

# Testing concrete —

## Part 201: Guide to the use of non-destructive methods of test for hardened concrete

UDC 666.972.017:691.32:620.1

# Committees responsible for this British Standard

The preparation of this British Standard was entrusted by the Cement, Gypsum, Aggregates and Quarry Products Standards Committee (CAB/-) to Technical Committee CAB/4 upon which the following bodies were represented:

Association of Lightweight Aggregate Manufacturers  
 Association of Metropolitan Authorities  
 British Aggregate Construction Materials Industries  
 British Precast Concrete Federation  
 British Ready Mixed Concrete Association  
 Building Employers' Confederation  
 Cement Admixtures Association  
 Cement and Concrete Association  
 Cement Makers' Federation  
 Concrete Society  
 County Surveyor's Society  
 Department of the Environment (Building Research Establishment)  
 Department of the Environment (Property Services Agency)  
 Department of the Environment (Transport and Road Research Laboratory)  
 Department of Transport (Highways)  
 Electricity Supply Industry in England and Wales  
 Federation of Civil Engineering Contractors  
 Institute of Concrete Technology  
 Institution of Civil Engineers  
 Institution of Highways and Transportation  
 Institution of Structural Engineers  
 Institution of Water Engineers and Scientists  
 Royal Institute of British Architects  
 Royal Institution of Chartered Surveyors  
 Sand and Gravel Association  
 Society of Chemical Industry

The following bodies were also represented in the drafting of the standard, through subcommittees and panels:

British Civil Engineering Test Equipment Manufacturers' Association  
 British Nuclear Fuels Limited  
 United Kingdom Atomic Energy Authority

This British Standard, having been prepared under the direction of the Cement, Gypsum, Aggregates and Quarry Products Standards Committee, was published under the authority of the Board of BSI and comes into effect on 28 February 1986

© BSI 01-1999

The following BSI references relate to the work on this standard:  
 Committee reference CAB/4  
 Draft for comment 84/10723 DC

ISBN 0 580 14767 3

## Amendments issued since publication

Amd. No.	Date of issue	Comments

# Contents

	Page
Committees responsible	Inside front cover
Foreword	ii
<hr/>	
Section 1. General	
1.1 Scope	1
1.2 Definitions	1
1.3 Principal considerations	1
1.4 Planning an investigation	2
<hr/>	
Section 2. Test methods	
2.0 Introduction	7
2.1 Resonant frequency	7
2.2 Electromagnetic cover measurement	7
2.3 Resistivity measurements	8
2.4 Half-cell potential measurements	8
2.5 Radiography	9
2.6 Radiometry	9
2.7 Neutron moisture measurement	10
2.8 Initial surface absorption	10
2.9 Surface permeability	10
2.10 Maturity measurements	11
2.11 Thermography	11
2.12 Radar	12
2.13 Ultrasonic pulse velocity measurement	12
2.14 Dynamic response techniques	13
2.15 Surface hardness	14
2.16 Screed test	14
2.17 Internal fracture	14
2.18 Pull-out test	15
2.19 Pull-off test	16
2.20 Break-off test	16
2.21 Penetration resistance	17
2.22 Depth of carbonation	17
2.23 Acoustic emission	18
2.24 Strain measurements	18
<hr/>	
Section 3. Combinations of methods	
3.1 General	19
3.2 Electromagnetic cover measurement or radiography to locate reinforcement	19
3.3 Non-destructive methods as preliminary to partially-destructive methods	19
3.4 Increasing the confidence level of test results	19
3.5 Improvement of calibration accuracy	19
3.6 Half-cell potential and resistivity tests to indicate likelihood of reinforcement corrosion	20
<hr/>	
Appendix A Bibliography	21
<hr/>	
Table 1 — Suitability of non-destructive test methods	4
Table 2 — Summary of principal test methods	5
<hr/>	
Publications referred to	Inside back cover
<hr/>	

# Foreword

This Part of BS 1881 has been prepared under the direction of the Cement, Gypsum, Aggregates and Quarry Products Standards Committee. All aspects of testing concrete are being included as parts of BS 1881 and this Part forms a general introduction to those on non-destructive testing.

Non-destructive testing of a body of hardened concrete as cast, whether in a structure or as a component, offers advantages of speed, cost and lack of damage in comparison with test methods which require the removal of a sample. The range of properties that can be measured in this way is considerable, and much valuable information may be obtained if the available methods are used with an understanding of what they can, and cannot, achieve.

This guide presents information on test methods of this type which will assist with the planning of investigations and the selection of methods which are most appropriate to the circumstances. It summarizes the principal features of currently available techniques together with their advantages, limitations and most reliable applications. Many of the methods will be described in detail in other Parts of BS 1881-202 onwards<sup>1)</sup>, while other techniques which are not yet so well established are also included with appropriate references. Additional guidance is given concerning the value of combinations of test methods.

The use of tests to assess strength is covered in greater detail in BS 6089. Strain gauges suitable for monitoring the behaviour of concrete structures in service, or under test load conditions, will be dealt with in Part 206<sup>1)</sup> of this standard. For details of methods which are not covered in these British Standards, reference should be made to specialist literature as indicated.

It is hoped that the guidance given in this Part will encourage the wider use of non-destructive testing in a worthwhile and economical manner; it is not intended to supplant engineering judgement or to inhibit the development and use of other test methods.

NOTE The numbers in parentheses in the text of this Part refer to the numbered bibliographic references given in Appendix A.

A British Standard does not purport to include all the necessary provisions of a contract. Users of British Standards are responsible for their correct application.

**Compliance with a British Standard does not of itself confer immunity from legal obligations.**

## Summary of pages

This document comprises a front cover, an inside front cover, pages i and ii, pages 1 to 22, an inside back cover and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.

---

<sup>1)</sup> In preparation.

# Section 1. General

## 1.1 Scope

This Part of BS 1881 gives guidance on the tests that are available for non-destructive testing of hardened concrete which forms a laboratory specimen or part of a structure, structural component or other type of engineering construction. Some tests cause varying degrees of localized damage or defacement and may therefore be considered partially destructive; these methods are all defined as non-destructive. All the tests can be performed on the concrete as cast and do not require the removal of samples for subsequent analysis or testing.

Methods of testing hardened concrete which require sample extraction are either dealt with in other Parts of BS 1881 or elsewhere (1,2).

NOTE 1 Damage caused by the extraction of small-diameter cores may not be significantly greater than that due to some of the near-to-surface methods included here, provided that reinforcement is not cut during extraction. In cases where strength determination is required they may offer similar or better accuracy with fewer calibration problems (3).

NOTE 2 The titles of the publications referred to in this standard are listed on the inside back cover.

## 1.2 Definitions

For the purposes of this Part of BS 1881, the definitions given in BS 2787 and BS 6100-6 apply, together with the following.

### 1.2.1 non-destructive test

a test that does not impair the intended performance of the element or member under investigation

### 1.2.2 location

a region of concrete that is being assessed and that, for practical purposes, is assumed to be of uniform quality

### 1.2.3 near-to-surface test

a test that measures some property of the concrete near to, but below, the surface

### 1.2.4 standard cube strength

the measured compressive strength of a cube made, cured and tested in accordance with BS 1881-108, BS 1881-111 and BS 1881-116 respectively

### 1.2.5 estimated in situ cube strength

the strength of concrete at a location in a structural member estimated by indirect means and expressed as the compressive strength of specimens of cubic shape

## 1.3 Principal considerations

### 1.3.1 Advantages of non-destructive testing

Non-destructive testing offers significant advantages of speed, cost and lack of damage in comparison with test methods which require the removal of a sample for subsequent examination. These factors will permit more extensive testing and thus enable an investigation to be wider ranging with respect to the concrete structure under examination than would otherwise be possible. The immediate availability of results may also be an important advantage of this type of testing.

### 1.3.2 Properties measured

The range of properties that can be assessed using non-destructive techniques is large and includes fundamental parameters of the concrete such as density and elastic modulus in addition to strength. Other properties which can be assessed include concrete surface hardness, surface absorption and moisture condition as well as reinforcement location, cover and corrosion risk. The quality of workmanship and structural integrity may also be checked by the ability to identify and locate voids, cracking and delamination.

The required property is not measured directly by a number of the available methods and precise correlations are not always easy to achieve. In some instances estimates of the required property can only be achieved by comparative means.

### 1.3.3 Importance of trained staff

Skill and care by the operator will generally be necessary, while the results obtained by some methods are particularly sensitive to variations in testing procedure. It is important that tests are performed by trained and reliable staff if worthwhile results are to be achieved, and it is recommended that two persons should normally be involved during testing on site.

### 1.3.4 Situations in which non-destructive testing may be valuable

Non-destructive testing may be applied to both new and existing structures. For new structures, the principal applications are likely to be for quality control or resolution of doubts about the quality of materials or construction. Testing of existing structures will usually be related to an assessment of structural integrity or adequacy. In either case, a small number of tests on a large structure, for example tests on a few cores, can be misleading, while non-destructive testing is often a valuable indicator, either on its own or as a preliminary to some other form of testing.

Non-destructive tests are useful for the following purposes:

- a) quality control of precast units or construction in situ;
- b) removing uncertainties about the acceptability of the material supplied owing to apparent non-compliance with specifications;
- c) confirming or negating doubt concerning the workmanship involved in batching, mixing, placing, compacting or curing of concrete;
- d) monitoring of strength development in relation to formwork removal, cessation of curing, pre-stressing, load application or similar purposes;
- e) location and determination of the extent of cracks, voids, honeycombing and similar defects within a concrete structure;
- f) determining the position, quantities or condition of reinforcement;
- g) determining the concrete uniformity, possibly as a preliminary to core cutting, load testing or other more expensive or disruptive tests;
- h) increasing the confidence level of a smaller number of destructive tests;
- i) determining the extent of concrete variability in order to help in the selection of sample locations representative of the quality to be assessed;
- j) confirming or locating suspected deterioration of concrete resulting from such factors as
  - 1) overloading,
  - 2) fatigue,
  - 3) external or internal chemical attack or change,
  - 4) fire,
  - 5) explosion,
  - 6) environmental effects;
- k) assessing the potential durability of the concrete;
- l) monitoring long term changes in concrete properties;
- m) providing information for any proposed change of use of a structure, for insurance or for change of ownership.

## 1.4 Planning an investigation

### 1.4.1 Reasons for testing

The situations in which non-destructive testing may be useful have been indicated in 1.3.4, and the reasons for testing should be clearly established before the details of a test programme are planned. These will establish the information that is required, e.g. strength, uniformity and density, and whether this should relate to the surface, near to the surface, or to the body of a member.

### 1.4.2 Acceptance of test data

Before any programme commences, it is essential that there is agreement between the interested parties on the validity of the proposed testing procedures, the criteria for acceptance and the appointment of a person and/or laboratory to take responsibility for the testing and interpretation of the results.

It is essential, despite the apparent simplicity of some test methods, that testing is performed only by skilled operators who are familiar with the methods and that the interpretation of results is entrusted to a suitably experienced engineer.

### 1.4.3 Selecting a test programme

**1.4.3.1 General.** The test programme will be determined by the objectives of the investigation coupled with the suitability of the available methods in relation to the site conditions and economic factors as outlined in 1.4.3.2 to 1.4.3.5.

The objective may be to investigate the overall quality of the fabric, in which instance a random choice of test locations will be appropriate. Where the objective is to investigate suspect material, the test locations will be selected for this purpose and the test results will only apply to this suspect material. In both cases, a sufficient number of test locations should be chosen to establish a satisfactory confidence level for the results.

Visual inspection should also be regarded as an essential preliminary to the planning of a programme of testing since observation of features such as deflection, cracking and colour may yield valuable information affecting the choice of methods and location of test points.

In some instances, calibration is necessary to relate the measured values or properties to those which are required. The availability and reliability of such calibrations are thus important.

**1.4.3.2 Choice of test methods.** The methods recommended in Table 1 are likely to be most suitable for the general circumstances indicated. Practical limitations may preclude the use of particular methods in some situations, while in other cases it may be appropriate or necessary to consider the use of methods other than those recommended. For example, surface treatments, such as those to reduce moisture permeability, or decorative coatings may prevent the use of some methods. The principal features of the methods, including their most important limitations and most reliable applications, are described in section 2 and summarized in Table 2.

The equipment required to perform the tests is easily portable in most cases, and all tests can be rapidly carried out, although extensive preparation may sometimes be necessary.

Important considerations affecting the choice of test method include the following.

- a) *Test locations.* Some factors to be considered are:
  - 1) the position within the member or structure;
  - 2) the variations of concrete properties through depth of lift;
  - 3) the position of reinforcement;
  - 4) the presence of local defects or influences, e.g. surface carbonation;
  - 5) the depth below the surface of the zone to which results apply.
- b) *Effect of damage.* The choice of method may be influenced by:
  - 1) the effects of testing on the surface appearance of the members;
  - 2) the possibility of structural damage resulting from the testing of small section members.
- c) *Size of member.* The size of the member may restrict the use of some test methods as a result of limitations on minimum edge distances, minimum or maximum thicknesses, or similar considerations.
- d) *Testing accuracy required.* The testing accuracy required will depend upon the purpose of the investigation. The level that can be achieved will depend on:
  - 1) the test method;
  - 2) the number and location of measurements;
  - 3) the accuracy and reliability of available calibrations.

In determining the necessary number of measurements, it should be remembered that an individual result relates only to the immediate test position and does not necessarily reflect the properties of the concrete in general.

**1.4.3.3 Combination of methods.** In some circumstances, the accuracy achieved may be improved by the use of two or more test methods. A combination of different test methods may be used for the following reasons.

- a) The use of one method as a preliminary to another.

The most common situations of this type are:

- 1) the location of reinforcement prior to core cutting or use of other non-destructive testing methods;
  - 2) the use of a non-destructive method to provide comparative data on concrete uniformity prior to core cutting or use of other non-destructive methods involving greater expense or damage.
- b) To obtain enhanced reliability of results on the basis of:
    - 1) the confirmation of observed patterns of concrete quality;
    - 2) the correlation of combinations of measured values with a desired property.

Suitable combinations of methods are discussed in section 3.

**1.4.3.4 Site condition.** The principal site conditions that should be considered include:

- a) the geographic location and ease of transport of test equipment;
- b) the accessibility of test locations;
- c) the environment;
- d) the safety of personnel and the general public during testing.

**1.4.3.5 Economic and social factors.** The test programme will be influenced by factors such as the value of the project and costs arising from:

- a) delays in construction, or restriction on usage or occupancy, while testing is conducted and decisions are made;
- b) remedial works that may be necessary;
- c) the features of different test methods, including time, materials and equipment, temporary works and making good;
- d) the need to select an adequate number of tests for an appropriate reliability of assessment;
- e) the need for a higher level of confidence in the assessment of structures where public safety is involved.

Table 1 — Suitability of non-destructive test methods

Methods <sup>a</sup>	Test situation					
	Quality control	Investigation of standard of workmanship	Control of formwork removal, pre-stress release or load application	Comparative survey of quality of concrete in the structure	Investigation of potential durability	Investigation of fire, frost, chemical attack or similar
Pull-out test (cast-in insert)	X		X			
Pull-out test (drilled hole)	X		X	X		X
Internal fracture	X		X	X		X
Break-off test	X		X			
Pull-off test	X		X	X		
Penetration resistance	X		X	X		
Surface hardness	X		X	X	X	
Screed test	X			X	X	
Dynamic response	X	X		X		
Ultrasonic pulse velocity measurement	X	X	X	X	X	X
Acoustic emission		X			X	
Electromagnetic cover measurement	X	X			X	
Radar		X		X		
Radiography		X				X
Radiometry	X	X		X		
Neutron moisture measurement				X	X	
Depth of carbonation				X	X	X
Initial surface absorption				X	X	
Surface permeability					X	
Resistivity measurements				X	X	
Half-cell potential measurements					X	
Strain measurements		X	X	X	X	X
Thermography					X	X
Maturity measurements			X			
Resonant frequency	X					

<sup>a</sup> Subject to the practical limitations outlined in section 2.

**Table 2 — Summary of principal test methods**

Method	Clause number	Principal reference	Principal applications	Principal properties assessed	Surface damage	Type of equipment	Remarks
<b>Pull-out test (cast-in insert)</b>	2.18	BS 1881-207 <sup>a</sup>	Quality control (in situ strength)	Strength related	Moderate/minor	Mechanical	Preplanned usage, surface zone test
<b>Pull-out test (drilled hole)</b>	2.18	BS 1881-207 <sup>a</sup>	In situ strength measurement	Strength related	Moderate/minor	Mechanical	Drilling difficulties on vertical surfaces or soffits, surface zone test
<b>Internal fracture</b>	2.17	BS 1881-207 <sup>a</sup>	In situ strength measurement	Strength related	Moderate/minor	Mechanical	High test variability, surface zone test
<b>Break-off test</b>	2.20	BS 1881-207 <sup>a</sup>	In situ strength measurement	Flexural tensile strength	Substantial/moderate	Mechanical	High test variability, substantial damage
<b>Pull-off test</b>	2.19	BS 1881-207 <sup>a</sup>	In situ strength measurement	Direct tensile strength	Moderate/minor	Mechanical	Care needed with adhesive, surface zone test
<b>Penetration resistance</b>	2.21	BS 1881-207 <sup>a</sup>	In situ strength measurement	Strength related	Moderate/minor	Mechanical	Specific calibrations required, limits on minimum member size, surface zone test
<b>Surface hardness</b>	2.15	BS 1881-202 (supersedes BS 4408-4)	Comparative surveys	Surface hardness	Very minor	Mechanical	Greatly affected by surface texture and moisture, surface test unrepresentative on concrete more than 3 months old, strength calibration affected by mix properties
<b>Initial surface absorption</b>	2.8	BS 1881-208 <sup>a</sup> (supersedes BS 1881-5)	Surface permeability assessment	Surface absorption	Minor	Hydraulic	Difficult to standardize in situ moisture conditions and to obtain watertight seal to surface, comparative test
<b>Surface permeability</b>	2.9	(11)	Surface permeability assessment	Surface permeability	Minor	Hydraulic	Surface zone test, water or gas
<b>Resistivity measurements</b>	2.3	(6)	Durability survey	Resistivity	Minor	Electrical	Surface zone test, related to moisture content, indicates probability of reinforcement corrosion in zones of high risk
<b>Half-cell potential measurements</b>	2.4	(9)	Survey of reinforcement corrosion risk	Electrode potential of reinforcement	Very minor	Electro-chemical	Cannot indicate corrosion rate
<b>Thermography</b>	2.11	(16)	Structural integrity survey and void location	Surface temperature differences	None	Infra-red radiation detection	Extraneous temperature effects have to be excluded, temperature differentials small, shortage of data and development
<b>Maturity measurements</b>	2.10	(14)	In situ strength development monitoring	Maturity	Minor	Thermo-sensitive chemical or electronic	Preplanned usage, specific calibration required

**Table 2 — Summary of principal test methods**

Method	Clause number	Principal reference	Principal applications	Principal properties assessed	Surface damage	Type of equipment	Remarks
<b>Screed test</b>	<b>2.16</b>	(21)	Quality control of screeds	Surface soundness	Minor	Mechanical	Sand/cement screeds only, cannot be used if screed over soft material
<b>Ultrasonic pulse velocity measurement</b>	<b>2.13</b>	BS 1881-203 <sup>a</sup> (supersedes BS 4408-5)	Comparative surveys	Elastic modulus	None	Electronic	Two opposite smooth faces preferably needed, strength calibration affected by moisture and mix properties, some surface staining possible
<b>Acoustic emission</b>	<b>2.23</b>	(34)	Monitoring during load testing	Internal crack development	None	Electronic	Increasing load required, not fully developed for site use
<b>Dynamic response techniques</b>	<b>2.14</b>	(20)	Pile integrity	Dynamic response	None	Mechanical/ electronic	Cannot yield bearing capacity
<b>Electromagnetic cover measurement</b>	<b>2.2</b>	BS 1881-204 <sup>a</sup> (supersedes BS 4408-1)	Location of reinforcement	Presence of embedded steel	None	Electro-magnetic	Affected by magnetic aggregates and unreliable for congested steel
<b>Radar</b>	<b>2.12</b>	(19)	Location of voids or reinforcement	Internal interfaces	None	Electronic	Experience limited, procedures under development
<b>Radiography</b>	<b>2.5</b>	BS 1881-205 <sup>a</sup> (supersedes BS 4408-3)	Location of voids or reinforcement	Relative density	None	Radioactive source or generator	Extensive safety precautions, limit on member thickness
<b>Radiometry</b>	<b>2.6</b>	(3)	Quality control	Density	None	Radioactive source or generator	Safety precautions and limit on member thickness for “direct” method, “backscatter” method is surface zone test
<b>Neutron moisture measurement</b>	<b>2.7</b>	(3)	Comparative moisture content	Moisture content	None	Nuclear	Surface zone test, calibration difficult
<b>Depth of carbonation</b>	<b>2.22</b>	(33)	Durability survey	Concrete alkalinity	Moderate/ minor	Chemical	Approximate indication of extent of carbonation
<b>Resonant frequency</b>	<b>2.1</b>	BS 1881-209 <sup>a</sup> (supersedes BS 1881-5)	Quality control	Dynamic elastic modulus	None	Electronic	Specially cast specimen required
<b>Strain measurements</b>	<b>2.24</b>	BS 1881-206 <sup>a</sup> (supersedes BS 4408-2)	Monitoring movements in structures	Changes in strain	Minor	Optical/ mechanical/ electronic	Attachment and reading requires skill, can only indicate changes in strain

<sup>a</sup> In preparation.

## Section 2. Test Methods

### 2.0 Introduction

The test methods described here are in varying stages of development. Those which are well established are detailed in other Parts of BS 1881, as indicated. Methods which are not fully developed are described in technical literature referred to in the bibliography in Appendix A, as indicated by the numbers in parentheses.

### 2.1 Resonant frequency

NOTE This method is currently described in BS 1881-5, but will eventually be revised as BS 1881-209.

#### 2.1.1 General

Measurement of the resonant frequency of a prismatic specimen and the determination of its density may be used to yield a value for the dynamic elastic modulus of the concrete of which the specimen is formed.

#### 2.1.2 Advantages

This procedure is quick, does not damage the specimen in any way and is reliable. The influence of operator technique is small and other testing errors are low.

#### 2.1.3 Limitations

This test has to be performed on a standard specimen of hardened concrete and is usually associated with laboratory-cast samples. The method as described is not applicable to in situ usage.

#### 2.1.4 Principal application

The principal application is to provide a value of dynamic elastic modulus of concrete. The test may also be valuable as a technique for monitoring changes of concrete properties as a result of various influences during laboratory investigations. A modified form of this test may be adapted for site use.

### 2.2 Electromagnetic cover measurement

NOTE This method is currently described in BS 4408-1, but will eventually be revised as BS 1881-204.

#### 2.2.1 General

Portable devices are available which are operated by rechargeable or dry batteries and are based upon measurement of the change of an electromagnetic field caused by steel embedded in the concrete. Such equipment is calibrated to indicate the distance of the steel below the surface, and in some cases may also indicate the diameters of reinforcing bars. When reinforcement is parallel to the surface, rotation of the search head will enable the alignment of the bar to be identified. Non-calibrated metal detectors are available which may detect metals (ferrous or non-ferrous) at depths outside the range of the above equipment.

#### 2.2.2 Advantages

This method for locating reinforcing steel within a concrete member is truly non-destructive.

Under reasonable conditions, a site accuracy of estimated cover of  $\pm 5$  mm within the working range of the instrument may be expected.

Techniques are available to permit estimates of both bar size and depth of cover when neither is known.

#### 2.2.3 Limitations

The effect of bar size is important if this is less than 10 mm or greater than 32 mm.

Calibrations are sensitive to steel type, bar diameter and deformity, and aggregate and cement type, and have to take these factors into account. Most commercially available equipment is calibrated for medium-sized mild steel round bars in ordinary Portland cement concrete.

The range of the equipment is limited according to type, but care and experience in interpretation of data are required in the following cases:

- a) multiple bars, e.g. laps, transverse steel or closely spaced parallel bars;
- b) light wire mesh, buried nails or other metals between the reinforcing bars and the surface;
- c) metal tie wires;
- d) aggregates with magnetic properties;
- e) stability of calibration, which may be particularly important in relation to temperature changes within the magnetic field;
- f) stray magnetic fields.

#### 2.2.4 Principal applications

The principal applications are the location of reinforcement and estimation of cover, orientation and, in some cases, diameter of reinforcing bars. The technique is most reliable for lightly reinforced members, and may be used for the following:

- a) quality control checking, to ensure correct location and cover of reinforcing bars;

- b) investigation of concrete members for which records are not available;
- c) location of reinforcement as a preliminary to some other form of testing in which reinforcement should be avoided, e.g. taking cores, ultrasonic pulse velocity measurement or near to surface methods.

## 2.3 Resistivity measurements

NOTE This method is discussed in references 4, 5 and 6 of Appendix A.

### 2.3.1 General

The electrolytic resistivity of concrete is known to be influenced by many factors including moisture, salt content and temperature, as well as mix proportions and the water/cement ratio. The presence of reinforcement may also influence measurements. In situ measurements may be made using a Wenner four-probe technique in which four electrodes are placed in a straight line on or just below the concrete surface at equal spacings. An electrical current is passed through the outer electrodes while the voltage drop between the inner electrodes is measured. The apparent resistivity of the concrete may be calculated from a knowledge of the current, voltage drop and electrode spacing. For practical purposes, the depth of the zone of concrete affecting the measurement may be taken as equal to the electrode spacing.

### 2.3.2 Advantages

This technique can provide a simple non-destructive indication of the electrical resistivity of the concrete at the test location. This can be related, principally by experience, to the corrosion hazard of embedded reinforcement or other features of the concrete.

### 2.3.3 Limitations

Correlation of resistivity measurements to properties such as mix proportions are at present only possible under laboratory conditions. The use of in situ measurements for this purpose is hindered by the sensitivity of readings to the factors outlined above. Practical application is thus generally restricted at present to comparative measurements. Limited damage to the concrete surface may sometimes be necessary.

### 2.3.4 Principal applications

Experienced investigators have used the method to assess or monitor the durability of concrete exposed to severe environments. In some circumstances, the likelihood of corrosion of embedded reinforcement may be predicted by this method where half-cell potential measurements show that corrosion is possible (5, 6). Other possible applications of the method include comparative assessment of moisture conditions and estimation of the thickness of a concrete pavement slab by varying the electrode spacings (7). Resistivity measurements may also be used to assist the integrity testing of reinforced concrete piles (8).

## 2.4 Half-cell potential measurements

NOTE This method is discussed in references 5, 6 and 9 of Appendix A.

### 2.4.1 General

The method of half-cell potential measurements normally involves measuring the potential of an embedded reinforcing bar relative to a reference half-cell placed on the concrete surface. This is usually a copper/copper sulphate or silver/silver chloride cell but other combinations are used. The concrete functions as an electrolyte and the risk of corrosion of the reinforcement in the immediate region of the test location may be related empirically to the measured potential difference (5). In some circumstances, useful measurements can be obtained between two half-cells on the concrete surface (6).

### 2.4.2 Advantages

The equipment is simple and enables an almost non-destructive survey to produce isopotential contour maps of the surface of a concrete member. Zones of varying degrees of corrosion risk may be identified from these maps.

### 2.4.3 Limitations

This method cannot indicate the actual corrosion rate. It may require a small hole to be drilled to enable electrical contact to be made with the reinforcement in the member under examination, and surface preparation may also be required. It is important to recognize that the use and interpretation of the results obtained from the test require an experienced operator who will be aware of other limitations such as the effect of protective or decorative coatings applied to the concrete.

#### 2.4.4 Principal applications

This technique is most likely to be used for assessment or monitoring of the durability of reinforced concrete members where reinforcement corrosion is suspected. Reported uses include the location of areas of high reinforcement corrosion risk in marine structures, bridge decks and abutments. Used in conjunction with other tests, it has been found helpful when investigating concrete contaminated by salts.

## 2.5 Radiography

NOTE This method is currently described in BS 4408-3, but will eventually be revised as BS 1881-205.

### 2.5.1 General

Radiography provides a method of obtaining a photograph of the interior of a concrete member from which variations of density may be identified. This is produced on a suitable film held against the rear face of the concrete, while a beam of gamma rays or high-energy X-rays is directed at the front face. The presence of high density materials, such as reinforcement, or low density areas caused by voids will produce light and dark areas on the film.

### 2.5.2 Advantages

This non-destructive method is the most direct means of providing pictorial evidence of the interior of a body of concrete.

### 2.5.3 Limitations

This technique requires extensive safety precautions and utilizes highly specialized equipment. It is therefore essential that this type of work is only performed by radiographers with experience of working with concrete. Gamma ray sources may be used for member thicknesses of up to 500 mm; high-energy X-rays are more suitable for greater thicknesses up to 1.6 m.

### 2.5.4 Principal applications

The principal applications are as follows.

- a) The method is particularly valuable for locating areas of variable compaction or of voids in the concrete, or in the grouting of post-tensioned constructions.
- b) The general location of reinforcing bars can be determined. In favourable conditions, the location and sizing of reinforcing bars may be determined fairly precisely by photogrammetric analysis of the radiograph. The accuracy of measurements declines in adverse radiographic conditions.

## 2.6 Radiometry

NOTE This method is discussed in references 3 and 10 of Appendix A.

### 2.6.1 General

A narrow beam of gamma rays is directed into the concrete and the intensity of radiation emerging is measured by means of either a Geiger counter or a scintillation detector. Measurements may be made either of radiation passing through a body of concrete (direct method) or of radiation reflected back to the same surface by collision with electrons within the concrete (backscatter method). In either case, the mass per unit area of the concrete is the property which has the greatest influence on the attenuation of the beam of rays and hence the measured value of radiation. Steel reinforcement has about three times the effect of normal concrete and its presence will thus influence measured values.

### 2.6.2 Advantages

This method provides a truly non-destructive method of assessing in situ density. The direct method permits examination of the interior of a concrete member. Portable equipment, which can provide either backscatter or direct readings and incorporates a microprocessor to compute results, is commercially available.

### 2.6.3 Limitations

Direct methods across the full thickness of a concrete element require extensive precautions, skilled personnel and highly specialized equipment. Calibration may be obtained by cutting cores in the path of radiation after test and using these as samples for physical density measurement. Otherwise, results are restricted to comparative use. Concrete up to at least 1.2 m thick can be tested. For larger bodies of concrete or ground supported slabs, it may be necessary to lower the source and/or detector into pre-drilled or formed holes.

Direct readings may only be made at depths of up to 300 mm below the surface using the commercially available portable equipment, while backscatter results relate to a surface zone approximately 100 mm thick. Although equipment of this type is calibrated, difficulties may be caused by the lack of uniformity of the radiation absorption characteristics of concrete or density gradients near the surface. Backscatter results will generally be more variable than direct measurements (10).

### 2.6.4 Principal applications

The principal applications are as follows.

- a) Measurements of density where large numbers of repetitive measurements are required, e.g. for specialized in situ locations such as cement bound road bases or for quality control of precast units.

b) The direct method may be used to detect member thickness or reinforcement in addition to density measurements.

c) The backscatter method may be used to measure the density of the surface zone.

## 2.7 Neutron moisture measurement

NOTE This method is discussed in reference 3 of Appendix A.

### 2.7.1 General

The energy of fast or high-energy neutrons is rapidly reduced by the presence of elements of low atomic weight. The resulting slow or low-energy neutrons may be counted by a detector designed for this purpose. Few elements of low atomic mass are found in concrete other than hydrogen contained in water, and the counts may be used to provide an indication of moisture content.

Measurements may either be made of the scattered neutrons reflected back to the same surface as the source (the backscatter technique) or a direct transmission value may be obtained by lowering the source into a pre-drilled hole. Best results are obtained using the direct technique when the moisture content is high.

### 2.7.2 Advantages

Portable equipment, which can provide either backscatter or direct readings and incorporates a microprocessor to compute results, is commercially available. This provides a truly non-destructive assessment of in situ moisture content when using the backscatter method.

### 2.7.3 Limitations

The results will only relate to a surface zone of the concrete a few millimetres deep when using the backscatter method. Direct measurements may be made at depths of up to 300 mm using the equipment currently available. Calibration of the instrument may not be straightforward and in situ measurements may be influenced by moisture gradients near to the surface and the presence of other neutron absorbers. The accuracy of the method is poor for concrete of low moisture content.

### 2.7.4 Principal application

The principal application is the estimation of the moisture content of the surface zone.

## 2.8 Initial surface absorption

NOTE This method is currently described in BS 1881-5, but will eventually be revised as BS 1881-208.

### 2.8.1 General

Initial surface absorption involves measurement of the rate of flow of water per unit area into a concrete surface subjected to a constant applied head.

The equipment consists of a cap which is clamped and sealed to the concrete surface, with an inlet connected to a reservoir and an outlet connected to a horizontal calibrated capillary tube and scale. Measurements are made of the movement of the water in the capillary tube over a fixed period of time following closure of a tap between the cap and the reservoir.

The absorption of water by a dry surface is initially high but decreases as the water-filled length of capillaries increases, thus measurements have to be taken at specified time intervals from the start of the test.

### 2.8.2 Advantages

This method provides a practical non-destructive method of in situ measurement of the rate of water penetration of a concrete surface. It may be used on exposed aggregate or profiled surfaces provided a water-tight seal is obtained.

### 2.8.3 Limitations

It is essential to provide a water-tight seal between the cap and the concrete surface and difficulties are likely to be encountered. Sometimes it will be necessary to drill the surface for fixings.

Results are affected by variations in moisture content of the concrete, and samples for laboratory testing should preferably be oven dry or at least have been in a dry atmosphere for 48 h. It is virtually impossible to achieve comparable conditions with in situ concrete and this will reduce the reliability of quantitative results in this application. In these circumstances, use will be restricted to comparative measurements. The standardized pressure used in the test, created by the 200 mm head of water, is low and although results may be related to surface weather exposure they are of little relevance to behaviour under higher water pressures.

The internal permeability characteristics of a body of concrete cannot be assessed by this method.

### 2.8.4 Principal application

The most reliable application is as a quality control test for precast units which can be tested when dry. The test has been shown to be sensitive to changes in quality and weathering performance, and thus may also be used comparatively on in situ concrete for the purposes of quality control and assessment of potential durability.

## 2.9 Surface permeability

NOTE These methods are discussed in references 11, 12 and 13 of Appendix A.

### 2.9.1 General

Several methods are available, or under development, which permit an assessment of the permeability of concrete in the surface zone to water, air, carbon dioxide or other gases under pressure. These techniques, which vary in detail, all require a hole to be drilled into the surface of the concrete.

### 2.9.2 Advantages

These methods provide practical ways of assessing the permeability of surface zone concrete under in situ conditions. Information of this type may be particularly valuable as an indicator of potential durability.

### 2.9.3 Limitations

Some surface damage will be caused by these methods. The results will relate only to the particular test points and it will generally be necessary to perform tests at a number of points to obtain a representative value for each location. Although use of tests of this type is increasing, experience in the interpretation of site results is still limited.

The internal permeability characteristics of a body of concrete cannot be assessed by these methods.

### 2.9.4 Principal application

The main application is the assessment of the permeability of surface zone concrete in relation to durability surveys.

## 2.10 Maturity measurements

NOTE This method is discussed in references 14 and 15 of Appendix A.

### 2.10.1 General

Maturity is an arbitrary parameter based on measurements of the internal temperature of a body of concrete throughout the setting, hardening and subsequent strength development stages.

Equipment for these measurements may be constructed in many forms. Two commercially available types are:

- a) disposable maturity meters, which are based on a temperature-dependent chemical reaction and are embedded in the concrete surface at the time of casting;
- b) electrically-operated integrating maturity meters, consisting of a microprocessor coupled to a reusable temperature sensor inserted into a metal tube which is cast into the concrete.

Maturity measurements may be related to strength development for a particular concrete mix and are especially valuable when combined with other non-destructive methods for monitoring strength development.

### 2.10.2 Advantages

The measurement of maturity is a simple non-destructive technique which takes account of the temperature history within the concrete during hydration. This is particularly valuable for construction during adverse weather conditions when a knowledge of strength development is important.

### 2.10.3 Limitations

Measurements relate only to the individual test points, and for a major pour it will thus be necessary to take measurements at several points simultaneously to account for variations within the concrete. This can involve considerable expense if used on a regular basis.

Correlations between maturity and strength will only apply to the particular mix and circumstances for which they have been developed.

### 2.10.4 Principal application

The principal application is the monitoring of in situ strength development in relation to stripping of formwork, removal of props or the application of load.

## 2.11 Thermography

NOTE This method is discussed in references 16 and 17 of Appendix A.

### 2.11.1 General

Thermography involves the recording of surface temperature differentials on a concrete member undergoing heating or cooling. Hidden features, including voids or cracks, will influence the local rate of heating or cooling and may be detected by examination of temperature contour plots. Infra-red measurement techniques are necessary to detect and record the temperature differentials involved, which are very small. The following alternative types of equipment are available:

- a) a *quantitative temperature measuring gun*, which will yield a digital reading of the surface temperature at the point at which it is aimed;
- b) a *qualitative thermal imager*, which will indicate relative temperature differentials within the field of view; the image may be recorded photographically;
- c) a *scanner and cathode-ray monitor*, which will produce a colour display of calibrated isotherms which may be video-recorded or photographed.

Experience suggests that observations are best made during cooling, for example in the afternoon when the surface has been exposed to sunlight.

### 2.11.2 Advantages

This method is non-destructive, non-contacting, requires only one exposed surface and does not require the safety precautions necessary for radiography. Thermography may be carried out with the apparatus near to, or at a considerable distance from, the concrete surface.

### 2.11.3 Limitations

For large-scale structural surveys, it may be necessary to use the relatively expensive scanner in conjunction with a cathode ray tube. Precautions have to be taken to avoid interference from extraneous heat sources. Experience of the use of these techniques for inspection of concrete is limited.

### 2.11.4 Principal applications

The principal reported applications are from North America, where the technique has been used for the detection of delamination within reinforced concrete bridge decks. The method has also been used successfully for the location of ingress of moisture and of reinforcement (18), ducts, voids or similar features within concrete walls or slabs, although published information is limited.

## 2.12 Radar

NOTE This method is discussed in reference 19 of Appendix A.

### 2.12.1 General

A surface-penetrating radar system may be used to examine the reflections of short duration pulses from interfaces between materials with different dielectric constants lying below the surface. Reinforcing bars, voids, ducts and similar features may be identified and the thickness of slabs may also be determined. The equipment, which consists of transmitting and receiving antennae together with a control unit and recorder, is available commercially.

### 2.12.2 Advantages

This method, which is non-destructive and may be non-contacting, provides a rapid method of locating and recording features lying below the surface of a concrete element.

### 2.12.3 Limitations

Many factors contribute to the characteristics of the results, which require skilled specialist interpretation. The resolution that can be obtained will depend upon the frequency used, which will in turn influence the depth of penetration possible. Where high speed testing of large areas is involved, as in highway surveys, data handling and presentation may present particular problems. Applications of this technique to concrete are at an early stage, and available data and experience are limited.

### 2.12.4 Principal applications

The principal areas of application are likely to be the identification and location of voids, cracks, delamination, and reinforcing bars. The thickness of slabs and location of voids beneath ground slabs can also be determined (17).

## 2.13 Ultrasonic pulse velocity measurement

NOTE This method is currently described in BS 4408-5, but will eventually be revised as BS 1881-203.

### 2.13.1 General

Ultrasonic pulse velocity equipment measures the transit time of a pulse between transducers placed on the surface of a body of concrete. The pulse velocity can then be calculated using the measured path length through the concrete.

The pulse velocity depends upon the dynamic Young's modulus, dynamic Poisson's ratio and density of the medium.

### 2.13.2 Advantages

The principal advantages of ultrasonic pulse velocity measurement are that it is totally non-destructive, quick to use and reflects the properties of the interior of a body of concrete. It is particularly valuable in circumstances where a considerable number of readings is required for the assessment of uniformity of hardened concrete.

### 2.13.3 Limitations

Although non-destructive, it is essential not to overlook surface staining from the use of some couplants. The pulse velocities for most practical concrete mixes lie within a narrow range and it is therefore necessary to measure both the transit time and path length to an accuracy of the order of  $\pm 1\%$  if the results are to be of greatest value.

Measured values may be affected by surface texture, moisture content, temperature, specimen size, reinforcement and stress. Correlations with strength are difficult to make and will be influenced considerably by the types and proportions of mix constituents and maturity. For comparative surveys, readings may be made with both transducers placed on the same surface but when it is necessary to measure pulse velocity accurately, e.g. for strength estimation, it will be necessary to place the transducers on opposite faces of the concrete element.

#### 2.13.4 Principal applications

The principal applications are as follows.

- a) Determination of concrete uniformity, which is most reliably achieved by taking measurements on a regular grid on a member, or at comparable locations on similar members.
- b) Detection of cracking and honeycombing, which will increase the effective path length resulting in a higher measured transit time. If such defects lie between the transducers, a higher measured transit time will not necessarily occur if the crack or voids are water filled or bridged by reinforcement. The depth of surface cracks may be estimated by placing transducers on either side. Honeycombing or voids may be identified by taking a series of measurements through a member on a regular grid. The minimum size of detectable defect depends upon the transducer size and the distance between them.
- c) In situ strength estimations, which are unlikely to have 95 % confidence limits of better than  $\pm 7$  MPa<sup>2)</sup> given ideal testing conditions and a specifically prepared calibration chart for the concrete mix in use. It may be possible to improve this value if the density is known, or by combination with measured rebound numbers.
- d) Strength development monitoring, which is possible if appropriate calibration charts can be obtained. Where results can be compared with predetermined limits for acceptance, the method may be used for quality control, formwork removal, stressing operations, etc.
- e) Assessment of concrete deterioration, using a general comparative survey to locate suspect areas. Techniques are also available to estimate the depth of surface fire damage or chemical attack. Long term performance of concrete may also be monitored by conducting repetitive tests at a location.

<sup>2)</sup> 1 MPa =  $10^6$  N/m<sup>2</sup> = 10 bar.

NOTE Although this method of test may be used on both in situ concrete and laboratory specimens, for purely laboratory investigations resonance tests may be more suitable owing to their greater sensitivity. One test of this type is outlined in 2.1.

f) Estimation of layer thickness, which may be possible where there is a surface layer of inferior quality to the body of the concrete due to construction, weathering or other damage such as fire.

### 2.14 Dynamic response techniques

NOTE Some of these methods are discussed in reference 20 of Appendix A.

#### 2.14.1 General

Several techniques are available that measure the response of a structural member to an imposed dynamic load. They may be used to deduce stiffness and other structural properties. A wide range of methods may be applied to entire structures or individual members of a structure, but the approach is most fully developed for integrity testing of piles. Applications to other types of structural member are under development.

Techniques for pile testing include single blow and continuous vibration methods (20). The simplest and most widely used of these is the pulse echo method in which the reflected shock waves, resulting from a single hammer blow, are monitored by a hand-held accelerometer coupled to a signal processor. The wave form is then generally displayed visually.

#### 2.14.2 Advantages

These methods are fast to use and non-destructive. A wide range of specialist equipment is commercially available, which is especially suitable for testing of piles.

#### 2.14.3 Limitations

The equipment is often very specialized in nature and expensive, and considerable skill and experience are necessary for the interpretation of results. Tests on piles cannot directly assess the cross-sectional area or bearing capacity, and limited preparation of the pile head may sometimes be necessary.

#### 2.14.4 Principal applications

The principal applications are as follows:

- a) assessment of structural integrity and remaining service life;
- b) fault finding;
- c) assessment of the need for and effectiveness of repairs;

d) identification of defects, varying support conditions and lengths of piles.

## 2.15 Surface hardness

NOTE This method is published as BS 1881-202 (previously described in BS 4408-4).

### 2.15.1 General

The surface hardness test is based on the principle that the rebound of an elastic mass depends upon the hardness of the surface which it strikes. A number of different handheld spring-loaded steel rebound hammers are available to suit a variety of concrete types. The results are expressed in terms of the rebound number which is affected by conditions near to the surface. The test is particularly suited to comparative surveys but the results may also be correlated with other properties of the concrete. In this case a specific calibration for the type of concrete under investigation should be established as the use of universal calibrations can give seriously erroneous results.

### 2.15.2 Advantages

The principal advantages of surface hardness tests are the speed and low cost of testing.

### 2.15.3 Limitations

Results relate only to a surface zone of up to 30 mm depth and may be greatly affected by localized hardening due to carbonation when the concrete is more than 3 months old. Although tests are easy to carry out, the results are influenced by many factors including surface texture, moisture conditions of the surface, cement type, mix characteristics and type and rigidity of the structure. Concrete made with high alumina cement develops a surface layer considerably stronger than the underlying material, so results can be misleading. Minor surface indentations may be caused, particularly with young or weak concrete.

### 2.15.4 Principal applications

The principal applications are as follows.

- a) Determination of concrete uniformity, which is most reliably achieved by taking measurements on a regular grid on a member, or at comparable locations on similar members.
- b) Strength development monitoring, which is possible if appropriate calibration charts can be obtained. Where results can be compared with predetermined limits for acceptance, the method may be used for quality control, formwork removal, etc.

c) In situ strength estimations, which are unlikely to have 95 % confidence limits of better than  $\pm 7$  MPa given ideal testing conditions and a specifically prepared calibration chart for the concrete mix in use.

d) Assessment of abrasion resistance of concrete floor slabs, which may be correlated with rebound number.

This test is often combined with ultrasonic pulse velocity testing (see 3.4 and 3.5).

## 2.16 Screed test

NOTE This method is discussed in references 21 and 22 of Appendix A.

### 2.16.1 General

Measurement of the surface indentation caused by a defined number of repeated controlled hammer blows at a point on a sand/cement screed may be empirically related to the soundness of the screed. Equipment is available in which a mass of 4 kg is dropped 1 m down a vertical rod onto a foot which impacts the surface over a 500 mm<sup>2</sup> area. The indentation caused by a specified number of blows may be measured with a simple dial gauge device. This test has been specifically developed as a performance test for assessing the soundness of sand/cement floor screeds, soundness being used to describe that property required of a screed to withstand the imposed loads and traffic in service.

### 2.16.2 Advantages

This method provides a simple and quick approach which involves self-contained hand-held equipment. The damage to sound screeds is very small.

### 2.16.3 Limitations

This test is not suitable for use on concrete. Experience is restricted to sand/cement mortar screeds. On sound screeds, minor surface indentations up to 5 mm may be caused. The test cannot be used if the screed is laid over a weak or soft insulating layer, and the test area has to be flat and free from all loose dirt and grit. The screed should normally be at least 14 days old, and measured indentations have to be related to predetermined acceptability limits (22). The interpretation of results requires experience and common sense.

### 2.16.4 Principal application

The principal application is the assessment of durability and quality of floor screeds.

## 2.17 Internal fracture

NOTE This method is discussed in reference 23 of Appendix A and will eventually be published in BS 1881-207.

### 2.17.1 General

A 6 mm diameter expanding wedge anchor bolt is fixed into a drilled hole in the concrete surface and the peak force is recorded when this bolt is pulled against a reaction tripod on the surface. The force may be calibrated against compressive strength for the particular load application technique employed, since failure is initiated by a combination of tensile and shear stresses for the standardized configuration of bolt depth and reaction tripod dimensions.

The most common technique for loading involves the use of a torquemeter on a greased nut bearing on the reaction tripod through a washer, but the twisting applied to the bolt increases the scatter of results compared with hydraulic or mechanical direct-pull methods (24, 25).

### 2.17.2 Advantages

This strength determination method is simple and cheap, requires only one exposed surface and is suitable for slender members. Strength calibrations are effectively independent of water/cement ratio, cement type and curing.

### 2.17.3 Limitations

The test depth is small (about 17 mm) and test variability is very high, especially using the torquemeter loading method. The maximum acceptable aggregate size is 20 mm and an average of six readings is required at any location. The loading rate and method are critical in relation to strength calibrations, and the 95 % confidence limits are unlikely to be closer to the mean than  $\pm 28$  % using a torquemeter. Testing technique and aggregate type influence the correlation with compressive strength, and specific calibrations are recommended if reliance is to be placed on strength estimates.

Surface damage may be limited to the drill holes if the test is stopped when the peak force is reached, but there remains the possibility that further surface damage may be caused by frost attack. If the bolt is pulled out of the concrete a crater approximately 80 mm in diameter will be formed.

### 2.17.4 Principal applications

The principal applications are as follows.

- a) Strength estimation of in situ concrete in situations where other methods are not practicable. This is particularly likely in the case of slender members or for concrete where specific calibrations for other methods are impossible to obtain because of the large number of variables involved.
- b) Comparative surveys of in situ concrete.

- c) Quality control or strength monitoring purposes, which are possible if a suitable calibration chart is available.

## 2.18 Pull-out test

NOTE This method is discussed in references 26 and 27 of Appendix A and will eventually be published in BS 1881-207.

### 2.18.1 General

Pull-out tests involve measurement of the force required to pull a metal insert from within the concrete against a reaction ring. The shape and location of the insert and the reaction ring are designed and standardized to give a force which can be related to the compressive strength of the concrete. This calibration is relatively independent of mix characteristics for natural aggregates up to 38 mm maximum size.

The insert may be cast in the concrete or may be positioned in an underreamed groove from a drilled hole. Load is applied at a steady predetermined rate by hand-operated hydraulic equipment on to a removable bolt which is connected to the insert. The peak value obtained is known as the pull force and may be correlated against compressive strength. If the load is reduced at this stage, surface damage is small and the bolt can be removed, but if loading is continued, a cone of concrete will be pulled from the surface. Experience of these methods in the UK is limited but they are in increasing use in Scandinavia and North America.

### 2.18.2 Advantages

This method is quick and requires only one exposed surface. Cast-in inserts may be fixed to soffit or side forms or on the top surface, and tests may be made through cut-outs in forms if required.

### 2.18.3 Limitations

The depth of test is small (25 mm) and the scatter of individual results is high, requiring an average of six readings to be used. Estimated compressive strengths are unlikely to have 95 % confidence limits of better than  $\pm 20$  % of the mean when a general calibration is used or  $\pm 10$  % when a specially prepared calibration for the aggregate type in use is available. A minimum edge distance of 100 mm is required and reinforcement has to be avoided. Although testing is quick and the equipment simple to use, either pre-planning is required or drilling and underreaming are necessary. This operation is basically straightforward but may present some practical difficulties in situ, involving the use of a hand-held electric core cutter with water supply. The extent of surface damage will depend upon the test procedures adopted.

### 2.18.4 Principal applications

Cast-in inserts are most likely to be used for quality control or strength monitoring purposes, especially related to acceptance, formwork stripping, post-tensioning or termination of winter curing or protection. Values of pull force should be compared with previously established limiting values for the particular circumstances. In some circumstances, it may be appropriate to apply proof loads to such inserts.

Inserts fixed into drilled holes may be used for the following:

- a) comparative surveys of in situ concrete;
- b) in situ strength estimation based on an appropriate calibration.

## 2.19 Pull-off test

NOTE 1 This method is discussed in references 28 and 29 of Appendix A and will eventually be published in BS 1881-207.

### 2.19.1 General

The pull-off test is a near-to-surface method in which a circular steel disc is glued to the surface of the concrete with an epoxy or polyester resin. The force required to pull this from the surface, together with an attached layer of concrete, is measured. Simple mechanical hand-operated loading equipment has been developed for this purpose. Partial coring may be used, if necessary, to eliminate surface skin effects.

NOTE 2 Attention is drawn to the fact that it is claimed that the pull-off test is the subject of British Patent No. 1549842, copies of which can be obtained from the Patent Office, 25 Southampton Buildings, London WC2A 1AY. BSI takes no position as to the validity of the patent or whether it is still in force. The patent is endorsed "licences of right" under Section 46 of the Patents Act 1977, which states:

- "3) Where such an entry is made in respect of a patent —
- a) any person shall, at any time after the entry is made, be entitled as of right to a licence under the patent on such terms as may be settled by agreement or, in default of agreement, by the Comptroller on the application of the proprietor of the patent or the person requiring the licence".

Licence details may be obtained from the registered proprietor of the patent.

### 2.19.2 Advantages

This method directly measures a strength-related property, requires only one exposed surface and is suitable for use on small-section members.

### 2.19.3 Limitations

Considerable care has to be given to surface preparation prior to fixing the steel disc. Sufficient time has to be allowed to enable the resin adhesive to cure prior to load application. Results may be correlated to strength properties measured on standard specimens. Correlation with compressive strength is likely, however, to be influenced by aggregate type and it will probably be necessary to derive a calibration with strength for a particular type of concrete to be investigated.

Laboratory tests on concrete cubes indicate that an accuracy of strength prediction, based on the mean of three readings, of  $\pm 15\%$  is possible. However, there is insufficient evidence available to enable detailed guidance to be given on the accuracy of the method under site conditions, although a greater variability is to be expected.

Localized surface damage will be caused, and test results are limited to the surface zone of the concrete with fracture occurring approximately 5 mm below the surface unless partial coring is used.

### 2.19.4 Principal applications

The principal applications are quality control, long term monitoring and in situ strength assessment (particularly of high alumina cement concrete and carbonated concrete made with ordinary Portland cement using partial coring). These all require a suitable correlation to be available. In some circumstances proof loads may be applied to a series of permanent probes. The method also provides a useful means of testing repairs to concrete surfaces.

## 2.20 Break-off test

NOTE This method is discussed in references 30 and 31 of Appendix A and will eventually be published in BS 1881-207.

### 2.20.1 General

The break-off test has been developed in Scandinavia and determines directly the flexural tensile strength in a plane parallel to the concrete surface at a specified distance below the surface. A 55 mm diameter core is effectively formed within the concrete to a depth of 70 mm either by means of a disposable tubular form, which is cast into the concrete and then removed, or by cutting. An enlarged slot is formed near to the surface into which a hydraulically-operated jack with a load cell is inserted to provide a transverse force to the top of the core. Measured values may be correlated to strength tests on standard laboratory specimens; the most reliable relationship is with flexural tests on prisms.

### 2.20.2 Advantages

This method directly measures a strength-related property and requires only one exposed surface. It is claimed to be especially suitable for young concretes and is quicker than conventional core testing.

### 2.20.3 Limitations

This method will leave a sizable damage zone and will either require pre-planning or the use of core-cutting equipment. The test variability is high and it is recommended that the mean of five tests should be used to represent the concrete at a given location. Insufficient evidence is available to permit guidance to be given on the accuracy of in situ strength estimates obtained by this method.

### 2.20.4 Principal applications

Principal applications are likely to be situations in which the tensile strength of the concrete is of importance, as follows:

- a) quality control of concrete pavements where results can be compared with predetermined limits for acceptance;
- b) in situ strength assessment in situations where a suitable correlation is available.

## 2.21 Penetration resistance

NOTE This method is discussed in references 3, 25 and 32 of Appendix A and will eventually be published in BS 1881-207.

### 2.21.1 General

Penetration resistance involves firing a steel bolt (probe) into the surface of the concrete. A standardized charge is used and the depth of penetration is measured. This may be calibrated against compressive strength, with the relationship principally affected by aggregate characteristics. Two power levels are available according to the concrete strength and the mean of three individual test results is normally required at any location.

### 2.21.2 Advantages

This strength determination method is quick and relatively insensitive to operator techniques and factors such as moisture content, cement type and curing. This may be particularly valuable in situations where access is poor. The method may be used with up to 50 mm aggregate size and with rough or lightly textured surfaces or through timber forms. The test depth is uncertain but results are likely to represent concrete between 25 mm to 75 mm from the surface.

### 2.21.3 Limitations

Damage in the form of cracking may be caused to slender members, and a minimum edge distance and member thickness of 150 mm are required. Reinforcement has to be avoided and simple safety precautions are necessary. Calibration for the aggregate in use is essential if results are to be used to assess compressive strength, and estimated values are unlikely to have 95 % confidence limits of better than  $\pm 20$  %.

After measurement, the probe may be pulled from the surface leaving a conical surface damage zone approximately 75 mm in diameter.

### 2.21.4 Principal applications

The principal applications are as follows:

- a) comparative strength estimation in situations where truly non-destructive methods are unsuitable or impracticable;
- b) quality control or strength development monitoring, where results can be compared with predetermined limits for acceptance, formwork removal, etc.;
- c) strength estimation of in situ concrete in cases where an appropriate calibration is available.

## 2.22 Depth of carbonation

NOTE This method is discussed in reference 33 of Appendix A.

### 2.22.1 General

Carbonation of surface zone concrete will be accompanied by a loss of alkalinity of the concrete affected. This may be detected by the use of a suitable indicator, e.g. phenolphthalein, which can be sprayed on to a freshly exposed cut or broken surface of the concrete.

### 2.22.2 Advantages

This method is quick and simple and gives an immediate visual indication.

### 2.22.3 Limitations

A suitable surface has to be provided by cutting or breaking and testing immediately. This procedure will cause localized surface damage. This method provides only an indication of the extent of carbonation.

### 2.22.4 Principal applications

A knowledge of the depth of carbonation combined with the age of the concrete may be useful when assessing potential durability and the likelihood of corrosion of reinforcement. This test may also be useful in conjunction with some of the near-to-surface test methods to ensure that the depth of carbonation is insufficient to influence results.

## 2.23 Acoustic emission

NOTE This method is discussed in references 3 and 34 of Appendix A.

### 2.23.1 General

This method involves the detection of small amplitude elastic stress waves which are propagated throughout a material as localized crushing or microcracking occurs under load. This emission is generally not in the audible range and may be monitored by transducers positioned on the concrete surface and connected to electronic processing and recording equipment. As the load level on a concrete element increases, both the emission rate and signal level increase steadily. A rapid increase in both parameters precedes failure.

### 2.23.2 Advantages

Crack initiation and propagation can be monitored non-destructively during a period of increasing stress within a concrete element. It may also be possible to identify the location of crack initiation and propagation by the use of multiple detectors.

### 2.23.3 Limitations

Concrete may recover some aspects of its pre-cracking internal structure, and reloading over a particular stress range may again generate emissions. Consequently, it is not always possible to establish a history of past stress levels, contrary to the behaviour of many other materials.

This method would not normally be used for either individual or comparative measurements under static load conditions.

The propagation of acoustic waves in concrete is limited to low ultrasonic frequencies where the noise background is often high. The method is not, therefore, suitable for use on most building sites nor for the precise location of propagation cracks even in quiet areas.

Specialist equipment is required, and applications of the technique to concrete outside of the laboratory have not yet been fully developed.

### 2.23.4 Principal application

The principal application is likely to be monitoring of the initiation, origin and development of internal cracking and local breakdown during load testing, and to provide a warning of impending failure.

## 2.24 Strain measurements

NOTE This method is currently described in BS 4408-2, but will eventually be revised as BS 1881-206.

### 2.24.1 General

Useful deductions concerning the suitability of concrete elements can be made by measuring strain. Strain gauges can measure strain, or apparent strain, caused by crack propagation, thermal changes, etc. They use one or more of the following to amplify and display the movement:

- a) levers;
- b) optics;
- c) electrical resistance;
- d) frequency of vibration;
- e) other means.

### 2.24.2 Advantages

The movement of structures can be monitored over long periods. The relationship between design parameters and the performance of the finished structure can be checked.

### 2.24.3 Limitations

The attachment and reading of many of these devices require skill. Not all strain gauges are suitable for use with concrete.

### 2.24.4 Principal applications

Principal applications include the following;

- a) monitoring of movements in structures at all ages;
- b) assessing elasticity of structural members;
- c) research work and model testing;
- d) load testing.

## Section 3. Combinations of methods

### 3.1 General

Situations in which it may be worthwhile to use combinations of test methods are outlined in 1.4.3.3. The most suitable methods will vary according to the circumstances but the following suggestions may be considered as typical.

### 3.2 Electromagnetic cover measurement or radiography to locate reinforcement

Electromagnetic cover measuring devices will frequently be valuable in conjunction with the near-to-surface test methods to ensure that reinforcement is avoided at test locations. The limited depth range of such equipment will not normally be a problem in this situation. This approach may similarly be valuable in relation to core drilling and ultrasonic pulse velocity measurements.

If the reinforcement is embedded at a depth beyond the range of this equipment, it may be necessary to use radiography to provide an indication of location, but this is only likely to be justified in particularly critical situations.

### 3.3 Non-destructive methods as preliminary to partially-destructive methods

It may often be worthwhile to perform an extensive survey quickly and cheaply with a rebound hammer or ultrasonic pulse velocity equipment prior to the use of other methods involving greater expense or damage but which give a more reliable indication of the required property of the concrete. This approach will enable suspect zones to be identified and can provide a calibration datum, thereby reducing the time and cost of examining a large body of concrete. The choice of a preliminary method has to be determined, taking account of the practical circumstances and the limitations of the test methods, and may also include radiography, radiometry or thermography. The subsequent testing will depend largely upon the property required but may include core cutting, pull-out, internal fracture, break-off or penetration resistance, where strength is important. When in situ strength development is to be monitored, maturity measurements may provide useful preliminary data prior to confirmation by more disruptive strength assessment tests, such as pull-outs (15, 35).

### 3.4 Increasing the confidence level of test results

As a general rule, the cheapest and quickest suitable test methods will have been chosen. The observed patterns of variation of quality may be confirmed by the use of additional methods. For example, on recently cast concrete the use of rebound hammer and ultrasonic pulse velocity may be the most appropriate combination. In other circumstances it may be necessary to combine one or the other of these with near-to-surface testing or radiometry. The patterns of results obtained should be compared directly, and results should not be converted to some other property before comparison. Confidence will be much increased if similar patterns emerge.

In situations where the volume of concrete is relatively small, and where a specific property, e.g. strength, is of primary interest, it may be worthwhile to compare two or more estimates of that property using different methods.

### 3.5 Improvement of calibration accuracy

In some cases where the correlation between measured values and required property is sensitive to a number of variables, it may be possible to achieve an improved accuracy of estimated property by mathematical combination of results.

The accuracy of strength prediction from ultrasonic pulse velocity may be improved by combination with values of density (36) obtained from the same specimens or sections, provided sufficiently accurate measurements can be made. Ideally, a velocity/strength relationship should be derived for each value of density. However, rebound hammer readings, which are surface-density related, have most often been used in combination with ultrasonic pulse velocity measurements.

In cases where strength calibrations are available for both methods relating to the concrete in use, multiple regression equations can be developed with compressive strength as the dependent variable (37, 38). This is likely to be of particular value for quality control applications. Correlation graphs may also be produced involving coefficients relating to various properties (39).

### **3.6 Half-cell potential and resistivity tests to indicate likelihood of reinforcement corrosion**

Half-cell potential surveys will usually indicate the level of possibility of the occurrence of reinforcement corrosion as a result of electrochemical action. Subsequent resistivity measurements in zones which are demonstrated to be at risk may sometimes indicate the likelihood of corrosion actually occurring. While combination of these methods cannot positively confirm that corrosion has occurred or is occurring, or assess the extent of any corrosion, they represent the most effective non-destructive approach currently available (6, 40). Other tests of a chemical nature are available for the concrete, e.g. chloride content analysis and carbonation depth, while steel monitoring tests, e.g. electrical resistance probes and linear polarization probes, may have to be incorporated at the time of construction (5). Tests of this type may be valuable in conjunction with half-cell potential and resistivity measurements, but are outside the scope of this standard.

## Appendix A Bibliography

1. AMERICAN SOCIETY FOR TESTING AND MATERIALS. *Air void content in hardened concrete*, ASTM C457, 1980.
2. AMERICAN SOCIETY FOR TESTING AND MATERIALS. *Petrographic examination of hardened concrete*, ASTM C856, 1977.
3. BUNGEY, J.H. *The testing of concrete in structures*, 1982.
4. McCARTER, W.J., FORDE, M.C. & WHITTINGTON, H.W. *Resistivity characteristics of concrete*. *Proc. I.C.E., Part 2*, 1981, **71**, 107–117.
5. VASSIE, P.R. A survey of site tests for the assessment of corrosion in reinforced concrete. *Transport & Road Res. Lab., Lab. Rep. 953*, 1980.
6. FIGG, J.W. & MARSDEN, A.F. Development of inspection techniques – a state-of-the-art survey of electrical potential and resistivity measurements for use above water level. In: CIRIA, *Concrete in the Oceans, Phase II, Technical Note P6d, Final Report*, **99**, 1983.
7. MALHOTRA, V.M. Testing hardened concrete – non-destructive methods. *ACI Monograph No. 9*, 1976.
8. McCARTER, W.J., WHITTINGTON, H.W. & FORDE, M.C. An experimental investigation of the earth resistance response of reinforced concrete piles. *Proc. I.C.E., Part 2*, 1981, **71**, 1101–1129.
9. AMERICAN SOCIETY FOR TESTING AND MATERIALS. *Standard test method for half-cell potentials of reinforcing steel in concrete*, ASTM C876, 1980.
10. SHERWOOD, P.T. & CLARK, A.J. The measurement of the in situ density of cement bound materials. *Transport & Road Res. Lab., Lab. Rep. 1109*, 1984.
11. FIGG, J.W. Methods of measuring the air and water permeability of concrete. *Mag. of Concrete Res.*, 1973, **25**, No. 85, 213–219.
12. CATHER, R., FIGG, J.W., MARSDEN, A.F. & O'BRIEN, T.P. Improvements to the Figg method of determining the air permeability of concrete. *Mag. of Concrete Res.*, 1984, **36**, No. 129, 241–245.
13. HANSEN, A.J., OTTOSEN, N.S. & PETERSEN, C.G. Gas permeability of concrete in situ: theory and practice. In: *ACI In situ/non-destructive testing of concrete*, SP-82, 543–556, 1984.
14. NAIK, T.R. Concrete strength prediction by the maturity method. *Proc. ASCE*, 1980, **106**, EM3, 465–480.
15. PETERSEN, C.G. & HANSEN, A.J. Timing of loading determined by pull-out and maturity tests. In: *Proc. Int. Conf. on concrete at early ages*, RILEM, 1982, **1**, 173–175.
16. MANNING, D.G. & HOLT, F.B. Detecting delamination in concrete bridge decks. *Concrete International*, 1980, **2**, No. 11, 34–41.
17. GODFREY, J.R. New tools help find flaws. *Civil Engineering*, 1984, **54**, No. 9, 39–42.
18. HILLEMEIER, B. & MÜLLER-RUN, U. Bewehrungssuche mit der thermographie. *Beton und Stahlbeton*, 1980, **75**, No. 4, 83–85.
19. CANTOR, T.R. Review of penetrating radar as applied to the non-destructive testing of concrete. In: *ACI In situ/non-destructive testing of concrete*, SP-82, 581–602, 1984.
20. STAIN, R.T. Integrity testing. *Civil Engineering*, April 1982, 54–59; May 1982, 71–73.
21. PYE, P.W. & WARLOW, W.J. A method of assessing the soundness of some dense floor screeds. *Building Res. Establishment Current Paper CP72/78*, 1978.
22. PYE, P.W. BRE Screed tester: classification of screeds, sampling and acceptance limits. *Building Res. Establishment Information Paper IP11/84*, 1984.
23. CHABOWSKI, A.J. & BRYDEN SMITH, D.W. Internal fracture testing of in situ concrete. *Building Res. Establishment Information Paper IP22/80*, 1980.
24. BUNGEY, J.H. Concrete strength determination by pull-out tests on wedge-anchor bolts. *Proc. I.C.E. Part 2*, 1981, **71**, 379–394.
25. KEILLER, A.K. Assessing the strength of in situ concrete. *Concrete International*, 1985, **7**, No. 2, 15–21.
26. BUNGEY, J.H. An appraisal of pull-out methods of testing concrete. In: *Proc. NDT 83*, 12–21, Engineering Technics Press, Edinburgh, 1983.

27. PETERSEN, C.G. Lok-test and Capo-test development and their applications. *Proc. I.C.E. Part 1*, 1984, **76**, 539–549.
28. LONG, A.E. & MURRAY, A. McC. The pull-off partially destructive test for concrete. In: *ACI In situ/non-destructive testing of concrete*, SP-82, 327–350, 1984.
29. LONG, A.E. Improvements in or relating to strength testing brittle materials. *British Patent Specification No. 1549842*, 1979.
30. CARLSSON, M., EEG, I.R. & JAHREN, P. Field experience in the use of the break-off tester. In: *ACI In situ/non-destructive testing of concrete*, SP-82, 277–292, 1984.
31. DAHL-JORGANSEN, E. & JOHANSEN, R. General and specialized use of the break-off concrete strength testing method. In: *ACI In situ/non-destructive testing of concrete*, SP-82, 293–308, 1984.
32. SWAMY, R.N. & AL-HAMED, A.H.M.S. Evaluation of the Windsor probe test to assess in situ concrete strength. *Proc. I.C.E., Part 2*, 1984, **77**, 167–194.
33. ROBERTS, M.H. Carbonation of concrete made with dense natural aggregates. *Building Res. Establishment, Information Paper IP6/81*, 1981.
34. MLAKAR, P.F., WALKER, R.E., SULLIVAN, B.R. & CHIARITO, V.P. Acoustic emission behaviour of concrete. In: *ACI In situ/non-destructive testing of concrete*, SP-82, 619–637, 1984.
35. PARSONS, T.J. & NAIK, T.R. Early age concrete strength determination by pull-out testing and maturity. In: *ACI In situ/non-destructive testing of concrete*, SP-82, 177–200, 1984.
36. REYNOLDS, W.N. Measuring concrete quality non-destructively. In: *Brit. J. of Non-destructive Testing*, 1984, **26**, 11–14.
37. SAMARIN, A. & DHIR, R.K. Determination of in situ concrete strength: rapidly and confidently by non-destructive testing. In: *ACI In situ/non-destructive testing of concrete*, SP-82, 77–94, 1994.
38. TANIGAWA, Y., BABA, K. & HIROSHI, M. Estimation of concrete by combined non-destructive testing method. In: *ACI In situ/non-destructive testing of concrete*, SP-82, 57–76, 1984.
39. FACAOARU, I. Romanian achievements in non-destructive strength testing of concrete. In: *ACI In situ/non-destructive testing of concrete*, SP-82, 35–56, 1984.
40. VASSIE, P. Reinforcement corrosion and durability of concrete bridges. *Proc. I.C.E. Part 1*, 1984, **76**, 713–723.

---

## Publications referred to

BS 1881, *Testing concrete*.

BS 1881-5, *Methods of testing hardened concrete for other than strength*.

BS 1881-108, *Method for making test cubes from fresh concrete*.

BS 1881-111, *Method of normal curing of test specimens (20° C method)*.

BS 1881-116, *Method for determination of compressive strength of concrete cubes*.

BS 1881-202, *Recommendations for surface hardness testing by rebound hammer*.

BS 1881-203, *Recommendations for the measurement of velocity of ultrasonic pulses in concrete*<sup>3)</sup>.

BS 1881-204, *Recommendations for the use of electromagnetic cover measuring devices*<sup>3)</sup>.

BS 1881-205, *Recommendations for the radiography of concrete*<sup>3)</sup>.

BS 1881-206, *Recommendations for the determination of strain in concrete*<sup>3)</sup>.

BS 1881-207, *Recommendations for near to surface tests for concrete*<sup>3)</sup>.

BS 1881-208, *Recommendations for the determination of initial surface absorption of concrete*<sup>3)</sup>.

BS 1881-209, *Recommendations for the dynamic modulus of elasticity*<sup>3)</sup>.

BS 2787, *Glossary of terms for concrete and reinforced concrete*.

BS 4408, *Recommendations for non-destructive methods of test for concrete*.

BS 4408-1, *Electromagnetic cover measuring devices*.

BS 4408-2, *Strain gauges for concrete investigations*.

BS 4408-5, *Measurement of the velocity of ultrasonic pulses in concrete*.

BS 6089, *Guide to assessment of concrete strength in existing structures*<sup>4)</sup>.

BS 6100, *Glossary of building and civil engineering terms*.

BS 6100-6, *Concrete and plaster*.

NOTE See also bibliography in Appendix A.

---

<sup>3)</sup> In preparation.

<sup>4)</sup> Referred to in the foreword only.

---

# BSI — British Standards Institution

BSI is the independent national body responsible for preparing British Standards. It presents the UK view on standards in Europe and at the international level. It is incorporated by Royal Charter.

## Revisions

British Standards are updated by amendment or revision. Users of British Standards should make sure that they possess the latest amendments or editions.

It is the constant aim of BSI to improve the quality of our products and services. We would be grateful if anyone finding an inaccuracy or ambiguity while using this British Standard would inform the Secretary of the technical committee responsible, the identity of which can be found on the inside front cover. Tel: 020 8996 9000. Fax: 020 8996 7400.

BSI offers members an individual updating service called PLUS which ensures that subscribers automatically receive the latest editions of standards.

## Buying standards

Orders for all BSI, international and foreign standards publications should be addressed to Customer Services. Tel: 020 8996 9001. Fax: 020 8996 7001.

In response to orders for international standards, it is BSI policy to supply the BSI implementation of those that have been published as British Standards, unless otherwise requested.

## Information on standards

BSI provides a wide range of information on national, European and international standards through its Library and its Technical Help to Exporters Service. Various BSI electronic information services are also available which give details on all its products and services. Contact the Information Centre. Tel: 020 8996 7111. Fax: 020 8996 7048.

Subscribing members of BSI are kept up to date with standards developments and receive substantial discounts on the purchase price of standards. For details of these and other benefits contact Membership Administration. Tel: 020 8996 7002. Fax: 020 8996 7001.

## Copyright

Copyright subsists in all BSI publications. BSI also holds the copyright, in the UK, of the publications of the international standardization bodies. Except as permitted under the Copyright, Designs and Patents Act 1988 no extract may be reproduced, stored in a retrieval system or transmitted in any form or by any means – electronic, photocopying, recording or otherwise – without prior written permission from BSI.

This does not preclude the free use, in the course of implementing the standard, of necessary details such as symbols, and size, type or grade designations. If these details are to be used for any other purpose than implementation then the prior written permission of BSI must be obtained.

If permission is granted, the terms may include royalty payments or a licensing agreement. Details and advice can be obtained from the Copyright Manager. Tel: 020 8996 7070.