BRITISH STANDARD

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*Incorporating Amendment Nos. 1 and 2*

# Testing concrete —

## Part 203: Recommendations for measurement of velocity of ultrasonic pulses in concrete

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# 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 Civil Engineering Test Equipment Manufacturers' Association
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)
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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 sub-committees and panels:

British Nuclear Fuels Limited
United Kingdom Atomic Energy Authority

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# Foreword

This Part of BS 1881 has been prepared under the direction of the Cement, Gypsum, Aggregates and Quarry Products Standards Committee. It supersedes BS 4408-5:1974, which is withdrawn. All aspects of testing concrete are being included as Parts of BS 1881, from sampling fresh concrete to assessing concrete in structures. Part 201 gives general guidance on the choice of non-destructive test methods and should be consulted for advice on methods which can be used to complement the measurement of ultrasonic pulse velocity.

Ultrasonic testing of concrete has been in use in a large number of countries for many years, in laboratories, in precast works and on site.

The technique generally used is the measurement of ultrasonic wave group velocity from the transit time of a pulse between separate transmitting and receiving transducers through a known path distance in the concrete. This provides a measurement of the mean ratio of elastic stiffness to density along the path and has been found to be a useful index of concrete quality.

The velocity is a function of the composition, degree of compaction, maturity and free water content which are inherent in concrete products and structures. Under certain conditions and for properly defined ranges of material, useful correlations may be established between the velocity and properties such as the modulus of elasticity and strength.

This ultrasonic technique is completely distinct from the pulse-echo technique commonly used for the detection of localized defects in metals. The high frequency waves necessary for metals cannot travel through concrete as they are rapidly scattered and dispersed by the aggregate particles and pores. However, individual defects can be detected if they are sufficiently extensive to influence pulse transit times by increasing the effective path length or cutting out the signal altogether.

All ultrasonic pulses passing through concrete are attenuated by an amount depending on their frequency and the properties of the concrete. This attenuation is not easy to measure and techniques based on this aspect of pulse propagation have not been widely used, but helpful additional information may be obtained under certain circumstances. Specialist literature should be consulted.

This standard is concerned with the measurement of the velocity of transmission of longitudinal ultrasonic pulses through concrete and it is hoped that better understanding of the measuring technique will result from its use. It includes some recommendations on the interpretation of test results and their correlation with elastic modulus and strength tests.

This 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 18, 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.

## 1 Scope

This Part of BS 1881 gives recommendations on the non-destructive testing of concrete in the form of plain, reinforced and prestressed test specimens, precast components and structures by the measurement of ultrasonic pulse velocity [1,2].

NOTE 1 The numbers in square brackets refer to the bibliographic references in appendix A.

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

## 2 Definitions

For the purposes of this Part of BS 1881 the definitions given in BS 3683-4 and BS 6100-6 apply, together with the following.

**2.1**
**transit time**

time taken for an ultrasonic pulse to travel from the transmitting transducer to the receiving transducer, passing through the interposed concrete

**2.2**
**onset**

leading edge of the pulse detected by the measuring apparatus

## 3 Applications

Measurement of the velocity of ultrasonic pulses of longitudinal vibrations passing through concrete may be used for the following applications, described in detail in clauses **8** to **12**:

a) determination of the uniformity of concrete in or between members [3, 4, 5], clause **8**

b) detection of the presence and approximate extent of cracks, voids and other defects [6, 7, 8], clause **9**

c) measurement of changes occurring with time in the properties of the concrete [9, 10, 11], clause **10**

d) correlation of pulse velocity and strength as a measure of concrete quality [12, 13, 14], clause **11**

e) determination of the modulus of elasticity and dynamic Poisson's ratio of the concrete [15, 16], clause **12**

The velocity of an ultrasonic pulse is influenced by those properties of the concrete which determine its elastic stiffness and mechanical strength. The variations obtained in a set of pulse velocity measurements made along different paths in a structure reflect a corresponding variation in the state of the concrete (see clause **8**).

When a region of low compaction, voids or damaged material is present in the concrete under test, a corresponding reduction in the calculated pulse velocity occurs and this enables the approximate extent of the imperfections to be determined (see clause **9**). As concrete matures or deteriorates, the changes which occur with time in its structure are reflected in either an increase or a decrease, respectively, in the pulse velocity. This enables the changes to be monitored by making tests at appropriate intervals of time (see clause **10**).

Pulse velocity measurements made on concrete structures may be used for quality control purposes. In comparison with mechanical tests on control samples such as cubes or cylinders, pulse velocity measurements have the advantage that they relate directly to the concrete in the structure rather than to samples which may not be always truly representative of the concrete in situ.

Ideally, pulse velocity should be related to the results of tests on structural components and, if a correlation can be established with the strength or other required properties of these components, it is desirable to make use of it. Such correlations can often be readily established directly for precast units and can also be found for in situ work (see clause **11**).

Empirical relationships may be established between the pulse velocity and both the dynamic and static elastic moduli and the strength of concrete (see clause **12**). The latter relationship is influenced by a number of factors including the type of cement, cement content, admixtures, type and size of aggregate, curing conditions and age of concrete. Caution should be exercised when attempting to express the results of pulse velocity tests in terms of strengths or elastic properties, especially at strengths exceeding 60 MPa.

## 4 Principle

A pulse of longitudinal vibrations is produced by an electro-acoustical transducer which is held in contact with one surface of the concrete under test. After traversing a known path length $L$ in the concrete, the pulse of vibrations is converted into an electrical signal by a second transducer. Electronic timing circuits enable the transit time $T$ of the pulse to be measured.

The pulse velocity $v$ (in km/s or m/s) is given by

$$v = \frac{L}{T} \qquad (1)$$

where

- $L$ is the path length;
- $T$ is the time taken by the pulse to traverse that length.

A pulse of vibrations of ultrasonic rather than sonic frequency is used for two reasons:

a) to give the pulse a sharp leading edge;

b) to generate maximum energy in the direction of propagation of the pulse.

When the pulse is coupled into the concrete from a transducer, it undergoes multiple reflections at the boundaries of the different material phases within the concrete. A complex system of stress waves is developed which includes both longitudinal and shear waves propagating throughout the concrete.

## 5 Measuring apparatus

**5.1** *General*

The apparatus consists essentially of an electrical pulse generator, a pair of transducers, an amplifier and an electronic timing device for measuring the time interval between the onset of a pulse generated at the transmitting transducer and the onset of its arrival at the receiving transducer. Two forms of electronic timing apparatus and display are available, one of which uses a cathode ray tube on which the received pulse is displayed in relation to a suitable time scale, the other uses an interval timer with a direct reading digital display.

**5.2** *Performance characteristics*

The apparatus should have the following characteristics.

a) It should be capable of measuring transit time over path lengths ranging from 100 mm to 3 m (see **5.7**), to an accuracy of ± 1 % as determined by the procedure described in **5.6**.

b) The electronic excitation pulse applied should have a rise time not greater than one quarter of the natural period of the transmitting transducer. This is to ensure a sharp pulse onset.

c) The interval between pulses should be long enough to ensure that the onset of the received signal in small concrete test specimens is free from interference by reverberations produced within the preceding working cycle.

d) The apparatus should maintain its performance over the ranges of ambient temperature, humidity and power supply voltage stated by the suppliers.

**5.3** *Transducers*

**5.3.1** *Type.* Any suitable type of transducer operating within the frequency range stated in **5.3.2** may be used. Piezo-electric and magneto-strictive types of transducers are normally used, the latter being more suitable for the lower part of the frequency range.

**5.3.2** *Natural frequency of transducers.* The natural frequency of the transducers should normally lie within the range of 20 kHz to 150 kHz, although frequencies as low as 10 kHz may be used for very long path lengths and, at the other extreme, frequencies up to 1 MHz for mortars and grouts.

High frequency pulses have a well defined onset but, as they pass through concrete, become attenuated more rapidly than pulses of lower frequency. It is, therefore, preferable to use high frequency transducers for short path lengths and low frequency transducers for long path lengths. Transducers with a frequency of 50 kHz to 60 kHz are suitable for most common applications.

**5.4** *Determination of the arrival time of the pulse onset*

**5.4.1** *General.* The object of the determination is to measure the time taken for the onset of the pulse to pass through the concrete. As explained in **5.3.2**, the onset becomes less well defined as the pulse proceeds further into the concrete. It is therefore necessary that the apparatus be able to detect the arrival of the earliest part of the pulse. Although it is technically possible to separate the signal from background noise if the signal/noise ratio is less than one, the required accuracy of 1 % of the measured transit time will only be achieved if this ratio is greater than one.

**5.4.2** *Cathode ray oscilloscope.* In the case of timing devices in which a cathode ray oscilloscope display is used, the received pulse should be amplified to the maximum possible level, limited only by the appearance of "grass" on the time-base trace of the display. The onset of the pulse should be taken as the point of tangent of the signal curve with the initial horizontal time-base line. Alternatively, some other well defined feature of the curve, such as the first crossover, may be used.

**5.4.3** *Digital instruments.* For digital instruments, the received pulse should be amplified and shaped to the level and rise time, respectively, required for triggering the digital timer.

The timer should trigger from a point on the leading edge of the pulse within a time corresponding to the range of accuracy specified in **5.2**. However, the absolute accuracy of the instrument will always be limited by the signal/noise ratio.

When using a digital indicating device, there may be occasions when the second wave of the pulse, rather than the first, triggers the instrument. The general pattern of results should be inspected to enable errors of interpretation from this cause to be eliminated.

**5.5** *Setting the zero for the timing equipment*

It is necessary to establish the correct zero reading for the apparatus, since the indicated measurement is influenced by a time delay due both to transmission of the pulse through the transducer material and transmission of the electrical signal along the transducer cables. The apparatus should incorporate a suitable time delay adjustment so that the indicated readings may be made independent of this effect.

The time delay adjustment should be made while the transducers are coupled to the opposite ends of a reference bar for which the transit time is accurately known. A bar having a pulse transit time of about 25 $\mu$s is suitable (see also **5.6**). It is important always to use the same technique to place the transducers on the reference bar. A minimum amount of couplant should be used and the transducer pressed firmly against the end of the bar. Any other technique, such as sliding the transducers onto the bar, may give a significantly different zero reading and should be avoided.

Adjustments to the time delay to provide a correct zero setting for the apparatus should be made each time the equipment is used, whenever transducers are interchanged, whenever different transducers are used and whenever different lengths of cables are used. It may also be necessary to carry out more frequent checks on the zero setting, depending on the stability of the electronic circuits or cables.

**5.6** *Checking the accuracy of transit time measurements*

The accuracy of the measurement of pulse transit time will depend on the accuracy of the electronic device used for measuring time intervals and also on its sensitivity in detecting the onset of the pulse.

Overall performance should be checked by making measurements on two reference bars in which the pulse transit times are known to an accuracy of ± 0.2 µs. This performance check should be carried out at intervals no longer than 5 years or if the instrument is damaged or malfunctions in such a way that it has to be returned to the manufacturer for repair. In all cases the performance check should be carried out and certified either by the manufacturer or by an accredited laboratory, in both cases using reference bars of which the transit times are traceable to the National Standard of Time.

The two reference bars should have pulse transit times of about 25 µs and 100 µs, respectively, and these times should be marked on the bars to the nearest 0.1 µs. The shorter of the reference bars should first be used to set the zero for the equipment, as explained in **5.5**. The longer of the reference bars should then be used to check the accuracy of pulse transit time measurement by the equipment. Measurements are made on these reference bars by placing a transducer at each end and taking the transit time reading as described in **5.4**. The measurement obtained should not differ from the known value for the longer reference bar by more than ± 0.5 %.

**5.7** *Accuracy of path length measurement*

The accuracy of measurement should be better than ± 1 %. Where direct measurement of path length is not physically possible, the nominal dimension and its tolerance as specified by the designer should be used and the fact reported. Where path lengths of less than 300 mm are tested in this way, unacceptable errors will occur.

## 6 Determination of pulse velocity

### 6.1 Transducer arrangement

The receiving transducer detects the arrival of that component of the pulse which arrives earliest. This is generally the leading edge of the longitudinal vibration.

Although the direction in which the maximum energy is propagated is at right angles to the face of the transmitting transducer, it is possible to detect pulses which have travelled through the concrete in some other direction. It is possible, therefore, to make measurements of pulse velocity by placing the two transducers on either:

a) opposite faces (direct transmission);

b) adjacent faces (semi-direct transmission); or

c) the same face (indirect or surface transmission).

These three arrangements are shown in Figure 1 a), Figure 1 b) and Figure 1 c). Figure 1 a) shows the transducers directly opposite to each other on opposite faces of the concrete. It is, however, sometimes necessary to place the transducers on opposite faces but not directly opposite each other. Such an arrangement is to be regarded as semi-direct transmission.

**6.2 Determination of pulse velocity by direct transmission**

Where possible, the direct transmission arrangement should be used since the transfer of energy between transducers is at its maximum and the accuracy of velocity determination is therefore governed principally by the accuracy of the path length measurement. The couplant used should be spread as thinly as possible to avoid any end-effects resulting from the different velocities in couplant and concrete.

**6.3 Determination of pulse velocity by semi-direct transmission**

The semi-direct transmission arrangement has a sensitivity intermediate between those of the other two arrangements and, although there may be some reduction in the accuracy of measurement of the path length, it is generally found to be sufficiently accurate to take this as the distance measured from centre to centre of the transducer faces. This arrangement is otherwise similar to direct transmission.

**6.4 Determination of pulse velocity by indirect or surface transmission**

Indirect transmission should be used when only one face of the concrete is accessible, when the depth of a surface crack is to be determined or when the quality of the surface concrete relative to the overall quality is of interest (see clause **9**).

It is the least sensitive of the arrangements and, for a given path length, produces at the receiving transducer a signal which has an amplitude of only about 2 % or 3 % of that produced by direct transmission. Furthermore, this arrangement gives pulse velocity measurements which are usually influenced by the concrete near the surface. This region is often of different composition from that of concrete within the body of a unit and the test results may be unrepresentative of that concrete. The indirect velocity is invariably lower than the direct velocity on the same concrete element. This difference may vary from 5 % to 20 % depending largely on the quality of the concrete under test. Where practicable, site measurements should be made to determine this difference.

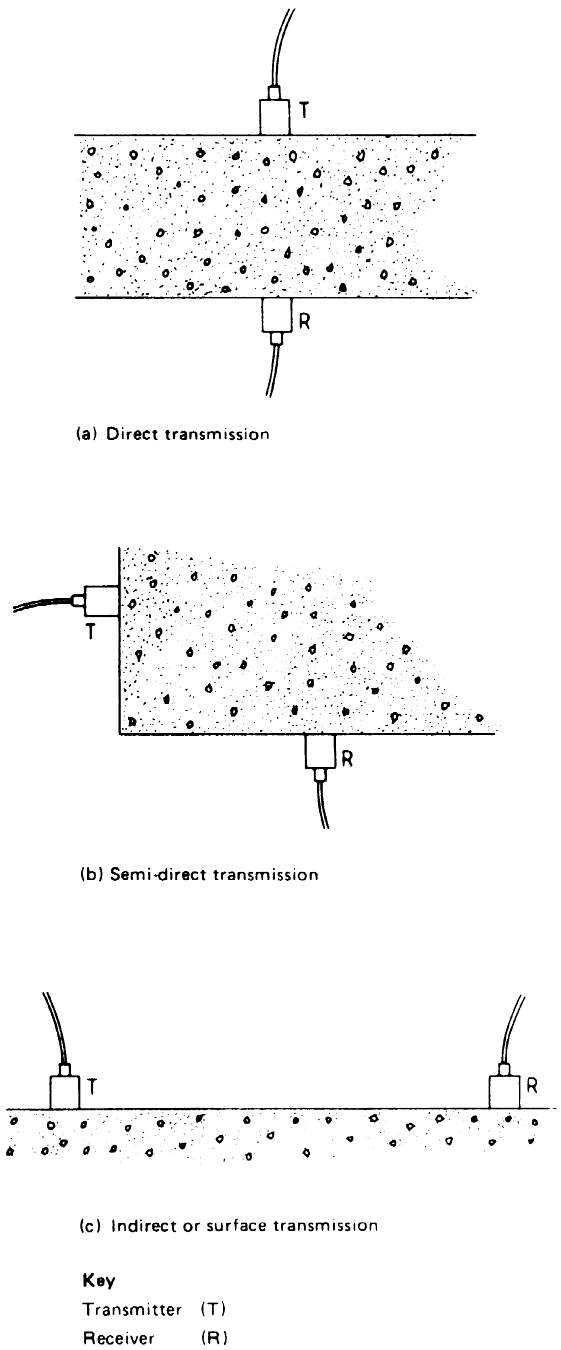



**Figure 1 — Methods of propagating and receiving ultrasonic pulses**

With indirect transmission there is some uncertainty regarding the exact length of the transmission path because of the significant size of the areas of contact between the transducers and the concrete. It is therefore preferable to make a series of measurements with the transducers at different distances apart to eliminate this uncertainty. To do this, the transmitting transducer should be placed in contact with the concrete surface at a fixed point $x$ and the receiving transducer should be placed at fixed increments $x_n$ along a chosen line on the surface. The transmission times recorded should be plotted as points on a graph showing their relation to the distance separating the transducers. An example of such a plot is shown as line (b) in Figure 2.

The slope of the best straight line drawn through the points should be measured and recorded as the mean pulse velocity along the chosen line on the concrete surface. Where the points measured and recorded in this way indicate a discontinuity, it is likely that a surface crack or surface layer of inferior quality is present (see **9.4**) and a velocity measured in such an instance is unreliable.

### 6.5 Coupling the transducer onto the concrete

To ensure that the ultrasonic pulses generated at the transmitting transducer pass into the concrete and are then detected by the receiving transducer, it is essential that there be adequate acoustical coupling between the concrete and the face of each transducer. For many concrete surfaces, the finish is sufficiently smooth to ensure good acoustical contact by the use of a coupling medium and by pressing the transducer against the concrete surface. Typical couplants are petroleum jelly, grease, soft soap and kaolin/glycerol paste. It is important that only a very thin layer of coupling medium separates the surface of the concrete from its contacting transducer. For this reason, repeated readings of the transit time should be made until a minimum value is obtained so as to allow the layer of couplant to become thinly spread.

Where possible, the transducers should be in contact with concrete surfaces which have been cast against form work or a mould. Surfaces formed by other means, e.g. trowelling, may have properties differing from those of the main body of material. If it is necessary to work on such a surface, measurements should be made over a longer path length than would normally be used. A minimum path length of 150 mm is recommended for direct transmission involving one unmoulded surface and a minimum of 400 mm for indirect transmission along one unmoulded surface.

When the concrete surface is very rough and uneven, the area of the surface where the transducer is to be applied should be smoothed and levelled. Alternatively, a smoothing medium such as quick-setting epoxy resin or piaster may be used, but good adhesion between the concrete surface and smoothing medium has to be ensured so that the pulse is propagated correctly into the concrete under test. It is important to ensure that the layer of smoothing medium is as thin as possible. If it is necessary to make a significant build-up, then the pulse velocity of the smoothing medium has to be taken into account.

In order to avoid the problems of obtaining good acoustical contact between the transducers and a surface which is not smooth enough to allow the use of a thin couplant, special transducers have been developed which impart or pick up the pulse through integral probes having 6 mm diameter tips. A receiving transducer with a hemispherical tip has been found to be very successful but the transmitter cannot impart enough energy into the concrete surface to ensure transmission over any but short path lengths. Other transducer configurations have been developed to deal with special circumstances. It should be noted that a zero adjustment will almost certainly be required when special transducers are used. Unsatisfactory seating of the transducers is often indicated by an excessive degree of "hunting"; with a satisfactory degree of coupling, the digital reading will settle rapidly.

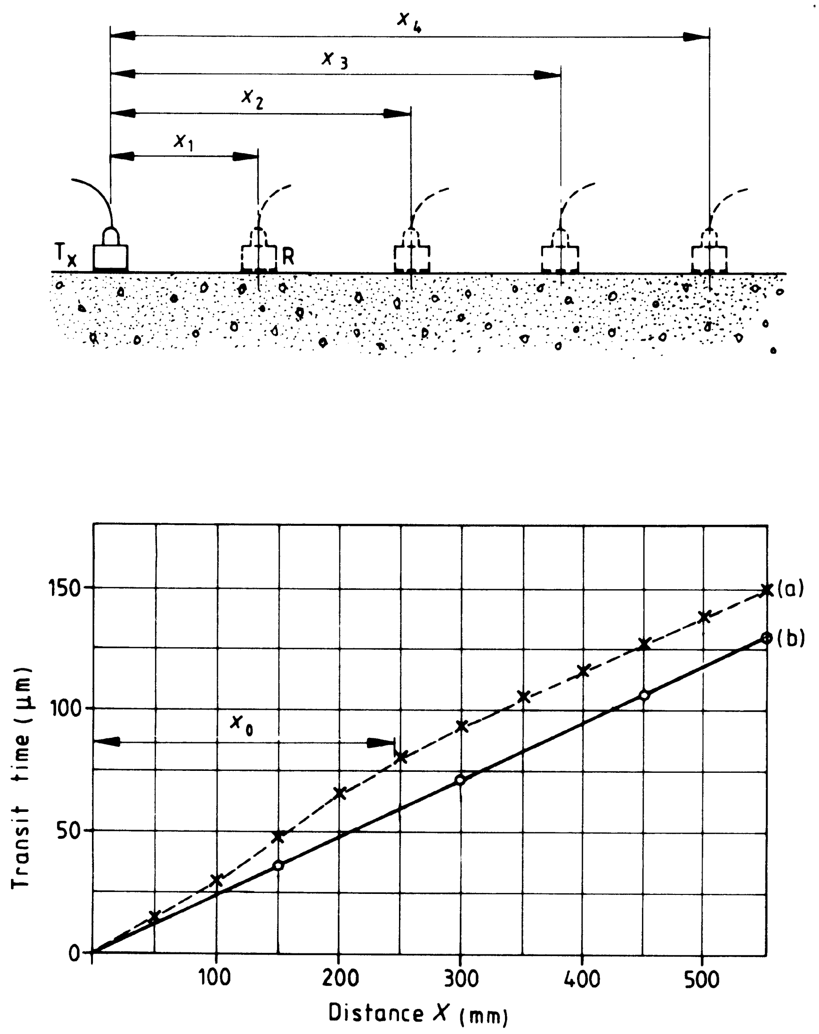
## 7 Factors influencing pulse velocity measurements

### 7.1 General

In order to provide a measurement of pulse velocity which is reproducible and which depends essentially on the properties of the concrete under test, it is necessary to consider the various factors which can influence pulse velocity and its correlation with various physical properties of the concrete.

### 7.2 Moisture content

The moisture content has two effects on the pulse velocity, one chemical, the other physical. These effects are important in the production of correlations for the estimation of concrete strength. Between a properly cured standard cube and a structural element made from the same concrete, there may be a significant pulse velocity difference. Much of the difference is accounted for by the effect of different curing conditions on the hydration of the cement while some of the difference is due to the presence of free water in the voids. It is important that these effects are carefully considered when estimating strength.




(a) Results for concrete with the top 50 mm of inferior quality (see **9.4**).
(b) Results for homogeneous concrete (see **6.4**).

**Figure 2 — Pulse velocity determination by indirect (surface) transmission**

### 7.3 Temperature of the concrete

Variations of the concrete temperature between 10 °C and 30 °C have been found to cause no significant change without the occurrence of corresponding changes in strength or elastic properties. Corrections to pulse velocity measurements should be made only for temperatures outside this range, as given in Table 1.

**Table 1 — Effect of temperature on pulse transmission**

| Temperature | Correction to the measured pulse velocity | |
|---|---|---|
| | Air-dried concrete | Water-saturated concrete |
| °C | % | % |
| 60 | + 5 | + 4 |
| 40 | + 2 | + 1.7 |
| 20 | 0 | 0 |
| 0 | – 0.5 | – 1 |
| – 4 | – 1.5 | – 7.5 |

### 7.4 Path length

The path length over which the pulse velocity is measured should be long enough not to be significantly influenced by the heterogeneous nature of the concrete. It is recommended that, except for the conditions stated in **7.5**, the minimum path length should be 100 mm for concrete in which the nominal maximum size of aggregate is 20 mm or less and 150 mm for concrete in which the nominal maximum size of aggregate is between 20 mm and 40 mm. The pulse velocity is not generally influenced by changes in path length, although the electronic timing apparatus may indicate a tendency for velocity to reduce slightly with increasing path length. This is because the higher frequency components of the pulse are attenuated more than the lower frequency components and the shape of the onset of the pulse becomes more rounded with increased distance travelled. Thus, the apparent reduction of pulse velocity arises from the difficulty of defining exactly the onset of the pulse and this depends on the particular method used for its definition. This apparent reduction in velocity is usually small and well within the tolerance of time measurement accuracy given in **5.2**.

### 7.5 Shape and size of specimen

The velocity of short pulses of vibrations is independent of the size and shape of specimen in which they travel, unless its least lateral dimension is less than a certain minimum value. Below this value, the pulse velocity may be reduced appreciably. The extent of this reduction depends mainly on the ratio of the wavelength of the pulse vibrations to the least lateral dimension of the specimen but it is insignificant if the ratio is less than unity. Table 2 gives the relationship between the pulse velocity in the concrete, the transducer frequency and the minimum permissible lateral dimension of the specimen.

If the minimum lateral dimension is less than the wavelength or if the indirect transmission arrangement is used, the mode of propagation changes and, therefore, the measured velocity will be different. This is particularly important in cases where concrete elements of significantly different sizes are being compared.

**Table 2 — Effect of specimen dimensions on pulse transmission**

| **Transducer frequency** | **Pulse velocity in concrete** (in km/s) | | |
|---|---|---|---|
| | $v_c = 3.5$ | $v_c = 4.0$ | $v_c = 4.5$ |
| | **Minimum permissible lateral specimen dimension** | | |
| kHz | mm | mm | mm |
| 24 | 146 | 167 | 188 |
| 54 | 65 | 74 | 83 |
| 82 | 43 | 49 | 55 |
| 150 | 23 | 27 | 30 |

### 7.6 Effect of reinforcing bars

**7.6.1** *General.* The pulse velocity measured in reinforced concrete in the vicinity of reinforcing bars is usually higher than in plain concrete of the same composition. This is because the pulse velocity in steel may be up to twice the velocity in plain concrete and, under certain conditions, the first pulse to arrive at the receiving transducer travels partly in concrete and partly in steel.

The apparent increase in pulse velocity depends upon the proximity of the measurements to the reinforcing bar, the diameter and number of bars and their orientation with respect to the propagation path [17]. The frequency of the pulse and surface conditions of the bar may both also affect the degree to which the steel influences the velocity measurements. Corrections to measured values to allow for reinforcement will reduce the accuracy of estimated pulse velocity in the concrete so that, wherever possible, measurements should be made in such a way that steel does not lie in or close to the direct path between transducers. Electromagnetic cover measuring devices (see BS 1881-204[1)]) should be used to assist in locating steel.

**7.6.2** *Axis of reinforcing bar parallel to direction of propagation.* The position of paths along which pulses are propagated should be chosen, whenever possible, so as to avoid the vicinity of reinforcing bars parallel to these paths. If this cannot be achieved, the measured values of pulse velocity should be corrected to take into account the presence of steel. The correction will depend on the distance between the line of the path and the edge of the nearest bar, the bar diameter, and the pulse velocity in the surrounding concrete.

[1)] Revision of BS 4408-1 in preparation.

The pulse velocity in the concrete $v_c$ (in km/s) is given by

$$v_c = \frac{2av_s}{\sqrt{(4a^2 + (Tv_s - L)^2)}} \qquad (2)$$

provided that $v_s \geqslant v_c$

where

$v_s$ is the pulse velocity in the steel bar (in km/s);

a is the offset, measured as the distance from the surface of the bar to the line joining the nearest point of the two transducers (in mm) (see Figure 3);

$T$ is the transit time (in µs);

$L$ is the length of the direct path between transducers (in mm).

The influence of the steel disappears when

$$\frac{a}{L} > \tfrac{1}{2}\sqrt{\frac{(v_s - v_c)}{(v_s + v_c)}}$$

and equation 2 is no longer applicable. The zone within which the steel may influence measurements thus depends upon the relative values of pulse velocity within the steel and concrete but an upper limit of $a/L$ of about 0.25 may be expected for large diameter bars in low quality concrete. For high quality concrete the limiting value of $a/L$ is unlikely to be greater than 0.15 but may be considerably less for bar diameters of 12 mm or below. Bars of 6 mm diameter or less will be virtually impossible to detect in practical situations and may be ignored.

The major difficulty in applying equation 2 lies in deciding on the value of $v_s$ since this is influenced both by the bar diameter and the pulse velocity in the surrounding concrete. A measure of this may generally be obtained by propagating a pulse along the axis of the embedded bar, making due allowance for any concrete cover at either end.

Equation 2 may conveniently be modified to give the following

$$v_c = k\, v_m \qquad (3)$$

where

$v_m$ is the measured apparent pulse velocity ($L/T$) (in km/s);

$k$ is the correction factor given by

$$\gamma + 2\left(\frac{a}{L}\right)\sqrt{(1 - \gamma^2)}$$

in which

$$\gamma = \frac{v_c}{v_s}$$

Typical values of $\gamma$ are plotted in Figure 3 for a range of commonly occurring values of $v_c$ and bar diameter for a pulse frequency in the order of 54 kHz. The value of $\gamma$ obtained from this figure, for an assumed $v_c$, may then be used in conjunction with Figure 4 to provide an estimate of $k$ for use in equation 3. An iterative procedure may be necessary to achieve a reliable estimate of $v_c$.

These equations will only be valid for offsets $a$ which are in excess of approximately twice the end cover to the bar. For smaller offsets the pulse is likely to pass through the full length of the bar. For bars lying directly in line with the transducers, the correction factor is given by

$$k = 1 - \frac{L_s}{L}(1 - \gamma) \qquad (4)$$

where

$L_s$ is the length of the bar (in mm).

An estimate of $v_c$ is likely to be accurate within ± 3 % provided that there is good bond between the steel and concrete and that there is no cracking of the concrete in the test zone.

Corrected pulse velocity measurements should be treated with caution since they relate only to the concrete in the immediate vicinity of the transducers and the reinforcing bar, and do not represent the concrete along the line joining the centres of the transducers.

**7.6.3** *Axis of reinforcing bar perpendicular to direction of propagation.* The maximum influence of the presence of the reinforcing bars can theoretically be calculated assuming that the pulse traverses the full diameter $d$ of each bar during its passage. This is illustrated in Figure 5. The effect of the bars on the pulse is complex and the apparent pulse velocity in the steel will be reduced below that to be expected along the axis of bars of similar size.

For practical purposes where 54 kHz transducers are being used, bars of diameter less than 20 mm may be ignored since their influence will be negligible. An estimate of the average influence can be obtained for well bonded bars of between 20 mm and 50 mm diameter by considering them as equivalent longitudinal bars of total path length $L'_s$ (see Figure 5). The method described in **7.6.2** for bars lying directly in line with the transducers (see equation 4) may be used for this purpose in conjunction with the value of $\gamma$ determined from Figure 5 which takes account of the reduced velocity in the steel. The influence of transverse steel will be reduced by bond deficiencies, and is difficult to assess with any degree of accuracy if the bars do not lie directly in line with the path between transducers.

## 8 Determination of concrete uniformity

Heterogeneities in the concrete within or between members cause variations in pulse velocity which, in turn, are related to variations in quality. Measurements of pulse velocity provide means of studying the homogeneity and, for this purpose, a system of measuring points which covers uniformly the appropriate volume of concrete in the structure has to be chosen.

The number of individual test points depends upon the size of the structure, the accuracy required and the variability of the concrete. In a large unit of fairly uniform concrete, testing on a 1 m grid is usually adequate but, on small units or variable concrete, a finer grid may be necessary. It should be noted that, in cases where the path length is the same throughout the survey, the measured time may be used to assess the concrete uniformity without the need to convert it to a velocity. This technique is particularly suitable for surveys where all the measurements are made by indirect transmission.

It is possible to express homogeneity in the form of a statistical parameter such as the standard deviation or coefficient of variation of the pulse velocity measurements made over the grid. However, such parameters can only be properly used to compare variations in concrete units of broadly similar dimensions.

Variations in pulse velocity are influenced by magnitude of the path length because this determines the effective size of concrete sample which is under examination during each measurement. The importance of variations should be judged in relation to the effect which they can be expected to have on the required performance of the structural member being tested. This generally means that the tolerance allowed for quality distribution within members should be related either to the stress distribution within them under critical working load conditions or to exposure conditions.

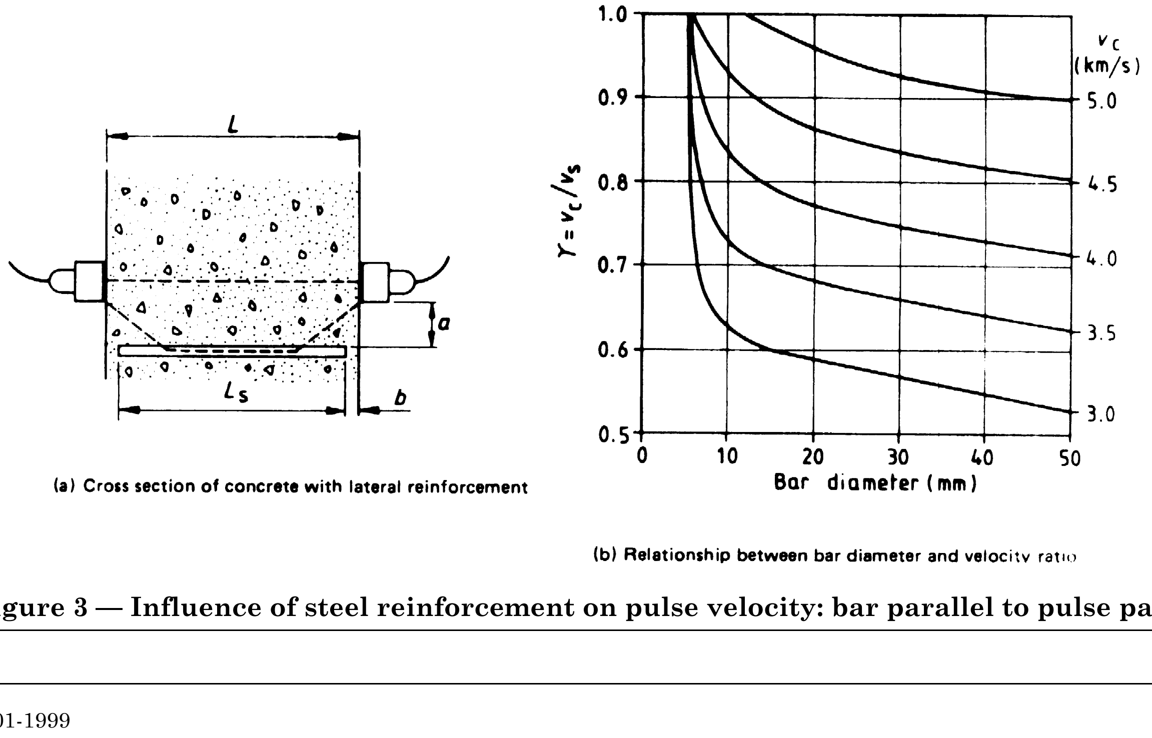



**Figure 3 — Influence of steel reinforcement on pulse velocity: bar parallel to pulse path**

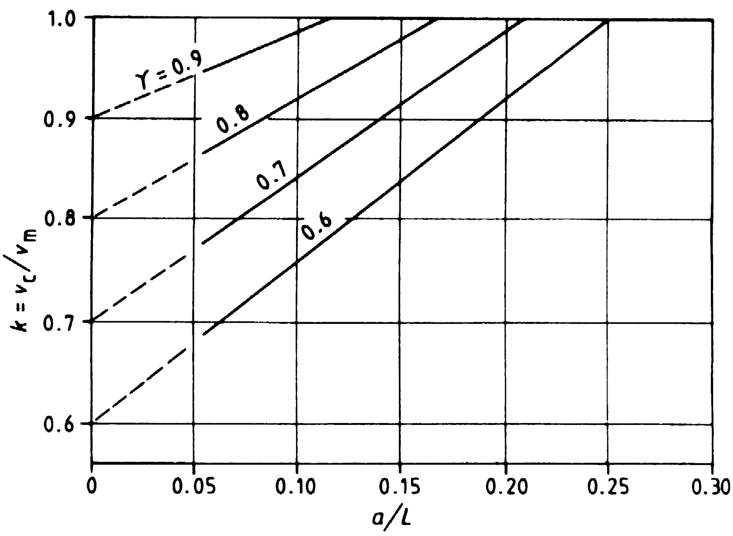



**Figure 4 — Influence of steel reinforcement on pulse velocity: correction factors for bars parallel to pulse path (*a* > 2 *b*) [see Figure 3 a)]**

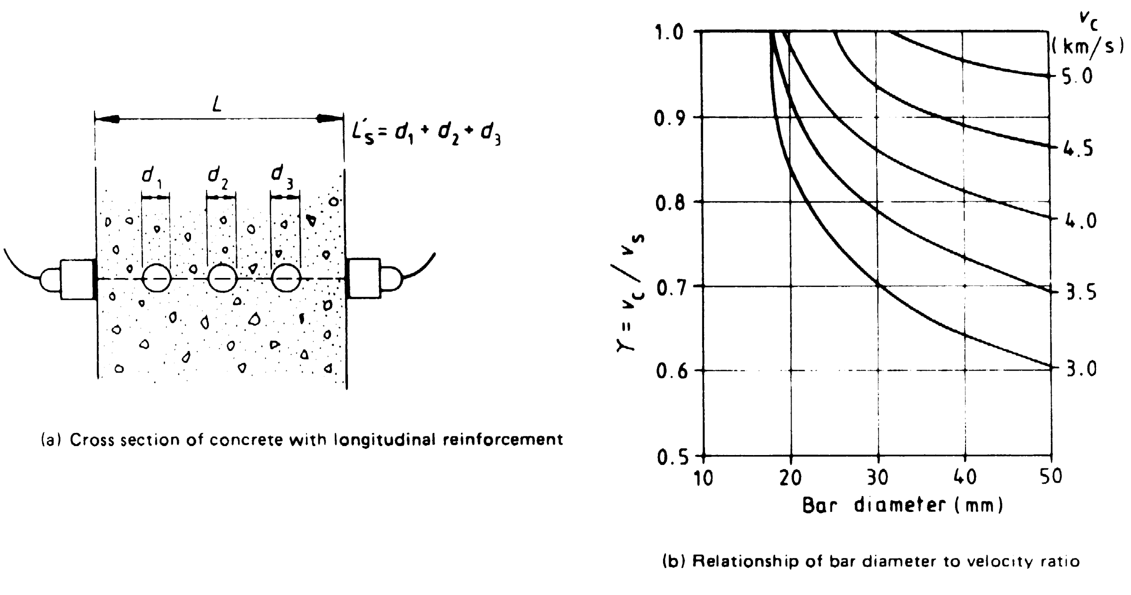



**Figure 5 — Influence of steel reinforcement on pulse velocity: bars normal to pulse path**

## 9 Detection of defects

NOTE See reference [18].

### 9.1 General

The use of the ultrasonic pulse velocity technique to detect and define the extent of internal defects should be restricted to well-qualified personnel with previous experience in the interpretation of survey results. It is important that ultrasonic pulse velocity measurements are made and interpreted by persons with experience and training in the technique. Attention is drawn to the potential risk of drawing conclusions from single results.

When an ultrasonic pulse travelling through concrete meets a concrete-air interface, there is negligible transmission of energy across this interface. Thus, any air-filled crack or void lying immediately between two transducers will obstruct the direct ultrasonic beam when the projected length of the void is greater than the width of the transducers and the wavelength of sound used. When this happens, the first pulse to arrive at the receiving transducer will have been diffracted around the periphery of the defect and the transit time will be longer than in similar concrete with no defect.

It is possible to make use of this effect for locating flaws, voids or other defects greater than about 100 mm in diameter or depth. Relatively small defects have little or no effect on transmission times, but equally are probably of minor engineering importance. Plotting contours of equal velocity often gives significant information regarding the quality of a concrete unit.

In cracked members, where the broken faces of the members are held tightly together in close contact by compression forces, the pulse energy may pass unimpeded across the crack. As an example, this may occur in cracked vertical bearing piles. If the crack is filled with liquid which transmits the ultrasonic energy, e.g. in marine structures, the crack is undetectable using digital reading equipment. Measurements of attenuation may give valuable information in these cases.

Recommendations on the interpretation of the results of tests made to detect defects are given in **9.2** to **9.4** but it is strongly emphasized that the assumptions made have been simplified.

### 9.2 Detecting large voids or cavities

A grid should be drawn on the concrete member with its points of intersection spaced to correspond to the size of void that would significantly affect its performance. A survey of measurements at the grid points enables a large cavity to be investigated by measuring the transit times of pulses passing between the transducers when they are placed so that the cavity lies in the direct path between them. The size of such cavities may be estimated by assuming that the pulses pass along the shortest path between the transducers and around the cavity. Such estimates are valid only when the concrete around the cavity is uniformly dense and the pulse velocity can be measured in that concrete.

### 9.3 Estimating the depth of a surface crack

An estimate of the depth of a crack visible at the surface may be obtained by measuring the transit times across the crack for two different arrangements of the transducers placed on the surface. One suitable arrangement is shown in Figure 6 a) in which the transmitting and receiving transducers are placed at a distance $x$ on opposite sides of the crack and equidistant from it. Two values of $x$ are chosen and transit times corresponding to these are measured; convenient values of $x$ are 150 mm and 300 mm. If these values are used, the depth of the air-filled crack $C$ (in mm) is given by:

$$C = 150\sqrt{\frac{(4t_1^2 - t_2^2)}{(t_2^2 - t_1^2)}} \qquad (5)$$

where

$t_1$ is the transit time when $x$ is 150 mm (in μs);

$t_2$ is the transit time when $x$ is 300 mm (in μs).

Equation 5 is derived by assuming that the plane of the crack is perpendicular to the concrete surface and that the concrete in the vicinity of the crack is of reasonably uniform quality.

A check may be made to assess whether or not the crack is lying in a plane perpendicular to the surface by placing both transducers near to the crack [as shown in Figure 6 b)] and moving each in turn away from the crack. If a decrease in in transit time occurs when one transducer is moved it indicates that the crack slopes towards that transducer.

In an alternative arrangement, the transmitting transducer is placed at a distance of 2.5$y$ from the centre of the crack and three readings of the transit time taken with the receiving transducer at distances of $y$, 2$y$ and 3$y$ from the transmitter in the direction of the crack. The transit times are plotted against distance as in Figure 6 c) in which $y$ is 150 mm. If the projection of the straight line through the points ($y$, $T$1) and (2$y$, $T$2) passes through 0 there are no hidden cracks and the depth of the visible crack $C$ (in mm) is given by:

$$C = \frac{y}{2}\sqrt{\left[\left(\frac{3T_2^2 + 2T_3^2}{T_2 T_3}\right)^2 - 25\right]} \qquad (6)$$

where

$T_2$ is the transit time for distance 2$y$ (in µs);

$T_3$ is the transit time for distance 3$y$ (in µs).

Figure 6 c) shows the way in which the transit time gradually returns to the value expected in uncracked concrete as the receiver is moved further from the crack.

### 9.4 Estimating the thickness of a layer of inferior quality concrete

Concrete may be suspected of having a surface layer of poor quality. This may occur during manufacture or arise as a result of damage by fire, frost, sulphate attack, etc. The thickness of such a layer of concrete can be estimated from ultrasonic measurements of transit times along the surface. The procedure described in clause **10** should be used and the results plotted on a graph as in Figure 2. At the shorter distance of separation of the transducers, the pulse travels through the surface layer and the slope of the experimental line gives the pulse velocity in this surface layer. Beyond a certain distance of separation the first pulse to arrive has passed along the surface of the under-lying higher quality concrete and the slope of these experimental points gives the velocity in that concrete.

The distance $x_0$ at which the change of slope occurs (see Figure 2) together with the measured pulse velocities in the two different layers of concrete, enables an estimate of the thickness $t$ (in mm) of the surface layer to be made as follows:

$$t = \frac{x_0}{2}\sqrt{\frac{(v_s - v_d)}{(v_s + v_d)}} \qquad (7)$$

where

$v_d$ is the pulse velocity in the damaged concrete (in km/s);

$v_s$ is the pulse velocity in the underlying sound concrete (in km/s);

$x_0$ is the distance from the transmitter at which the slope changes (in mm).

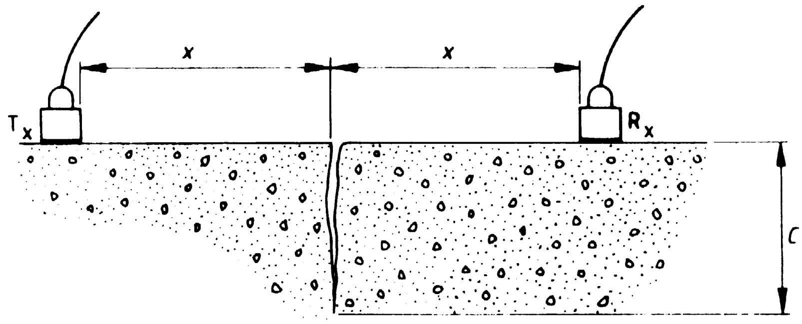
The method is applicable to extensive surface areas in which the inferior concrete forms a distinct layer of fairly uniform thickness and when $v_d$ is appreciably smaller than $v_s$.

Localized areas of damaged or honeycombed concrete are more difficult to test but it is possible to derive an approximate thickness of such localized poor quality material if both direct transmission and surface propagation measurements are made.

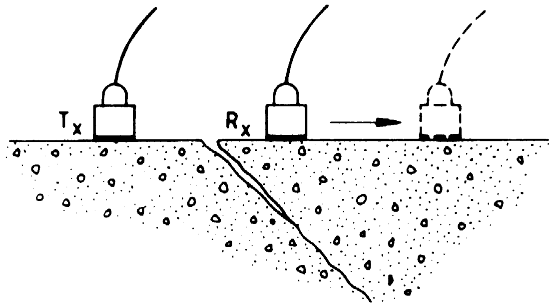
## 10 Determination of changes in concrete properties

Changes occurring with time in the properties of concrete caused by the hydration process, by the influence of environmental effects or by overloading, may be determined by repeated measurements of pulse velocity at different times with the same transducers in the same position. Measurements of changes in pulse velocity are usually indicative of changes in strength and have the advantage that they can be made over progressive periods of time on the same test piece throughout the investigation.

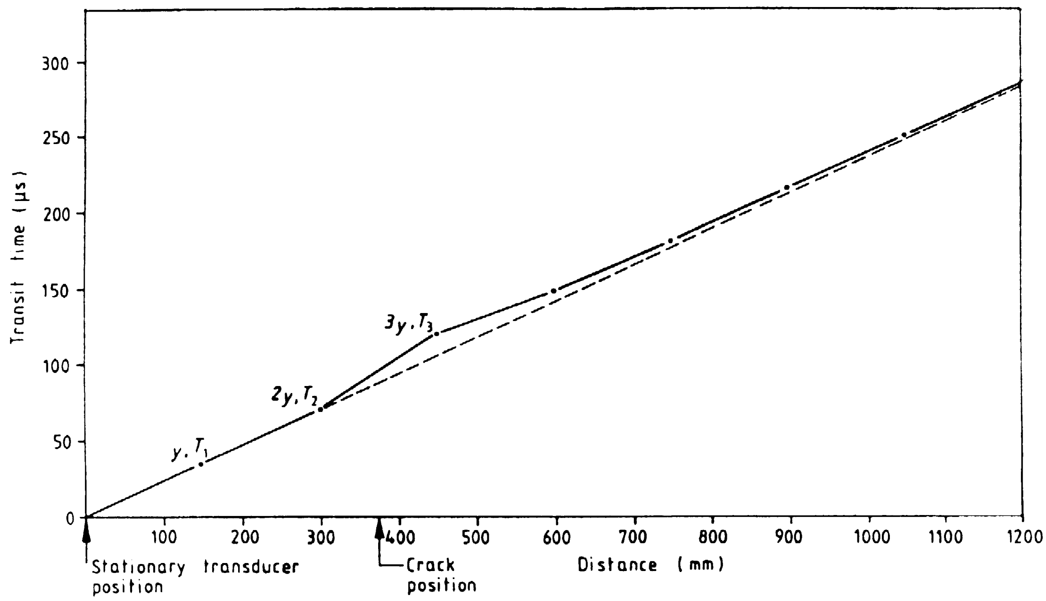
Pulse velocity measurements are particularly useful for following the hardening process, especially during the first 36 h. Here, rapid changes in pulse velocity are associated with physio-chemical changes in the cement paste structure and it is desirable to make measurements at intervals of 1 h or 2 h if these changes are to be followed closely. As the concrete hardens these intervals may be lengthened to 1 day or more after the initial period of 36 h has elapsed.




(a) Crack perpendicular to surface




(b) Oblique crack




(c) Effect of crack on surface measurement

**Figure 6 — Arrangement for determination of crack depth**

## 11 Correlation of pulse velocity and strength

### 11.1 General

The quality of concrete is usually specified in terms of strength and it is, therefore, sometimes helpful to use ultrasonic pulse velocity measurements to give an estimate of strength.

The relationship between ultrasonic pulse velocity and strength is affected by a number of factors including age, curing conditions, moisture condition, mix proportions, type of aggregate and type of cement. If an estimate of strength is required it is therefore necessary to establish a correlation between strength and velocity for the particular type of concrete under investigation. This correlation has to be established experimentally by testing a sufficient number of specimens to cover the range of strengths expected and to provide statistical reliability. The confidence that can be ascribed to the results will depend on the number of samples tested. It is possible to establish a correlation between ultrasonic pulse velocity and strength either as measured in accordance with any of the test methods described in BS 1881-116 and BS 1881-119 or by carrying out tests on a complete structure or unit.

The reliability of the correlation will depend on the extent to which the correlation specimens represent the structure to be investigated. The most appropriate correlation will be obtained from tests in which pulse velocity and strength are measured on a complete structure or unit. It is sometimes more convenient to prepare a correlation using tests on moulded specimens. It should be noted that experience has shown that correlations based on moulded specimens generally give lower estimates of strength than would be obtained by cutting and testing cores.

### 11.2 Correlation using moulded specimens

The strengths of a particular mix of cement and aggregate may be varied by altering either:

a) the water-cement ratio, or

b) the age at test.

The method used for varying the strength of the specimens influences the correlation. It is therefore essential that only one method of strength variation be used for a particular correlation and that it be appropriate to the application required. The correlation of pulse velocity with strength is less reliable as the strength of concrete increases.
A correlation obtained by varying the age of the concrete is appropriate when monitoring strength development but for quality control purposes a correlation obtained by varying the water-cement ratio is preferable.

The appropriate test specimens should be made in accordance with the methods described in BS 1881-108, BS 1881-109 and BS 1881-110. At least three specimens should be cast from each batch. The pulse velocity should be measured across a specimen between moulded faces. In the case of beams, it is preferable to measure the pulse velocity along their length to obtain greater accuracy. For each specimen there should be at least three measurements spaced between its top and bottom (see Table 2 for edge distances). The variation between the measured transit times on single test specimens should be within ± 5 % of the mean value of these three measurements, otherwise the specimen should be rejected as abnormal. The specimens should then be tested for strength according to the methods described in BS 1881-116 and
BS 1881-119.

The mean pulse velocity and mean strength obtained from each set of three nominally identical test specimens provide the data to construct a correlation curve. A correlation curve produced in this way relates only to specimens produced, cured and tested in a similar way; different correlation curves will be obtained for the same mixes if air curing is substituted for water curing.

### 11.3 Correlation by tests on cores

When making a correlation from tests on cores it will not generally be possible to vary the strength of the concrete deliberately. Pulse velocity tests should, therefore, be used to locate areas of different quality and cores taken from these areas will give a range of strengths. The pulse velocity through the concrete at proposed core locations should be used for preparing the correlation. Pulse velocities taken from cores after cutting and soaking will generally be higher than those in the structure and should not be used for direct correlation. The cores should be cut and tested for strength in accordance with the method described in BS 1881-120 and a correlation curve plotted as described in **11.2**. The shape of the correlation line is sensibly the same for any given concrete notwithstanding the curing conditions. It is therefore possible to use the curve derived from reference specimens to extrapolate from the limited range that will normally be obtained from core samples.

### 11.4 Correlation with the strength of precast units

When precast components are required to conform to strength requirements it may be possible to establish correlations between the pulse velocity measurements and the particular types of strength tests. This should be done by making pulse velocity measurements on the components in the appropriate regions where the concrete would be expected to fail under the test loading conditions. The procedure for obtaining a graphical correlation in such cases should be as described in **11.2**.

### 11.5 Combination of pulse velocity with other measurements

Some improvement in the accuracy of strength estimates may be obtained by combining ultrasonic pulse velocity measurements with rebound hammer measurements as described in BS 1881-202 (see [19], [20] and BS 1881-201). Greater improvement can be made by combining ultrasonic pulse velocity with density measurements. In a structure, the density measurements should ideally be made along the same line of sight as the pulse velocity measurements. The density should be measured either by the methods described in BS 1881-114 or by a gamma ray attenuation technique, provided that the influence of reinforcing steel can be avoided. A separate correlation curve may then be constructed for each value of density in the required range.

## 12 Determination of the modulus of elasticity and dynamic Poisson's ratio

The relationship between elastic constants and the velocity of an ultrasonic pulse travelling in an isotropic elastic medium of infinite dimensions is given by the following equation:

$$E_d = \rho v^2 \frac{(1 + \upsilon)(1 - 2\upsilon)}{(1 - \upsilon)} \qquad (8)$$

where

$E_d$ is the dynamic elastic modulus (in $MN/m^2$);

$\upsilon$ is the dynamic Poisson's ratio;

$\rho$ is the density (in $kg/m^3$);

$v$ is the pulse velocity (in km/s).

As stated in **7.5**, the pulse velocity is not significantly affected by the dimensions of the test specimen except when one or more of the lateral dimensions is small relative to the wavelength of the pulse.

If, therefore, the values of $\rho$ and $\upsilon$ are known, it is possible to use equation 8 to determine the value of $E_d$ in concrete samples for a wide range of shape or size. Similarly $\upsilon$ could be determined if the values of $\rho$ and $E_d$ are known.

For laboratory specimens the ratio of $E_d/\rho$ may be obtained from the results of a longitudinal resonance test as described in BS 1881-5. In this test the value of the fundamental frequency of longitudinal vibration of a prism is determined. The ratio of $E_d/\rho$ is given by

$$\frac{E_d}{\rho} = 4n^2 L^2\, 10^{-6} \qquad (9)$$

where

$n$ is the resonant frequency (in Hz);

$L$ is the length of test specimen (in m).

Combining equations (8) and (9) we obtain

$$\frac{(1 + \upsilon)(1 - 2\upsilon)}{(1 - \upsilon)} = \frac{4n^2 L^2\, 10^{-6}}{v^2} \qquad (10)$$

The value of $\upsilon$ may be determined from Table 3.

**Table 3 — Values of dynamic Poisson's ratio**

| $\frac{nL10^{-3}}{v}$ | $\upsilon$ |
|---|---|
| 0.257 | 0.45 |
| 0.342 | 0.40 |
| 0.395 | 0.35 |
| 0.431 | 0.30 |
| 0.456 | 0.25 |
| 0.474 | 0.20 |
| 0.487 | 0.15 |
| 0.494 | 0.10 |
| 0.499 | 0.05 |

The values of modulus of elasticity (both dynamic and static), Poisson's ratio and density all vary from point to point in a concrete structure.

It is not often possible to carry out resonance tests on structural members in order to determine the values of these properties. It is, however, possible to use empirical relationships to estimate the values of the static and dynamic modulus of elasticity from pulse velocity measurements made at any point on a structure. These relationships are given in Table 4 and apply to concrete made with most commonly used types of natural aggregate. The estimate of modulus of elasticity obtained from this table will have an accuracy better than ± 10 %.

**Table 4 — Empirical relationship between static and dynamic moduli of elasticity and pulse velocity**

| Pulse velocity | Modulus of elasticity | |
|---|---|---|
| | Dynamic | Static |
| km/s | MN/m$^2$ | MN/m$^2$ |
| 3.6 | 24 000 | 13 000 |
| 3.8 | 26 000 | 15 000 |
| 4.0 | 29 000 | 18 000 |
| 4.2 | 32 000 | 22 000 |
| 4.4 | 36 000 | 27 000 |
| 4.6 | 42 000 | 34 000 |
| 4.8 | 49 000 | 43 000 |
| 5.0 | 58 000 | 52 000 |

## 13 Report

The report should affirm that the ultrasonic pulse velocity was determined in accordance with the recommendations given in this Part of BS 1881 and should include the following information:

a) Date, time and place of the investigation

b) Description of structure or specimens tested.

c) Nominal composition of the concrete, including:

1) cement type;

2) cement content;

3) water/cement ratio;

4) aggregate type and size;

5) any admixtures used.

d) Curing conditions, temperature and age of concrete at time of test.

e) Specification of the environment for which the concrete was designed.

f) Sketch showing location of transducer position and paths of pulse propagation. This sketch should indicate the details of reinforcing steel or ducts in the vicinity of the test areas.

g) Surface conditions at test points (e.g. smooth, trowelled, rough, presence of surface cracking or spalling as a result of fire damage).

h) Estimated internal moisture conditions of concrete at time of test and long term curing conditions, where known, e.g. wet surface, surface dry (having not long been demoulded), or air-dry (demoulded in drying conditions for some time).

i) Type and make of apparatus, its reading accuracy, pulse frequency and any special characteristics.

j) Path lengths, methods of measurement and estimated accuracy of measurements.

k) Measured values of pulse velocity.

l) Pulse velocity values corrected for presence of steel reinforcement where necessary.

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

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

BS 1881-109 , *Method for making test beams from fresh concrete.*

BS 1881-110, *Method for making test cylinders from fresh concrete.*

BS 1881-114 , *Methods for determination of density of hardened concrete.*

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

BS 1881-119 , *Method for determination of compressive strength using portions of beams broken in flexure (equivalent cube method).*

BS 1881-120, *Method for determination of compressive strength of concrete cores.*

BS 1881-201, *Guide to the use of non-destructive methods of test for hardened concrete.*

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

BS 1881-204, *Recommendation for the use of electromagnetic cover measuring devices*[2].

BS 1881-4, *Ultrasonic flaw detection Guide to assessment of concrete strength in existing structures.*

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