured cubes.*

BS EN 13791:2007, **7.1**, Note 3, recommends that the core compressive strength is not modified for the direction of drilling. The National Annex to BS EN 12504-1 also recommends not modifying the core compressive strength for the direction of drilling.

NOTE 3 Past practice in the UK has been to take account of the direction of drilling. As this British Standard recommends that the tested core does not contain concrete from the top of a section, enhancing the core compressive strength of vertically cut cores for the direction of drilling is not justified.

The 0.85 ratio is used for calculating the minimum acceptable in-situ strength in cases of doubt over concrete quality. BS EN 206-1 permits the strength of an individual batch, which, for example, can comprise the concrete in several columns, to be (f_{ck} – 4) N/mm^2. Therefore, the minimum acceptable in-situ compressive strength for a conforming batch of concrete is: 0.85 (f_{ck} – 4) N/mm^2.

In BS EN 13791:2007, Clause **9**, this equation is used to check if a local area came from concrete conforming to BS EN 206-1. If this requirement is satisfied, further checks on structural adequacy are not needed.

In practice, the in-situ strength is also a function of the location in the section. Generally, the concrete is weaker on the upper sections, particularly with columns, and stronger at the base of a section. This is why the selection of the test locations is so important.

5 Planning an investigation

5.1 Information required from the tests

Knowledge of the in-situ compressive strength of concrete in a structural member might be required for one or more of the following reasons:

a) assessment of an existing structure prior to refurbishment or new use;

b) deterioration of concrete due to:
   - overloading;
   - fatigue;
   - chemical action;
   - fire;
   - explosion;
   - weathering;

c) to ascertain whether the in-situ strength of concrete is acceptable for:
   - the designed loading system;
   - the actual loading system;
   - a projected loading system for a new use;

d) doubt concerning the strength of concrete in the structure due to:
   - nonconformity of concrete;
   - differences between identity testing and conformity;
   - workmanship involved in placing, compacting or curing of concrete.

NOTE Where the strength in the structure is unknown, e.g. in assessing an old structure, the assessment of characteristic in-situ compressive strength ought to be conservative and the fewer the number of data, the more conservative the estimated characteristic strength ought to be to compensate for the uncertainty associated with few data.

*Where the assessment of the in-situ compressive strength is undertaken to resolve doubt over the quality of concrete supplied to the structure, the validity of whether the concrete in the structure came from a population meeting the specified compressive strength class is being tested. In these situations, the null hypothesis is that the concrete came from a conforming population and the fewer the data that are available, the less evidence there is to reject the hypothesis and the concrete. Even when the tests show the concrete in the structure lacks the required strength, it is a complex process with a high level of uncertainty to show that the concrete failed to meet its specification. The reasons for this are that the corrected core strengths (**3.1.1**) have to be adjusted for excess voidage, curing and maturity to obtain the estimated potential strength (**3.1.2**). The maturity of concrete depends upon its temperature history, which is not normally known and is a function of cement type and content, section size, formwork type, placing temperature and ambient temperature. The strength–maturity relationship depends upon the type and source of cement and whether additions are used. The source of cement is more significant when taking cores at early ages (before a maturity equivalent to 28 days at 20 °C has been achieved). However, from a structural viewpoint, it is having an adequate strength in the structure that matters, regardless of whether this was due to poor concrete, poor workmanship on site or a combination of these factors.*

Any structural investigation should be carefully planned and executed to ensure that the information obtained is sufficient to provide an adequately reliable assessment of concrete strength in a structure. The detailed test programme will depend upon the reason for the investigation and whether:

1) an estimate of the characteristic in-situ compressive strength of concrete in a structural member is required (see BS EN 13791 and **6.2**);
2) a comparison of the suspect concrete with satisfactory concrete in other parts of the structure is adequate (see **6.4**);
3) the investigation is required on the immediate surface, near to the surface, or in greater depth (see **5.4**);
4) additional information is required, e.g. uniformity and density of concrete.

Figure 1, Figure 2, Figure 3, Figure 4 and Figure 5 give guidance as to where relevant information is located. Figure 2 relates to the situation where normal conformity on test specimens is replaced by conformity based on measurements taken directly on the elements. As the uncertainty associated with differences between test specimens and the element is minimized by this process, this should be reflected in the conformity requirements and a reasonable approximation is to take:

$$f_{ck,\,is} + 1.48\sigma_{is} \simeq 0.85(f_{ck} + 1.48\sigma)$$

and

$$f_{ck,\,is} - 4 \simeq 0.85(f_{ck} - 4).$$

Figure 1 **Purpose of the investigation**

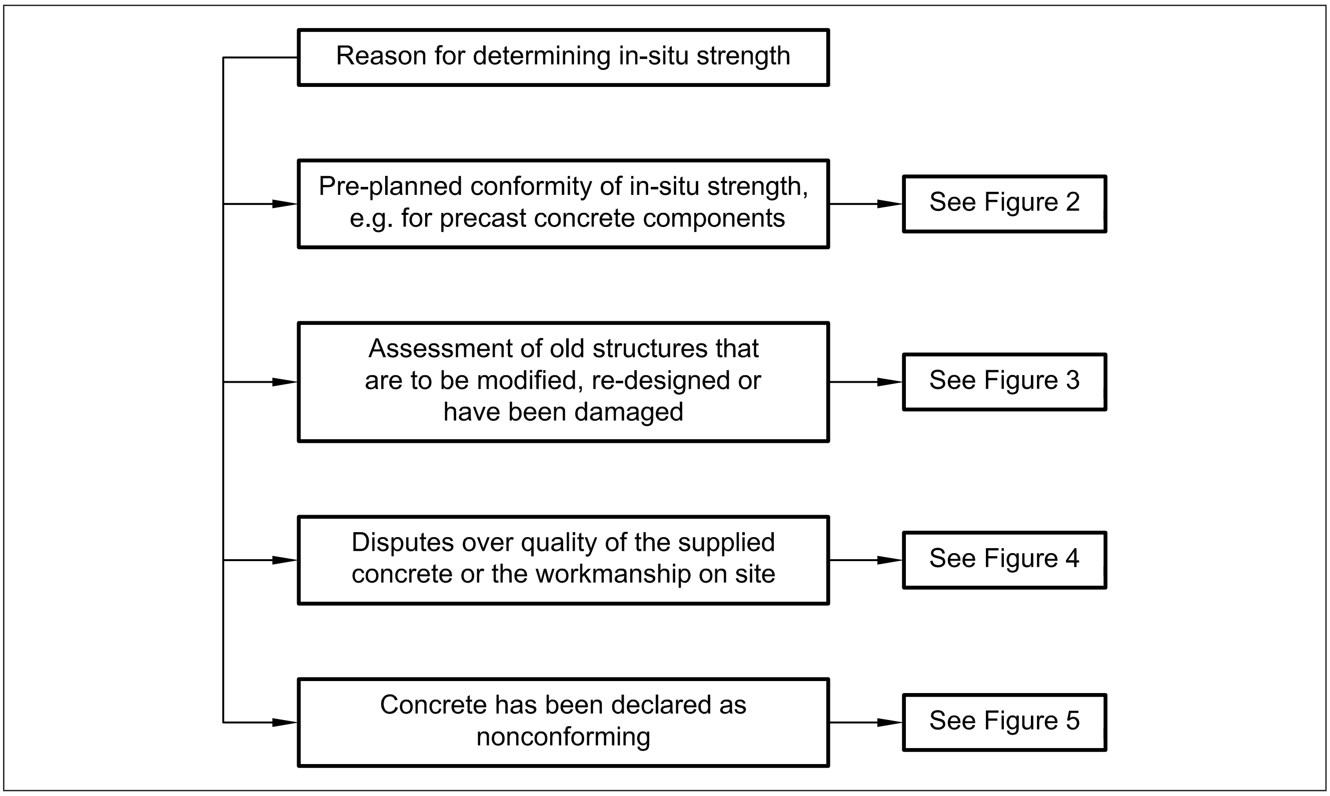


Figure 2 **Pre-planned conformity of in-situ strength**

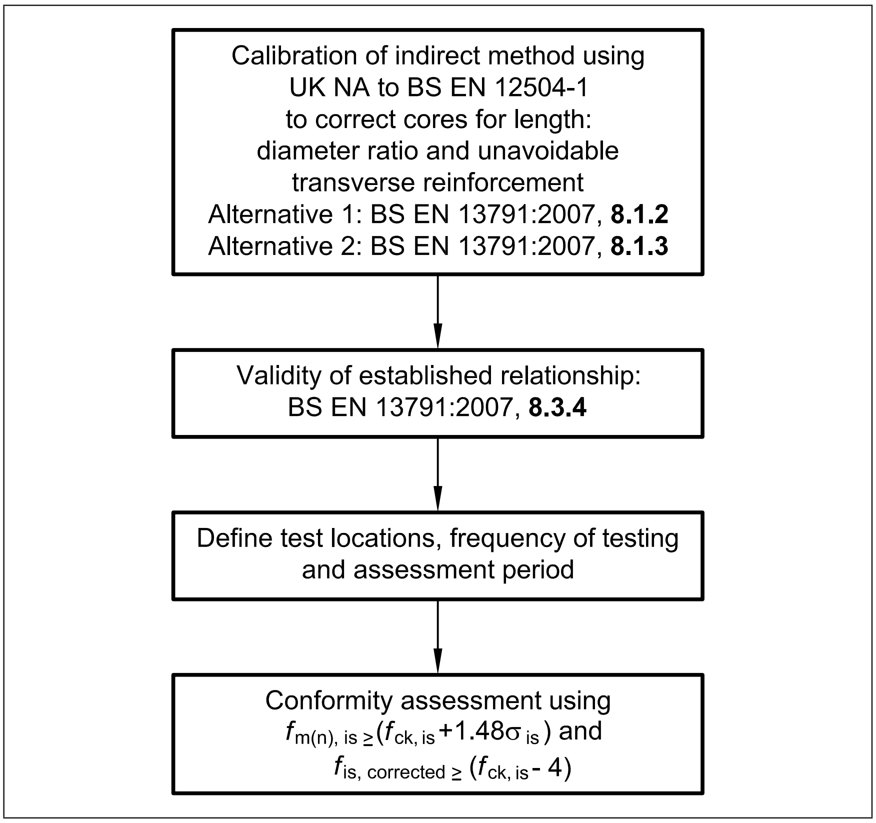


Figure 3 **Assessment of old structures**

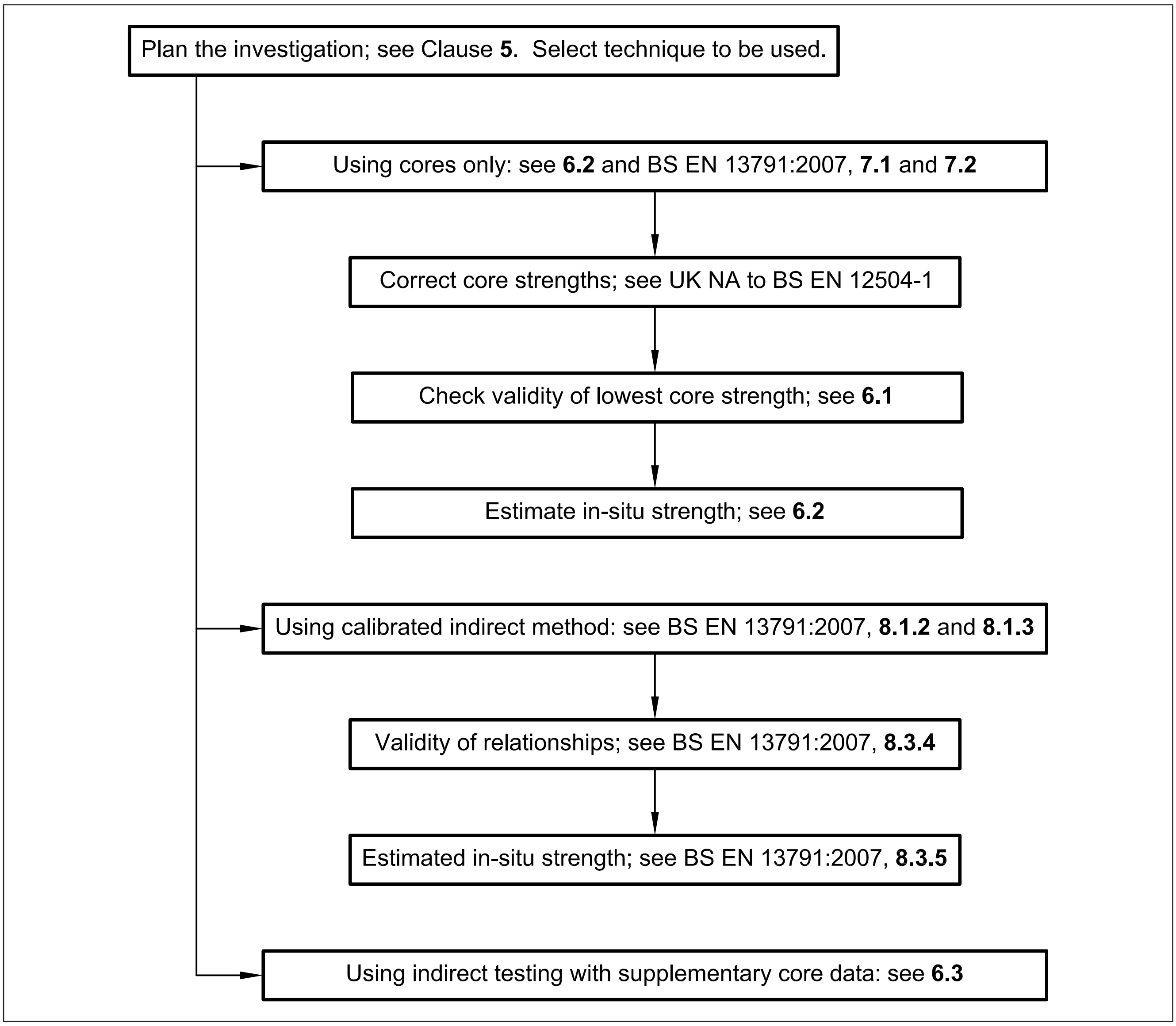


Figure 4 **Dispute over quality of concrete supplied or workmanship on site**

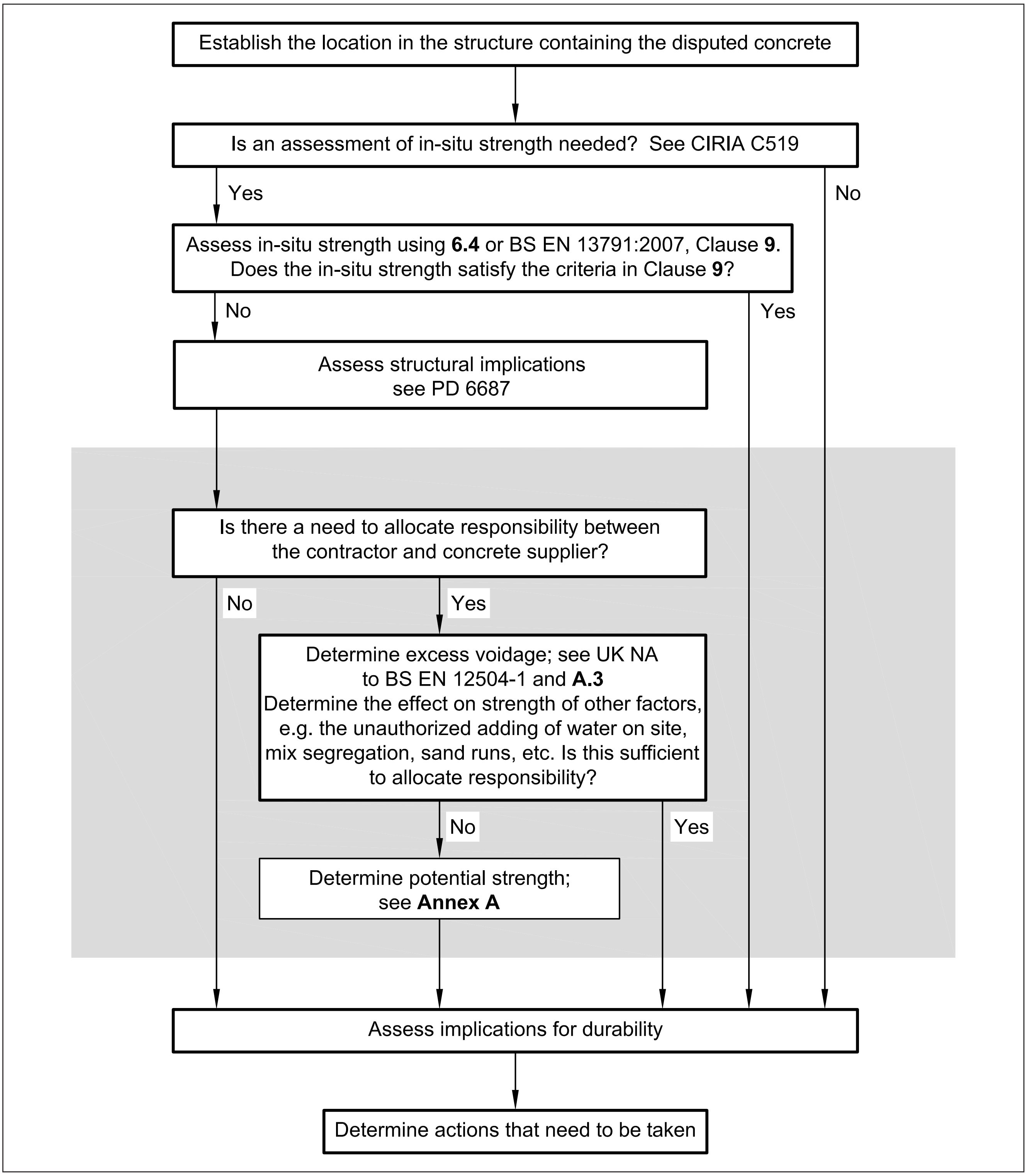
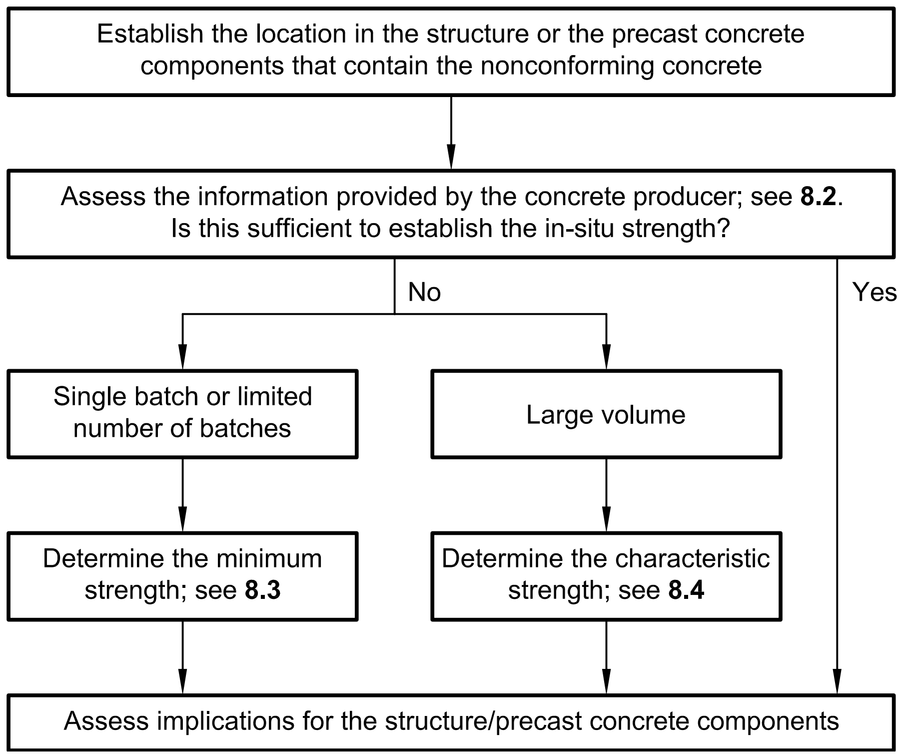


Figure 5 **Concrete declared as nonconforming, including implications for durability**



5.2 Method of structural assessment

When there is no dispute over the quality of concrete and the purpose of the investigation is to determine the characteristic in-situ compressive strength and, where needed, the compressive strength class, the options are:

- core testing with 15 or more cores (see **6.2**);
- core testing with 3 to 14 cores (see **6.2**);
- indirect methods with calibration against core data (see BS EN 13791:2007, Clause **8**);
- indirect methods without calibration (see **6.3**).

With all these options it is necessary to:

- select the test region(s) and test locations (see **5.5**, **5.6** and BS EN 13791:2007, Annex D) and the minimum requirements for the option selected;
- select the core length:diameter ratio (1:1 if the results are to be in terms of equivalent cube strength and 2:1 if the results are to be in terms of equivalent 2:1 cylinder strength) (see Clause **4** and BS EN 13791:2007, **7.1**).

Where there is a potential nonconformity of concrete, the procedures given in CIRIA C519 should be followed. If this identifies the need for an investigation to resolve a dispute over the compressive strength of the concrete supplied to the site, the options are:

- core testing with 15 or more cores (see BS EN 13791:2007, Clause **9**);
- indirect testing with a few cores to determine if the volume of concrete satisfies the minimum in-situ strength requirement (see BS EN 13791:2007, Clause **9**);
- relative testing against acceptable concrete (see **6.4**).

If the selected option leads to a conclusion that the structure is not strong enough and there is a need to allocate responsibility for this lack of strength, the contractor and concrete supplier may agree to determine the potential strength (see Annex A). However, with a marginal failure and the uncertainties associated with estimating the potential strength, it is very difficult to prove that the concrete did not conform to its specification. Therefore, consideration should be given to reaching a fair arrangement on the basis of excess voidage and the effects of any water added at site under the responsibility of the user, as this could prove to be the solution that costs the least.

Where the purpose of the investigation is to determine in-situ strength and structural adequacy after the concrete has been declared as nonconforming in accordance with BS EN 206-1, the options are:

- accept the producer's estimated value of characteristic strength (see **8.2**);
- indirect testing with a few cores to determine if the volume of concrete satisfies the minimum in-situ strength requirement (see **8.3**);
- determination of characteristic in-situ compressive strength (see **8.4**).

The assessment of compressive strength in old structures is an area where strict rules do not apply. The guidance supplied in this British Standard needs to be considered in the light of the specific situation and engineering judgement applied to the specific case.

If the Engineer plans to assess the adequacy of the structure using British Standards of national origin such as BS 8110, the core tests should be carried out on cores with a length:diameter ratio of 1:1 and this requirement should be specified to the coring/testing company. When using this approach, the relationships between the different strengths are given in Table 2.

If the Engineer plans to assess the adequacy of the structure using European standards such as BS EN 1992-1-1, the core tests should be carried out on cores with a length:diameter ratio of 2:1 and this requirement should be specified to the coring/testing company. When using this approach, the relationships between the different strengths are given in Table 3.

By using length:diameter ratio of 1:1 or 2:1, the test results ($f_{is, cube}$ or $f_{is, cyl}$) are obtained directly without having to use the correction factors given in the UK National Annex to BS EN 12504-1.

To be able to assess the structure correctly, the Engineer should specify the reporting of the following additional information from core testing:

- corrected core strength;
- density of the core;
- excess voidage;
- any other observations that might be relevant, e.g. cold joint in core.

NOTE Both of the methods for estimating excess voidage given in the NA to BS EN 12504-1 have limitations. The comparison with reference photographs is subjective and while attempts are being made to develop a method to scan and record the areas of voids, such a method is not yet fully developed. In addition, the "normal" voidage might not be the true normal voidage as it has been set at a fixed 0.5%.

The problem with the density method is that if the low test specimen strength is due to the addition of water on site under the responsibility of the user, such test specimens will have lower density than the true density of the mix and lead to a lower excess voidage. This complicates the allocation of responsibility if it is needed.

5.3 Acceptance of test data

Before any programme is commenced, there should be complete agreement between the interested parties on the validity of the proposed testing procedure, the criteria for acceptance and the appointment of a person and/or laboratory to:

- take responsibility for the testing;
- interpret the results.

Users of this British Standard are advised to consider the desirability of testing being undertaken by a laboratory that is accredited for the test procedure and, in the case of core testing, the taking of the cores. This could minimize the risk of a dispute over the quality of the test data.

It should be agreed on whether the analysis is to be based on the individual test results or the average strength at each location and whether the analysis is to determine structural adequacy or to determine if the concrete conformed to its specification. In some cases, it will be necessary to use the data for both purposes.

5.4 Selection of test methods

The relative merits and limitations of tests for various depths from the surface are summarized in Table 4. There are other tests, e.g. gamma radiography and radar, not listed in Table 4, but the main purpose of using those tests is something other than the determination of strength. Due to the uncertainty associated with using a limited number of test data, it is recommended that any investigation of an old structure where the number of cores is fewer than fifteen be supported by additional indirect test data, e.g. ultrasonic pulse velocity data (see Figure 3).

The effect of damage to the structure caused by the testing should be taken into account and the method of reinstatement specified.

Table 4 **Relative merits and limitations of various tests for measuring in-situ compressive strength**

Region tested	Test	Standard	Accuracy of strength estimate	Speed of test	Ease of test	Economy of test	Lack of damage to structure
In depth	Core	BS EN 12504-1	✓✓✓✓	✓✓	✓✓	✓	✓
	Ultrasonic pulse velocity	BS EN 12504-4	✓✓ A)	✓✓✓	✓✓✓	✓✓✓	✓✓✓✓
Near to surface	Pull-out	BS EN 12504-3	✓✓✓	✓✓	✓✓	✓✓	✓
	Penetration resistance	BS 1881-201	✓✓ A)	✓✓✓	✓✓✓	✓✓	✓✓
Immediate surface	Rebound hammer	BS EN 12504-2	✓✓ A)	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓

NOTE More ticks (✓) indicate better performance.

A) Only if calibrated for the particular concrete under investigation.

The choice of test methods should include consideration of:

- general site location and ease of transporting test equipment;
- accessibility to test region;
- safety of personnel onsite and general public;
- availability of suitably trained and qualified personnel;
- delays in construction whilst testing is conducted and decisions are made;
- damage to the structure caused by the testing;
- delays in completion and handover.

It might be beneficial to combine different testing techniques, e.g. combining ultrasonic pulse velocity measurements with core tests. The accuracy of estimates of in-situ strength obtained from indirect non-destructive tests depends upon the reliability of the correlation between test method and core strength. BS EN 13791 provides methods for obtaining reliable, safe relationships. Two procedures for using combined techniques are as follows.

- Use of a comprehensive survey using indirect techniques, e.g. ultrasonic pulse velocity, with sufficient core testing to establish the relationship between the indirect method and core strength for the concrete under investigation. Then all the test data are converted into equivalent cube or 2:1 cylinder strengths. BS EN 13791:2007, Clause **8**, provides details of this procedure.

  NOTE 1 The procedure given in BS EN 13791 provides a suitable method for estimating the strength at a given location, but if used to determine in-situ characteristic strength, the estimated value is conservative.

- Use of an indirect method to locate the weaker areas from which to obtain at least two cores each from two locations or single cores from four locations (see **6.3**). In this procedure there are insufficient core data to establish the relationship between the indirect method and core strength. This technique is for structural assessment purposes only and it should not be used to assess the quality of the concrete supplied, as it is an assessment of the lowest in-situ strength and not an assessment of the average in-situ concrete quality.

The ease of taking a large number of ultrasonic pulse velocity or rebound hammer measurements on structural elements provides a more comprehensive evaluation of the strength of a structure.

Core testing should be undertaken in accordance with BS EN 12504-1. Unless specified otherwise, BS EN 13791:2007, **7.1**, requires the cores to be tested after at least three days' storage in laboratory air. The UK NA to BS EN 12504-1 contains the process for correcting the core compressive strength for:

- length:diameter ratio to convert the core compressive strength (f_{is}) to equivalent cube ($f_{is,\ cube}$) or cylinder ($f_{is,\ cyl}$) strengths;
- reinforcement transverse to the direction of loading.

A core containing longitudinal reinforcement should be rejected on visual examination and a replacement core taken.

BS EN 12504-1 permits cores to be tested in a wet condition and according to BS EN 13791:2007, **A.2.1**, this will result in a reduced strength typically in the range of 10% to 12% when compared with cores with a moisture content in the range 8% to 12%. BS EN 13791 is based on cores that have been exposed to laboratory air for at least three days prior to testing and this is the recommended procedure. However, if cores are tested immediately after water storage, the measured strength should be increased by 10% to 12% if they are to be used for assessment in accordance with BS EN 13791.

NOTE 2 The lowest of the reported differences (10%) is recommended, as three days' air curing is unlikely to completely dry the centre of the core.

Both the core compressive strength (f_{is}) and the corrected core strength ($f_{is,\ cube,\ corrected}$ or $f_{is,\ cyl,\ corrected}$) should be reported. These values do not include any adjustment for testing cores immediately after water curing, as this is not the standard procedure. If the cores are tested immediately after water curing, this should be reported as a deviation from the standard procedure. The UK NA to BS EN 12504-1 states that the density and excess voidage should be reported as relevant information.

Rebound hammer, ultrasonic pulse velocity and pull-out tests should be undertaken in accordance with BS EN 12504-2, BS EN 12504-4 and BS EN 12504-3 respectively.

5.5 Test locations

Core locations should be selected to avoid:

- highly stressed sections;
- reinforcement and prestressing steel and ducts.

The use of a covermeter prior to coring to determine locations that are free of reinforcement or prestressing steel is strongly recommended.

The selection of the test locations should enable the purpose of the investigation to be achieved. A sufficient number of test locations should be selected so that the required accuracy is achieved while maintaining economy.

The test locations within the test region should be selected to take account of the typical variations in strength within the element.

The site conditions that should be considered include:

- general site location and ease of transporting test equipment;
- accessibility to suspect region onsite;
- safety of personnel onsite and of the general public.

The test locations should be such that after cutting the core to length, the core does not contain:

- concrete from within 50 mm of any surface;
- concrete within 50 mm or 20% of the top of the lift, whichever is the higher amount, in sections where the depth of lift is not more than 1.5 m;
- concrete from the top 300 mm of the lift, where the depth of lift is 1.5 m or more.

Where the selected technique is to compare an element under investigation with other elements that are acceptable (see **6.4**), the same test locations in the element under investigation and the reference elements should be selected.

In the absence of indirect test data, a vertical element may be assumed to have a reduction in strength over the upper third and an enhancement of strength immediately adjacent to its foundation. If the procedure in **6.3** is being followed, the weaker areas are selected as the test locations and in a vertical element where there is no indirect test data to help identify suitable locations, the locations should be selected in the upper third of the element excluding the top 300 mm. They should be taken at a depth that is below any starter bars. However, if the procedure in **7.2** is being followed where an average concrete quality is required, the test locations should be selected from the middle third of the height of the element. For thin horizontal elements, e.g. floors, it is not normally possible to identify the weaker areas without indirect testing. Consequently, for thin horizontal elements without indirect testing, the test locations should be selected at random.

5.6 Number of test locations

NOTE 1 The confidence with which it is possible to assess in-situ strength of concrete increases with the number of assessments made. In the case of some tests (e.g. ultrasonic pulse velocity, rebound hammer), little extra cost is incurred by obtaining a large number of test data. In other cases (e.g. core data), the cost of each test is appreciable. The decision on the number and type of tests to be made ought, therefore, to be based upon an assessment of the cost of obtaining a result of adequate reliability.

The most direct method of assessing in-situ strength of concrete in a structural element is by core tests. The confidence given to the calculated mean in-situ core strength is estimated from the repeatability/$\sqrt{n}$. For cores with ends prepared by grinding, there is a 95% probability that the true mean value is within $\pm 14\%/\sqrt{n}$ of the calculated value. Therefore, it is recommended that a minimum group of four cores should be taken to represent a test region within the concrete structure. If more than four cores are taken from a test region, confidence in the average result will be greater.

BS EN 13791 recommends minimum numbers of test locations for various procedures. Different test locations are needed to ensure a representative sample. Taking more than one sample at a test location, e.g. twelve rebound hammer measurements or a long core that is cut to give two specimens, gives a measure of the variability of the test but not the concrete. In these cases, the results should be averaged to give a single result. The procedures described in **6.3** and **7.2** require a minimum of two locations. To follow the recommendation given in this subclause to have a minimum of four cores, this would require two cores to be taken at each location. For the assessment of outliers (see **6.1**) the four cores are treated as individual results and for the purpose of strength assessment, the core results ($f_{\text{is, cube or cyl, corrected}}$) taken at a single location are combined to give a single test result ($f_{\text{is, cube or cyl, location}}$). In these situations, two test results are acceptable, as no attempt is being made to apply statistical techniques to these two results. Alternatively, a minimum of four locations should be selected and in this case each core is treated as an individual result for the purposes of strength assessment. This alternative approach should always be used for thin horizontal elements, e.g. floors. A minimum of four cores is essential if a determination of potential strength might be required (see Annex A).

*NOTE 2 If the concrete producer has declared a batch as nonconforming, the criteria in BS EN 13791:2007, Clause **9**, may be applied to determine if the in-situ concrete is of adequate strength. However, as the producer has already declared the batch as nonconforming, there is no need to determine the potential strength.*

6 Additional procedures

6.1 Assessment of individual core results within a group

The procedures in BS EN 13791 use both the mean value of a group of core results and the lowest individual core result. It is implicit that this lowest core result is a valid result, but the normative part of BS EN 13791 provides no guidance on how the lowest result should be checked to see if it is a valid result.

Individual core results might not be representative of the concrete within the structure due to a number of reasons. They might have suffered damage that is not visible, contain excess voidage, reinforcing steel, etc. that could lead to results that are significantly lower than the others within a group of core results. By assessing the difference between the lowest result and the mean of the remaining results, it is possible to determine if the lowest result is a statistical outlier. When testing for statistical outliers, each individual core strength is used in the assessment even when two or more core strengths are subsequently combined into a single result. The following method is a simple way of testing for statistical outliers.

NOTE The formula given here is from P/3.5.2.3 of CSTR 11 [1] but resolved to a simple ratio.

$$R_t = t \times \left(\frac{6}{100}\right) \times \sqrt{1 + \left(\frac{1}{n-1}\right)}$$

It assumes a population standard deviation of 6% of the mean of other core results.

The t-value is based on degrees of freedom of n – 2.

The following ratio should be calculated.

$$R_t = \frac{\text{Mean of other core results} - \text{Lowest result}}{\text{Mean of other core results}}$$

If the calculated R_t exceeds the value given in Table 5, the core result should be treated as being suspicious or rejected as appropriate. If rejected, the mean of the other core results should be taken as the mean in-situ strength. In some situations, it is appropriate to repeat the process to determine if there is more than one outlier. With air entrained concrete, it might be appropriate to check whether the highest result is a statistical outlier as this could be an indication that the required air content has not been achieved. The purpose of identifying statistical outliers is to separate the concrete that is normally distributed in strength from elements or parts of structures that require special attention.

The reason for a core result being a statistical outlier (either suspicious or rejected) should be determined. If on re-examination it is concluded that the outlier was not a valid result, e.g. that it contained a crack which was not noticed prior to testing, the core result should be rejected and not used in the assessment of the strength in a structure or precast concrete element. If the core result is valid and represents a local defect, e.g. an area that is not properly compacted, the action to be taken should be determined. For example, the local area might need removal and replacement. If the outlier represents a local defect that is being remedied, the core result should not be included in any calculation of characteristic in-situ compressive strength. An outlier should not be included in the estimation of potential strength. There are situations where an outlier should be taken into account when assessing structural adequacy, e.g. where the weak area is not being removed and replaced.

Table 5 **Checking the validity of the lowest core result**

No. of cores	Ratio (R_t) above which a low result should be treated as being suspicious	Ratio (R_t) above which a low result should be rejected [A)]
4	0.202	0.298
5	0.158	0.213
6	0.140	0.182
7	0.131	0.167
8	0.125	0.157
9	0.121	0.150
10	0.118	0.146
11	0.115	0.142
12	0.114	0.140
13	0.112	0.137
14	0.111	0.136
15	0.110	0.134
16	0.109	0.133
17	0.108	0.132
18	0.108	0.131
19	0.107	0.130
20	0.107	0.129
21	0.106	0.129
22	0.106	0.128
23	0.106	0.128
24	0.105	0.127
25	0.105	0.127
> 25	0.099	0.118

A) It is rejected from the calculation of the mean strength, but the result might still be valid, e.g. because it represents an area of poor compaction.

NOTE The ratio (R_t) is based on an assumed population standard deviation of 6% of the mean of the other core strengths and "t" values for n – 2 degrees of freedom.

6.2 Alternative approach to that given in BS EN 13791:2007, Clause 7

BS EN 13791:2007, Clause **7**, gives procedures for calculating the in-situ characteristic strength with three or more cores. Approach A (BS EN 13791:2007, **7.3.2**) is used where there are 15 or more cores and Approach B (BS EN 13791:2007, **7.3.3**) is used where there are 3 to 14 cores. However, BS EN 13791 also permits a national standards body to define an alternative approach for existing structures about which there is no prior knowledge. It has been decided that the BS EN 13791:2007, **7.3.2** and **7.3.3** approaches are not applicable in these situations in the UK and are replaced by the procedure described in this subclause.

NOTE 1 The procedure described in this subclause uses the t-statistic to determine the characteristic strength, as this approach has a well established and accepted statistical basis.

The corrected core strengths should be checked to ensure that all values are valid using the procedure described in **6.1**. All valid results should be used to calculate the mean strength ($f_{m(n), is}$) and sample standard deviation, (s). The in-situ characteristic strength ($f_{ck, is}$) should be calculated from: $f_{ck, is} = f_{m(n), is} - t_{0.05}s$, where $t_{0.05}$ is taken from Table 6 or standard statistical tables.

Table 6 **$t_{0.05}$-values for determining the characteristic strength based on (n – 1) degrees of freedom (v)**

n	$t_{0.05}$
3	2.92
4	2.35
5	2.13
6	2.02
7	1.94
8	1.89
9	1.86
10	1.83
11	1.81
13	1.78
15	1.76
17	1.75
19	1.73
21	1.72
26	1.71
31	1.70
61	1.67
121	1.66
> 121	1.64

Whether the value of in-situ characteristic strength so calculated should be used in a structural assessment depends upon the particular circumstances. If the calculated value is based on a large number of core data, it is an appropriate value for structural calculations provided it is not more than ($f_{is, lowest}$ + 4). If it is more than ($f_{is, lowest}$ + 4), the lower value should be used as the characteristic in-situ strength. However, as the number of test data reduces, the confidence that, with an unknown structure, the structure does not contain (unknown) weaker areas reduces. In such circumstances, it is advisable to take a more conservative approach and use a lower core strength for structural calculations.

BS EN 13791:2007, Clause **7**, provides no guidance on the use of fewer than three cores. It is not statistically valid to try to estimate a characteristic strength from one or two core results.

*NOTE 2 BS EN 13791:2007, **7.3.3**, Note, states that Approach B is not to be used in cases of dispute over concrete quality. The reason for this is that there is a very high probability of indicating nonconforming concrete, when in reality the concrete was conforming.*

6.3 Estimation of compressive strength using indirect methods and selective coring where there is no dispute over the quality of the supplied concrete

Ultrasonic pulse velocity (UPV) and rebound hammer tests do not measure the strength of concrete but some other property (pulse-transit time in the case of UPV and surface hardness in the case of rebound hammer) that has a concrete-specific relationship to compressive strength. If the relationship between ultrasonic pulse velocity or rebound hammer and compressive strength is established for a particular concrete as described in BS EN 13791:2007, Clause **8**, a safe and reliable relationship can be determined. Where it is not practical to take at least nine cores from nine test locations, which is the minimum required in BS EN 13791:2007, **8.3.1** for the application of this particular technique, and where the determination of the lowest in-situ strength is adequate for structural assessment purposes, an alternative technique should be used. In the situation where it is not practical or economic to obtain an adequate number of core test data to calibrate an indirect test method, it is recommended that the following approach be adopted for structural assessment purposes only. The procedure described here does not attempt to estimate the average quality of the concrete or the quality of the concrete supplied and it should not be used for this purpose.

Using ultrasonic pulse velocity testing or rebound hammer testing, survey the suspect/unknown element to determine variability and identify the weaker zones. If this indirect testing does not clearly identify weaker areas, use knowledge of the distribution of strength in elements to select locations for coring. Either select a minimum of two locations from the weaker zones and take two cores from each location or a minimum of four locations and take a single core from each location (see **5.6**). Using the procedure described in **6.2**, check for outliers and decide whether to include/exclude any outlier in the assessment. Where two cores are taken at a single location, the strength at the location ($f_{\text{is, cube or cyl, location}}$) is taken as the average of the two values of $f_{\text{is, cube or cyl, corrected}}$, or if it is agreed to eliminate an outlier, the single value. From the lowest of the location strengths, the characteristic in-situ strength may be determined using the appropriate equation from BS EN 13791:2007, **8.2.4**.

The use of the pull-out test conforming to BS EN 12504-3 is usually pre-planned and used to determine the time of construction operations such as formwork striking or prestressing. It is rarely used post-construction, although there is a variation of this test that permits post-construction assessment. A pull-out test has a specific relationship with compressive strength and the general relationship between pull-out force and compressive strength provided by the manufacturer of the pull-out test is usually reliable. However, it is recommended that the applicability of the general relationship is checked using four pull-out tests from the proposed concrete and companion standard compressive strength specimens.

6.4 Relative testing method

When the concrete under investigation is in one or more of a series of elements where other elements have been accepted as having been made with conforming concrete, an approach is to compare the concrete in the suspect elements with that in the elements that have been accepted (the reference elements). This can be done using ultrasonic pulse velocity or rebound hammer data. It is not a suitable procedure to use with cores, since if cores are taken, there is no need to compare them with reference elements and the procedure is better when comparing large sets of data. The null hypothesis is that the mean strengths are the same and the fewer the data, the lower the chance of showing that the hypothesis is not correct. For this reason, it is recommended that at least twenty data are taken from the element under investigation and at least twenty data from the reference element.

The following is a simple method based on taking twenty measurements on the element under investigation and twenty from a reference element. By applying the accepted statistical principles of hypothesis testing, this technique can be applied to any combination of data sets, but this general approach is not detailed in this standard.

Agree a reference element that is similar to the element under investigation. Select a reference element that has a similar maturity to the element under investigation or select a more mature element where the difference in maturity will have a minor effect. Select a set of twenty test locations that are the same in the element under investigation and the reference element (to minimize differences due to location in the element). At the twenty test locations in the reference element measure the ultrasonic pulse velocity or the rebound hammer number. Calculate the mean value ($\overline{X}_r$) and the sample standard deviation (s_r). Repeat with the element under investigation and in this case the mean value is denoted $\overline{X}_s$ and the standard deviation as s_s.

Calculate:

$$t_{calc} = \frac{\overline{X}_r - \overline{X}_s}{\sqrt{\frac{(s_r^2 + s_s^2)}{20}}}$$

If the numerical value is not more than 2.024 and not less than –2.024, there is a 95% probability that the element under investigation came from the same population as the reference concrete and it should be accepted as having adequate strength.

7 Assessment where the strength of concrete based on test specimens is in doubt

7.1 General

The procedures given in Clause **7** apply to situations where there is a need to resolve a dispute over the quality of the concrete supplied.

NOTE 1 BS EN 13791 only covers the assessment of compressive strength and it does not provide guidance on resolving other issues such as whether the concrete structure is adequately durable.

The recommended procedure is:

a) the Engineer responsible for the design should be an active participant in resolving the issue and in particular in determining the structural implications of any lower strength;

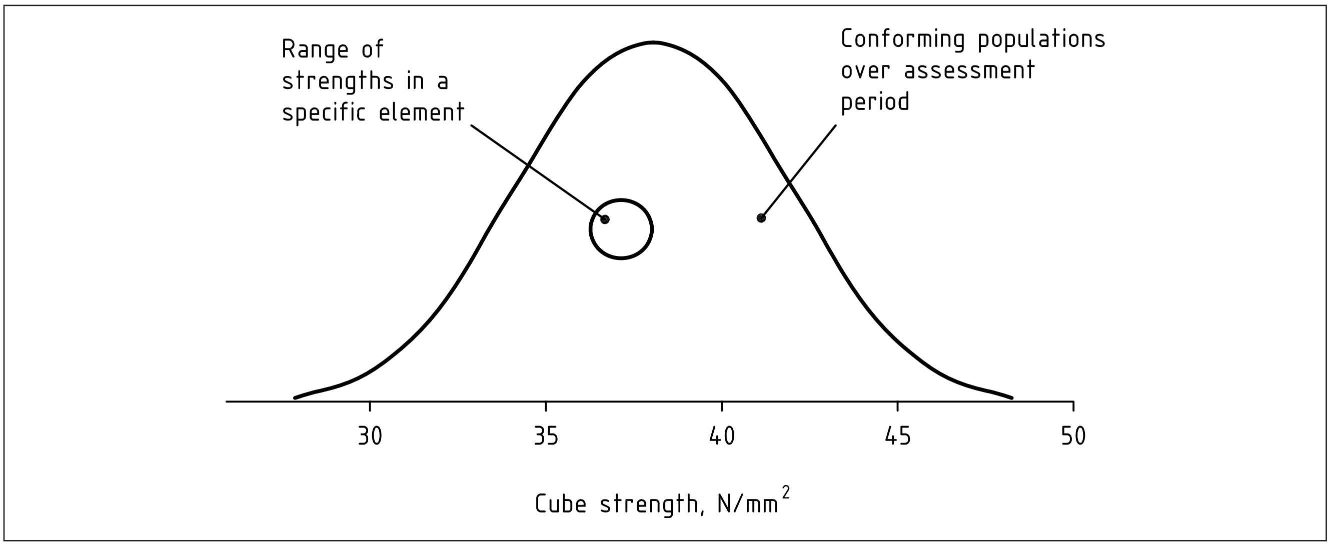
b) use CIRIA C519 to determine if an assessment of strength is needed;

c) if an assessment of strength is needed, follow the procedure in BS EN 13791:2007, Clause **9**, or determine whether the compressive strength of the elements in doubt come from the same population as that in other acceptable elements (see **6.4**).

BS EN 13791:2007, Clause **9**, states that if the structure is deemed to satisfy the strength criterion, the concrete is deemed to have satisfied its specification. However, there might be situations where the concrete is shown to conform to its specification, but when the structural element is assessed using BS EN 1992-1-1:2004, Annex A, (see also PD 6687) be shown to be inadequate. This British Standard provides no guidance on what to do in this situation. However, in the case of a declared nonconformity, the investigation might show the structure to be adequately strong, but the declared nonconformity remains. Should the structure be shown to be inadequate with respect to strength, this does not automatically prove that the supplied concrete failed to satisfy its specification. This is a matter the contractor and concrete producer should resolve and the Engineer is advised to avoid any involvement in the resolution of this issue. To show that the concrete failed to meet its specification, the corrected core strengths should be adjusted for excess voidage, curing and maturity (see Annex A). The uncertainties associated with any estimated potential strength are so large that this procedure is best avoided, but in some cases it is needed to enable the producer and purchaser to agree on who has to cover the costs of the investigation and resulting actions. Delivery tickets should be reviewed as they should contain a record of any water added at site under the responsibility of the user. In this situation, the concrete producer can provide data to show the reduction in strength caused by this addition of water. In addition, a study of the excess voidage is helpful as this indicates how well the concrete was compacted (see **A.3**).

NOTE 2 Resolving disputes over concrete quality is an area that is fraught with difficulties and one fundamental problem: when concrete is produced in accordance with BS EN 206-1, conformity is based on achieving the characteristic strength over an assessment period, which can be up to one year in time. While a concrete producer achieves conformity over an assessment period, this does not mean that concrete supplied on one day, or part of one day, has the same statistics as this larger population. In reality, it is highly unlikely that they will have the same mean strength and standard deviation; see Figure 6.

Figure 6 **Distribution of data for a producer's assessment period compared with that in a single element**



BS EN 206-1 permits a single acceptable batch of concrete to have a compressive strength of (f_{ck} – 4) N/mm^2 and if the structure comprised a single batch, the structure would not have been built with concrete having a characteristic strength of f_{ck}. This means that in rare cases, concrete structures could be built with concrete having strengths less than the characteristic strength. However, such structures would still be adequately strong and reliable, since the design margins take this variability into account. The reliability of the structure is reduced below that allowed for in the design when the in-situ compressive strength falls below 0.85($f_{ck,\ spec}$ – 4) N/mm^2 and this is the key criterion for determining the acceptability of a structure.

The use of the concept of "characteristic strength" can be regarded as a practical means by which there is a strong probability that the minimum strength [($f_{ck,\ spec}$ – 4) N/mm^2] is achieved.

7.2 Estimation of minimum in-situ strength ($f_{is,\ lowest}$)

BS EN 13791:2007, Clause **9**, provides an equation that can be used to check if a local area satisfies the conformity criterion for minimum compressive strength. This is a suitable technique for assessing the adequacy of elements constructed with, for example, a single batch. BS EN 13791:2007, Clause **9**, uses the term "small region", but this term is not defined. This has to be agreed on a case-by-case basis, but as general guidance, if a batch is used to produce multiple elements, e.g. a series of small columns, a "small region" could be a single batch. However, in a large section comprising many batches, a "small region" could contain several batches of concrete.

Where the assessment of strength in a small region is being undertaken, **5.5** provides guidance on test locations and **5.6** provides guidance on the minimum number of test locations and a recommendation that at least four cores are taken. The purpose of this investigation is different from that described in **6.3**. In **6.3** the purpose was to identify the lowest strength within an element, but in this case it is to check whether the batch(es) conformed to the minimum strength criterion and for this purpose the test locations should be selected to give the average quality of the concrete in the element (see **5.5**).

Using the procedure described in **6.2**, outliers should be checked for and whether to include/exclude any outlier in the assessment should be decided. For checking conformity to the minimum strength requirement, the strength at a location ($f_{is,\ cube\ or\ cyl,\ location}$) is taken as:

- $f_{is,\ cube\ or\ cyl,\ corrected}$ if a single core is taken at each location and it is not shown to be an outlier;
- $f_{is,\ cube\ or\ cyl,\ location}$ if more than a single core is taken at a test location and none of the cores are outliers; or
- if it is agreed to eliminate an outlier, the remaining valid single value or the average of the remaining valid cores at that location.

According to BS EN 13791: 2007, Clause **9**, conformity to the minimum strength requirement is shown if the strength at the test location with the lowest strength satisfies the minimum strength requirement. If the test locations are selected as recommended in this British Standard, the measured strengths should all be estimates of the average strength of the batch and variability between the results is a reflection of test variability rather than concrete variability. This hypothesis suggests that the average strength of the batch would be more accurately estimated as being the average of the strengths at the test locations and this average strength used to determine if the batch(es) met the minimum strength criterion.

8 Assessment where the producer has declared the concrete as nonconforming with respect to compressive strength

8.1 General

Concrete might be declared as nonconforming for a number of reasons, including:

- failure of an individual batch to satisfy the (f_{ck} – 4) criterion;
- failure to satisfy the mean strength criterion for an assessment period;
- failure by the contractor to satisfy the Engineer's specification, e.g. when a purchaser has instructed the producer to change the specification by adding water at site, but the Engineer requires conformity to the original specification.

NOTE This situation is different from investigating an unknown structure, because in this case, the producer is likely to supply additional data on the concrete supplied, as part of the analysis of the nonconformity and its consequences.

As the concrete producer has declared nonconformity, there is rarely the need to determine the potential strength (see Annex A). An exception is where the producer has accepted that the concrete is nonconforming on the basis of being instructed to add additional water on site by the purchaser and the purchaser is claiming that the concrete would have been nonconforming even if they had not changed the specification, e.g. added more water on site.

The options available to the Engineer are described in **8.2**, **8.3** and **8.4**.

8.2 Accept producer's estimated characteristic strength

In many cases of nonconformity, the producer is able to estimate the actual characteristic strength of the concrete supplied from the test data, batch records and knowledge of the cause of the nonconformity. Provided that the uncertainty associated with such an estimate is taken into account, the Engineer may use such data for the checks on the structure without having to undertake in-situ testing.

8.3 Determine if a batch or limited number of batches satisfy the minimum strength criterion

Even when the concrete is nonconforming or part of a nonconforming population, the structure might be adequately strong. A structural assessment is needed to determine whether this is the case.

8.4 Determine the characteristic in-situ compressive strength

The characteristic in-situ compressive strength may be determined using any of the options listed in **5.2**, as the concrete has already been declared as nonconforming.

Annex A (normative) Guidance on the estimation of potential strength

A.1 General

Determining the average potential strength is a method for estimating the 28-day compressive strength of the concrete supplied to the structure. It takes the corrected core strength and modifies it to take account of excess voidage, differences caused by different curing conditions and differences between the maturity of the core at testing and 28 days at 20 °C. The average of these potential strengths is then calculated together with an estimate of the uncertainty. All these corrections lead to an increased uncertainty in the calculated result. The best that can be achieved by this process is a high probability that the supplied concrete conformed to its specification, a high probability that the supplied concrete did not conform to its specification and a wide range of uncertainty between these bands.

It should be noted that conformity control and evaluation of conformity are the responsibilities of the producer of the concrete; see BS EN 206-1.

To estimate the potential cube strength, the number of core samples taken is critical in obtaining accurate results. In these circumstances at least four cores should be taken from a limited area of the structure to represent the concrete that is under investigation. Each core result should be converted to its equivalent potential cube or cylinder strength ($f_{\text{pot, cube or cyl}}$), the average of the values calculated and an estimate of the uncertainty made.

A procedure for calculating the potential strength was given in Concrete Society Technical Report 11 [1] but an extensive investigation (CS126 [2]) indicates that the adjustment factors are not constants even for CEMI concretes. Unfortunately, the large data set has not yet been analysed in a way that would permit a best estimate of potential strength together with the uncertainty associated with this estimate to be made. Even when such an analysis is completed, there will still be significant uncertainties that cannot be quantified, e.g. the impact of different sources of cement of the same type. However, the difficulties are not insurmountable if all that is required is a best estimate of potential strength.

NOTE CSTR 11 uses the approach in which the null hypothesis is that the concrete conformed to its strength specification and it has to be shown that this hypothesis is not correct.

A.2 Measurement of core strength and adjustment to $f_{\text{is, cube, corrected}}$

Cores drilled for the estimation of potential strength should be taken so that each test location represents an approximately equal amount of the suspect concrete. However, in addition to the obvious need to avoid badly compacted concrete and reinforcement, the locations should be such that the test length of the core does not contain concrete from within 50 mm of a surface or the top of the lift (see **5.5** for details) which the suspect concrete partly or wholly comprised. Whenever possible, the tested cores should have a length:diameter ratio of 1:1, since the standard specimen used by concrete producers in the UK to determine strength is the cube. The purpose of these recommendations is to minimize the corrections to the core compressive strength and the uncertainty associated with such corrections.

The uncertainty associated with testing the core is estimated from the repeatability/$\sqrt{n}$, where n is the number of cores.

NOTE Analysis of 528 sets of 4 cores (CS126 [2]) which were all prepared by grinding in the same laboratory indicates the standard deviation achieved was 1.9 MPa (N/mm²) or 5.2% of the mean strength. Therefore, the repeatability for preparation by grinding would be ~14% (95% confidence limits) and the uncertainty ±14%/$\sqrt{n}$ (95% confidence). Information on the repeatability or reproducibility of the other capping methods is not available.

If the tested core contains no reinforcement and it has a length:diameter ratio of 1:1, there are no corrections to the core strength and no uncertainty associated with these corrections. The uncertainty associated with these corrections has not been established.

A.3 Corrections for excess voidage

Fully-compacted concrete, for example in a well-made test specimen, will always have some entrapped air, typically ~0.5%. In the structure, the compaction is such that there is likely to be some excess voids over that found in a test specimen. This excess voidage reduces the core compressive strength of the concrete relative to a fully compacted test specimen. The UK NA to BS EN 12504-1 describes the procedure for determining the excess voidage and **5.2** recommends that it be reported.

An excess voidage in the range of 0.5% to 2.5% should be considered normal. An adjustment for excess voidage is only required when the potential strength is being estimated.

NOTE As the excess voidage in the structure is the reality of the structure, the corrected core strength does not include an adjustment for excess voidage because the corrected core strength is used to determine the characteristic in-situ compressive strength or the minimum in-situ compressive strength.

The estimate of the in-situ cube strength if it has been fully compacted is calculated from:

$$(f_{\text{is, cube or cyl, corrected, compacted}}) = K_{\text{v}} \,.\, f_{\text{is, cube or cyl, corrected}}$$

where the excess voidage correction factor, K_{v}, is given in Table A.1.

Where the excess voidage exceeds 2.5%, the estimated fully-compacted in-situ cube strength and any subsequent estimate of the potential strength should not be regarded as being reliable. However, excess voidage above 2.5% is an indication that the concrete has not been compacted properly.

There are two uncertainties associated with the effect of excess voidage. The first is the estimate of excess voidage itself and it is often regarded as being subjective if it is done by comparison with the reference samples and not by measurement. This uncertainty associated with a comparison can be minimized by having more than one determination of the excess voidage and taking the average value.

The other uncertainty is associated with the relationship between excess voidage and strength reduction. The values given in Table A.1 are average values. The uncertainty associated with this relationship has not been established.

Table A.1 **Correction factor for excess voidage, K_v**

Estimated excess voidage	Correction factor to in-situ cube strength (K_v)
0.0	1.00
0.5	1.03
1.0	1.06
1.5	1.09
2.0	1.12
2.5	1.15
3.0	1.18 [A)]
3.5	1.21 [A)]
4.0	1.24 [A)]
4.5	1.27 [A)]
5.0	1.30 [A)]

[A)] This figure should be treated with caution.

A.4 Correction for curing

This factor takes account of curing history, e.g. the effect of temperature on the pore structure and resulting strength, and other factors, e.g. internal water movements caused by the process of vibrating the concrete. As **A.2** recommends that the tested core does not include concrete that is within 50 mm of a surface, it may be assumed that in normal UK conditions, the tested concrete core has retained enough of the initial mix water for hydration to continue.

The effects of curing are complex and include:

- if the temperature of the concrete is low for the first few hours, the ultimate strength is increased;
- if the temperature of the concrete is high for the first few hours, the ultimate strength is decreased;
- as the peak temperature of the concrete increases due to the release of the heat of hydration or due to accelerated curing, the early strength is increased but the long term strength is reduced (*Concrete Properties* [3]);
- maturity equations are valid for normal conditions and they might not reflect the effects listed here.

There is no simple factor for taking the effects of curing into account. If the concrete was placed on a hot day, placed in a large section or accelerated cured, the effect of curing might be significant. Provided the recommendations in this British Standard for core locations are followed, the effects of curing for many other situations are likely to be modest.

If the locations of the at least four cores are carefully selected, the effects of vibration can be evened out.

A.5 Correction for maturity

Provided there is sufficient water for hydration, concrete will continue to develop strength with time. The rate of strength gain is dependent upon the temperature of the concrete. For a given concrete, the relationship between compressive strength, temperature and time can be estimated using an appropriate maturity function (see *Formwork striking times* [4]).

For the determination of potential strength, the core strengths need to be adjusted to what they would have been if they had been tested when they had a maturity equivalent to 28 days at 20 °C.

Depending upon the cement/combination type used, a suitable maturity function should be selected (see *Formwork striking times* [4]). The concrete producer should be able to provide information on the rate of strength development under standard conditions for the concrete under investigation. From this information, the strength–maturity relationship is established.

Determining the temperature history of the cores is the more difficult task and this is needed to determine the maturity of the cores when tested. For thin sections that have not been insulated, e.g. most suspended slabs, the maturity up to the time the cores were taken could be based on the average ambient temperature. For thicker sections or sections that have been insulated or accelerated cured, the temperature rise associated with the release of the heat of hydration or accelerated curing will have increased the sections' temperature above ambient, resulting in the cores having a higher maturity at testing. Thermal modelling or agreement might be needed to establish the maturity of the tested cores.

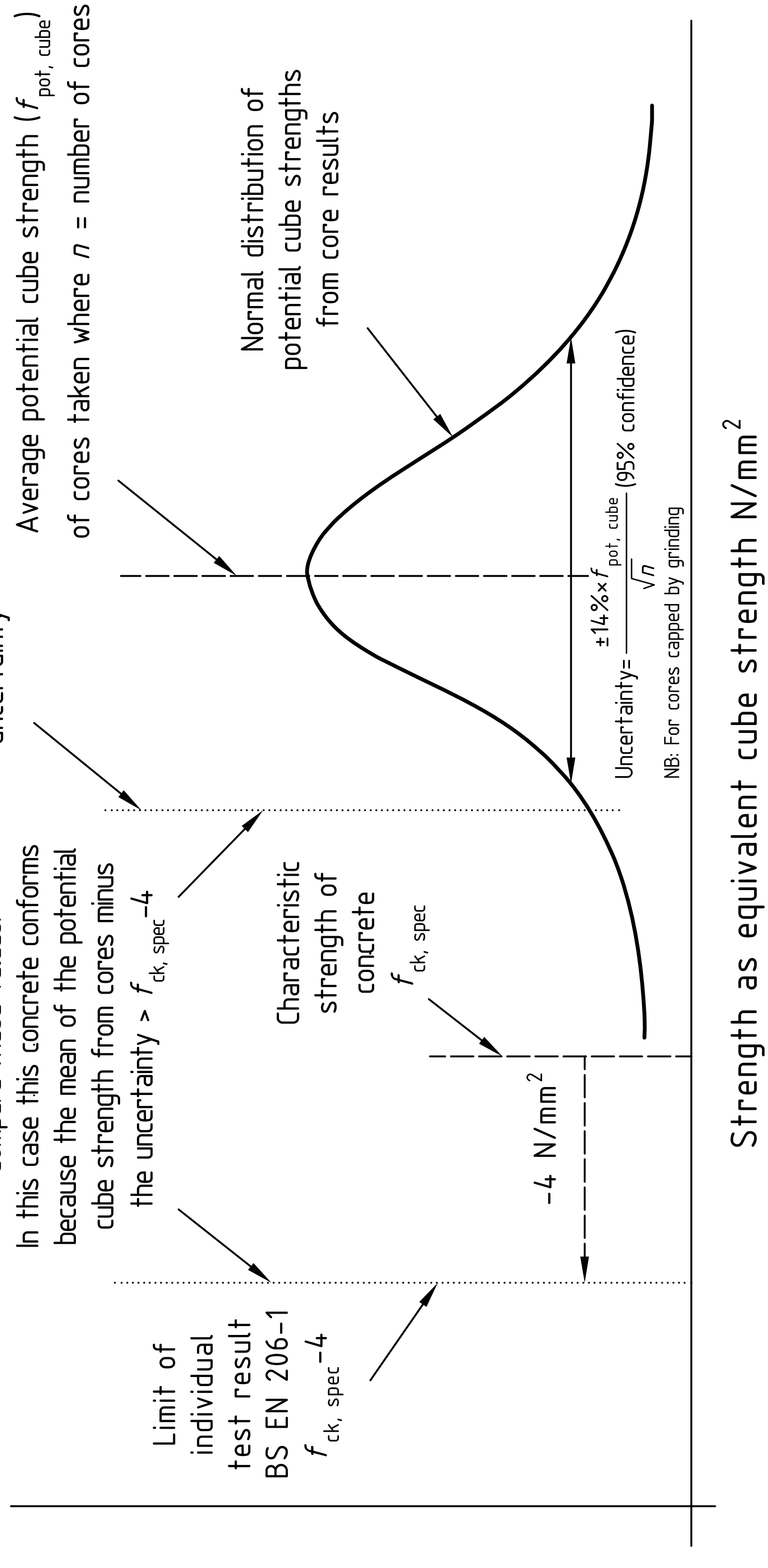
NOTE The data gathered in the Concrete Society Core Project [2] may be helpful in determining appropriate factors for specific situations.

A.6 Analysis

The concrete under investigation should be treated as a single "batch" and so the average potential strength should be compared with the minimum strength for a single batch criterion in BS EN 206-1. If the average of the potential cube strengths minus the uncertainty, as shown in Figure A.1, is equal to or greater than ($f_{ck, spec}$ – 4), the concrete may be deemed to have satisfied its specification. If the potential strength minus the uncertainty is less than ($f_{ck, spec}$ – 4), the concrete is unlikely to have satisfied the specification (see Figure A.1). However, as many of the uncertainties are not known and by prior agreement on the factor for curing and the adjustment for maturity, the concrete could be accepted or rejected on the basis of only taking the uncertainty of measurement into account.

If multiple groups of cores are taken that represent more than a single batch of concrete, more detailed statistical analysis should be carried out on the resulting potential cube strength values.

Figure A.1 **Comparing the potential cube strength from cores and the specified characteristic strength of the concrete**



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Standards publications

For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

BS 8110 (all parts), *Structural use of concrete* [2)]

BS EN 1992-1-1:2004, *Eurocode 2: Design of concrete structures – Part 1-1: General rules and rules for buildings*

Other publications

[1] THE CONCRETE SOCIETY. *Concrete core testing for strength*, Concrete Society Technical Report 11. The Concrete Society, 1987.

[2] THE CONCRETE SOCIETY. *In-situ concrete strength – An investigation into the relationship between core strength and standard cube strength*, CS126. The Concrete Society, 2004.

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[4] HARRISON, T A. *Formwork striking times: Criteria, prediction and methods of assessment*. CIRIA Report 136, 1995.

2) It is anticipated that BS 8110 will be withdrawn in due course due to the publication of BS EN 1992-1-1. Up-to-date information can be obtained from BSI Customer Services.

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