

Testing concrete —

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

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- British Nuclear Fuels Limited
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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 It supersedes BS 4408-5:1974, which is withdrawn.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:

- determination of the uniformity of concrete in or between members [3, 4, 5], clause 8
- detection of the presence and approximate extent of cracks, voids and other defects [6, 7, 8], clause 9
- measurement of changes occurring with time in the properties of the concrete [9, 10, 11], clause 10
- correlation of pulse velocity and strength as a measure of concrete quality [12, 13, 14], clause 11
- 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

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

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 $\pm 1\%$ 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 μs 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 $\pm 0.2 \mu\text{s}$. 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 $\pm 0.5 \%$.

5.7 *Accuracy of path length measurement*

The accuracy of measurement should be better than $\pm 1 \%$. 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.

