Recommendations for testing concrete by the ultrasonic pulse method

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RÉSUME

Ces recommandations concernent l'application des ultra-sons à la détermination des propriétés élastiques, de la résistance et de l'homogénéité du béton structural, ainsi qu'à la localisation des défauts internes, etc. On examine les méthodes de mesure de la vitesse de propagation et l'influence des conditions d'essai sur la précision des mesures. On attend de ces recommandations qu'elles entraînent une meilleure normalisation des techniques de mesure. On expose les difficultés d'interprétation associées à la détermination des propriétés élastiques et de la résistance à partir des mesures sur chantier; des méthodes sont recommandées pour venir à bout de ces difficultés.

SUMMARY

These recommendations deal with the application of the ultrasonic pulse method to derive the elastic properties, strength and homogeneity of structural concrete, and for locating internal defects, etc.

Methods of measuring the pulse velocity, and the influence of test conditions on the accuracy of the measurements are discussed. Recommendations are made which it is hoped will lead to better standardization of measuring techniques.

Interpretational difficulties associated with the derivation of elastic properties and strength from in-situ measurements of pulse velocity are given, and methods are recommended for overcoming these difficulties.

1. INTRODUCTION

These recommendations deal with the non-destructive testing of concrete and reinforced concrete test specimens, precast components and structures by the ultrasonic pulse method.

The objects of the ultrasonic pulse method are to establish:

a) the dynamic modulus of elasticity and the Poisson's ratio of the concrete,

b) the compressive strength of the concrete,

c) the homogeneity of the concrete,

d) changes in the concrete properties caused by time, corrosion, wear etc.

e) defects in the concrete.

The above method can be applied:

a) at factories making precast concrete,

b) at building sites,

c) to test structures in use,

d) in research work.

The application of the ultrasonic pulse method is based on the correlation between the elastic properties or concrete strength and the propagation velocity of the onset of a pulse of ultrasonic longitudinal waves (in future this will be called simply—pulse velocity). Measurements of the pulse attenuation are not yet considered to be precise enough to include in these recommendations, although the usefulness of approximate comparative measurements of pulse amplitude is indicated later for defectoscopy (§ 9).

2. BASIC PRINCIPLES OF THE METHOD

A pulse of longitudinal vibrations is produced by an electro-acoustical transducer which is held in contact with one surface of the concrete member 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 electro-acoustical transducer, and electronic timing circuit enable the transit time T of the pulse to be measured. The pulse velocity (v) is given by:

$$v = L/T \qquad (1)$$

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

a) to give a pulse with a sharp onset

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

2.1. Coupling the pulse into the concrete

There are two ways of making the measurements:

a) by direct transmission through the concrete, here the transducers are held on opposite faces of the member under test (fig. 1).

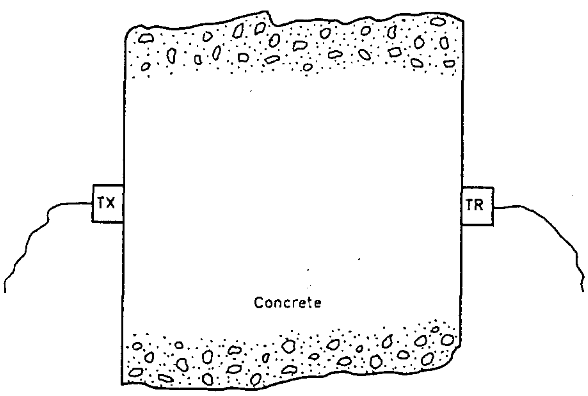


FIG. 1. — **Direct transmission of ultrasonic pulse through concrete (TX = emitter, TR = receiver).**

b) propagation along the surface (fig. 2) is used when only one face of the concrete is accessible. In this configuration the transducers are less efficient than for 2.1. (a) because the maximum energy of the pulse is being directed into the concrete. This method will not give information about weaker concrete which may be below a stronger surface layer.

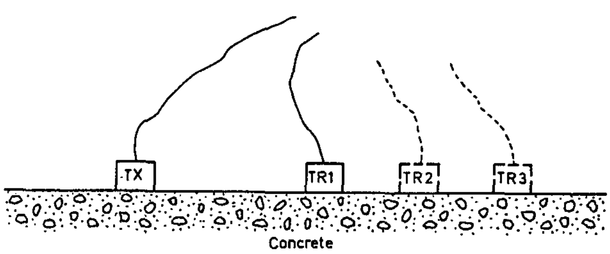


FIG. 2. — **Propagation of ultrasonic pulse along a surface (TX = emitter, TR1 = receiver at position 1, TR2 = receiver at position 2 etc.).**

It is essential that there be adequate acoustical coupling between the concrete and the face of each transducer. For most concrete surfaces met with in building constructions, precast units, etc. the finish is usually 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 Solidol, technical vaseline, liquid soap and kaolin/glycerol paste. When the concrete surface is very rough and uneven it is necessary to smooth and level an area of the surface where the transducer is to be fixed.

3. MEASURING THE PULSE VELOCITY IN CONCRETE

It will be seen from equation (1) that the pulse velocity is derived from measurements of the path length (L) and the transit time (T) in the concrete

3.1. Measurement of path length

In most structural units the path length can be measured easily; the accuracy of measurement should always be better than ± 1 %.

3.2. Measurement of transit time

The measuring apparatus is discussed in Section 10. Two ways have been suggested and are in use for measurement of the transit time:

a) The received pulse is amplified to the maximum possible level, limited usually only by the appearance of noise on the time-base trace of the oscilloscope display. The onset of the pulse is taken to be the point of tangent of the signal curve with the initial horizontal time-base line, and this point is indicated by A in figure 3.

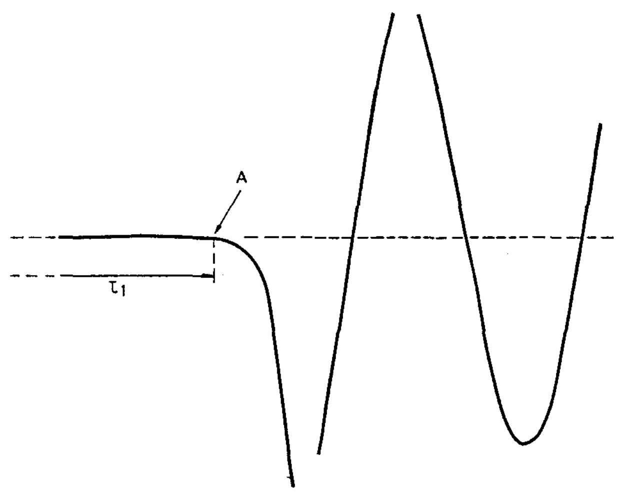


FIG. 3. — **Oscilloscope display for maximum amplitude measuring technique.**

b) The received pulse is amplified to a fixed half-amplitude of one quarter to one third of the visible height of the cathode ray tube measured at the first quarter cycle (fig. 4). The onset of the pulse is taken to be the slightest vertical displacement i.e. about 0.5 mm which is perceptible by eye, the point of measurement is indicated by B in figure 4.

The accuracy of time measurement by either technique should be better than ± 2 %. It was noted earlier that the path length can be measured to better than ± 1 %. If the transit time can be measured to an accuracy of ± 2 %, the pulse velocity measured

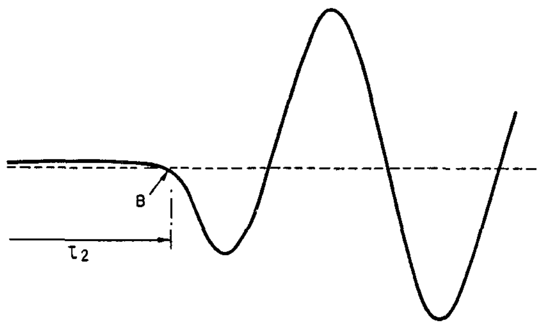


FIG. 4. — **Oscilloscope display for fixed amplitude measuring technique.**

at a single point is obtainable to an accuracy of about ± 3 %. As is shown in equation (2) below, the elastic modulus varies as the square of the pulse velocity, so that the accuracy of measurement of the modulus at a single position of the transducers is about ± 6 %.

The ' pulse velocity ' measured by the two techniques will only be identical when the pulse onset is perfectly sharp (i.e. a right-angle), and, as the start of the pulse becomes more rounded, T_2 (fig. 4) will tend to become greater than T_1 (fig. 3).

The first technique provides a pulse velocity (v_m) which is a close approximation to the velocity α of longitudinal waves in bulk media, and is related to the elastic constants by the equation:

$$v_m = \frac{L}{T_1} = \sqrt{\frac{E}{\rho}\frac{(1-\delta)}{(1+\delta)(1-2\delta)}} \qquad (2)$$

where E and δ are the dynamic Young's Modulus and dynamic Poisson's ratio of the concrete, and ρ is the density.

If the object is to obtain the elastic properties of the concrete then the first technique should be used. The measured pulse velocity provides a fairly reliable measure of α when the pulse onset is sharp and well-defined. There is inevitably some rounding of the pulse onset as it passes through the concrete, especially poor quality concrete or along a slender section, and a lack of precision in defining the pulse inset will lead to errors in the estimation of α.

The second technique, especially the use of a fixed signal amplitude, provides more comparable conditions of measurement irrespective of the path length or quality of the concrete. The pulse velocity (v_f) measured by this technique is almost always less than the pulse velocity measured by the first technique, and it is therefore less well correlated with the elastic constants of the concrete. The deviation between the pulse velocity at fixed signal amplitude and at maximum amplitude tends to increase as the pulse onset becomes more rounded and differences of up to 5 % have been observed at 60 kHz and path lengths of 100 to 150 mm; the discrepancies tend to increase at lower frequencies but decrease with increase of path length and frequency. The pulse velocity at fixed amplitude is more sensitive to changes in the quality of the concrete than is α because of the influence of the quality of the concrete on the shape of the pulse. Pulse-velocity measurements by the second technique are used in several countries for testing in-situ concrete, especially to assess its strength.

4. INFLUENCE OF TEST CONDITIONS ON MEASUREMENT OF PULSE VELOCITY

The object of the method is to provide a measurement of pulse velocity by either of the techniques described in 3.2 above which is reproducible and which depends only on the properties of the concrete under test. It is therefore essential to examine test-conditions which of themselves could produce changes of pulse velocity irrespective of changes in the properties of the concrete.

4.1. Surface conditions

The degree of smoothness required for the concrete surface and the coupling conditions between the tranducer and concrete have been discussed in Section 2.1. It is also desirable, when possible, to avoid working with the transducers in contact with the unmoulded or casting surface of the concrete because the properties of the concrete near this surface are not necessarily representative of the remainder of the concrete. If it is necessary to work on this surface then it is desirable to measure over a longer path length than would normally be used. A minimum path length of 150 mm is recommended for direct transmission (2.1.a) involving one unmoulded surface and a minimum of 400 mm for the surface type of propagation (2.1.b) along an unmoulded surface.

4.2. Ambient temperature

Variations of the ambient temperature between 5 and 30 °C have been found to cause no significant change in the measured pulse velocity in concrete. At higher and lower temperatures changes in pulse velocity in air-dried and water-saturated concrete have been observed, and suggested corrections to the measured pulse velocity are given in Table I. Corrections for temperatures above 30 °C may be obtained by linear interpolation of the values quoted at 40 °C and 60 °C. The results given in Table I are based on tests on one type of concrete made with normal Portland cement, and are therefore of a tentative nature.

TABLE I. — Corrections to pulse velocity arising from changes in temperature

Temperature °C	Correction (%)	
	Air-dried concrete	Water-saturated concrete
+ 60	+ 5	+ 4
+ 40	+ 2	+ 1.7
+ 20	0	0
0	— 0.5	— 1
Under — 4	— 1.5	— 7.5

The reduction in pulse velocity at 40 °C and 60 °C is likely to be caused by internal microcracking within the concrete. There is no corresponding reduction in compressive strength at these temperatures, and the corrections given in Table I can be used in correlations between pulse velocity and compressive strength (see later § 6.2) on concrete tested at higher temperatures. It is not known whether the tensile properties of the concrete remain unaffected at the higher temperatures and the corrections in Table I may not be justified in correlations between pulse velocity and flexural strength.

The increase in pulse velocity at temperatures below freezing is the result of the water freezing within the concrete. The corrections in Table I for the temperature range of under — 4 °C apply to concrete which is in a frozen condition. They do not necessarily apply to concrete which is subjected to freeze-thaw conditions because any damage sustained by the concrete will be more apparent in the thawed than in the frozen condition.

4.3. Path Length, Shape of Specimen and Natural Frequency of Transducers

There are still different opinions as to whether the measured pulse velocity is influenced by changes in path length, or changes in the natural frequency of the transducer. From other studies it can be inferred that the velocity α of continuous longitudinal waves in mass concrete is not significantly influenced by changes in path length or the frequency of the vibrations. In the propagation of a longitudinal pulse in mass concrete, the higher frequency components are attenuated more than the lower frequency components, and the shape of the onset of the pulse changes, becoming more rounded at greater distances. Deviations in pulse velocity with distance or with natural frequency (between 20 kHz and 200 kHz) arise from difficulties of defining accurately the onset of the pulse. The deviations are usually small and are invariantly less than $\pm$ 2 % for variations of distance and natural frequency when the pulse velocity is measured by either the technique described in Section 3.2.(a) or in 3.2.(b).

When continuous longitudinal waves travel along specimens of thin section i.e. bars or plates, the waves become dispersive and a large number of modes of propagation are possible in which the velocity is a different function of the wavelength of the vibrations in relation to the thickness of the plate or cross-section dimension of the bar. These dispersive relations for continuous waves cannot be applied directly to pulse propagation but they do indicate that different frequency components of the pulse onset will travel with different velocities (i.e. less than α), and will cause the pulse to become more and more ill-defined as it travels along the plate or bar. Ultimately, the initial pulse loses its identity and at large path lengths the measured pulse velocity may approach the velocity of longitudinal waves in infinitely long plates or bars; these are likely to have maximum deviations below α of 16 and 22 % respectively when the Poisson's ratio of the concrete is 0.35. As the measured pulse velocity may lie anywhere between α and these limits, depending upon the transverse dimensions of specimen, the longitudinal path length, the natural frequency of transducers, the amplification and frequency response of apparatus etc., it is recommended that measurements along thin sections be made by resonance or other continuous wave techniques.

In order to make these recommendations of practical value, the following paragraphs, 4.3.1 and 4.3.2, suggest limitations which are desirable in the minimum path length and the choice of transducer natural frequency for various path lengths and transverse dimensions. These recommendations are based mainly on practical experience, and may need to be modified in the light of future knowledge.

4.3.1. Minimum recommended path length. It is desirable to measure over a path length which is sufficiently long to avoid the so-called ' near-field ' of the transducers, and also long enough not to be significantly influenced by the heterogeneous nature of the concrete. The latter is the more important, and the following minimum path lengths are recommended:—

100 mm for concrete in which the maximum size is less than 30 mm,

150 mm for concrete in which maximum aggregate size is less than 45 mm.

4.3.2. Choice of transducer natural frequency for different path lengths and minimum transversal dimensions. Guidance is given in Table II below. It will be seen that a recommended minimum frequency is quoted in column 2, and the minimum transverse dimension in column 3; transducers with higher frequencies up to about 200 kHz can be used with advantage especially on shorter path lengths up to 500 mm to obtain a sharper pulse onset, provided the apparatus is designed for their use.

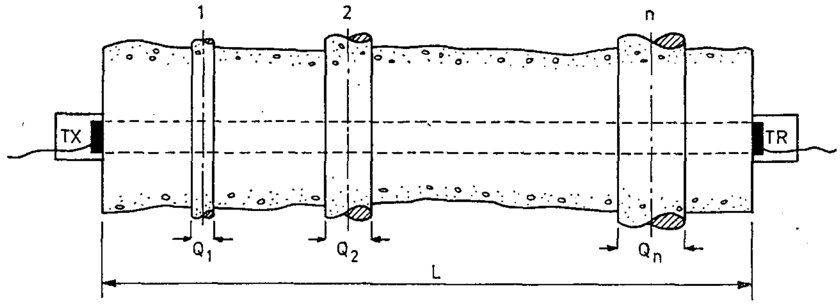
TABLE II

Path length (mm)	Natural Frequency of Transducer (kHz)	Minimum transverse dimensions of members (mm)
100-700	$\geqslant 60$	70
200-1 500	$\geqslant 40$	150
> 1 500	$\geqslant 20$	300

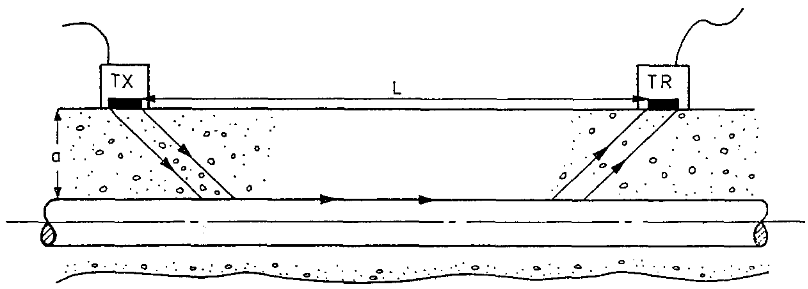
4.4. Effect of Reinforcing Bars

The pulse velocity measured in reinforced concrete in the vicinity of reinforcing bars is often higher than in plain concrete of the same composition. This is because the pulse velocity in steel is 1.2 to 1.9 times 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 dimensions and number of the reinforcing bars, their orientation with respect to the propagation path, and the pulse velocity in the surrounding concrete.

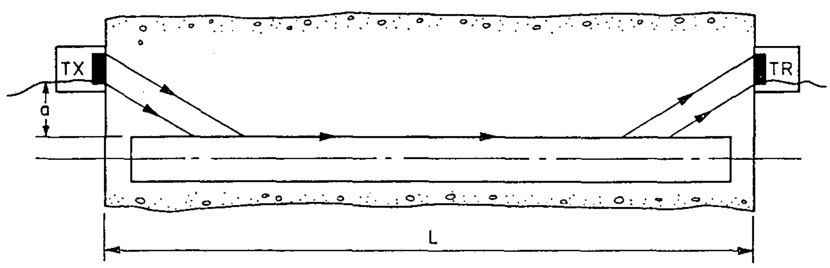
4.4.1. Axis of reinforcing bar perpendicular to direction of propagation. The maximum influence of the presence of the reinforcing bars can be calculated, assuming that the pulse traverses the full diameter of each bar during its path. If there are n different bars of diameter Qi (i = 1 to n) directly



a) Reinforcing bars perpendicular to direction of propagation.



b) Reinforcing bar parallel to test surface.



c) Reinforcing bar parallel to direction of propagation.

FIG. 5. — **Measurements on reinforced concrete.**

in the path of the pulse, with their axes at right angles to the path of propagation (see fig .5):

$$\frac{v_c}{v} = \frac{\left(1 - \frac{L_s}{L}\right)}{\left(1 - \frac{L_s v}{L v_s}\right)} \qquad (3)$$

where v is the pulse velocity in the reinforced concrete i.e. the measured pulse velocity

v_c is the pulse velocity in the plain concrete

v_s is the pulse velocity in the steel

L is the total path length

$L_s = \sum_1^n Q_i$ is the path length through steel

Values of $\frac{v_c}{v}$ are given in Table III for different amounts of steel in three types of concrete which could probably be rated as very poor, fair and very good materials.

TABLE III. — Influence of steel reinforcement — line of measurement perpendicular to axis of bar

L_s/L	$\frac{v_c}{v} = \frac{\text{pulse velocity in concrete}}{\text{measured pulse velocity}}$		
	very poor quality $v_c = 3\,000$ m/s	fair quality $v_c = 4\,000$ m/s	very good quality $v_c = 5\,000$ m/s
1/12	0.96	0.97	0.99
1/8	0.94	0.96	0.98
1/6	0.92	0.94	0.97
1/4	0.88	0.92	0.96
1/3	0.83	0.89	0.94
1/2	0.75	0.83	0.92

In practice, $\frac{v_c}{v}$ is likely to be slightly higher than the values given in Table III because of misalignment of the reinforcing bars and because only a small fraction of the pulse energy will traverse the full diameter of each bar.

4.4.2. Axis of bar parallel to direction of propagation. If the edge of the bar is located at a distance ' a ' from the line joining the nearest points of the two transducers, and the path length between transducers is L, then the transit time T in either of the configurations of figures 5b or 5c is:—

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

for

$$\frac{a}{L} < \frac{1}{2}\sqrt{\frac{v_s - v_c}{v_s + v_c}}$$

There is no influence of the steel when

$$\frac{a}{L} \geqslant \frac{1}{2}\sqrt{\frac{v_s - v_c}{v_s + v_c}}$$

The difficulty of applying equation (4) lies in deciding on the velocity (v_s) of propagation of the pulse along the steel bar. Propagation of the pulse is influenced by geometrical dispersion and the discussion in Section 4.3 is apposite. The value for v_s is thus likely to be between about 6,000 m/s (i.e. the α velocity in the steel) and 5,200 m/s (i.e. the bar velocity in the steel). A measure of this velocity can often be obtained by propagating along the axis of the embedded bar, and making allowance for any concrete cover at either end.

Corrections to the measured pulse velocity in the direction parallel to the reinforcement are given in Table IV. This table also indicates that, for bars which span most of the section, the lateral displacement of the line of measurement from the axis of the bar will usually be of the order of 0.2 to 0.25 L before the influence of the steel becomes negligible.

TABLE IV. — Influence of steel reinforcement — line on measurements parallel to axis of bar

$\frac{a}{L}$	True pulse velocity in concrete / Measured pulse velocity in concrete $= \frac{v_c}{v}$			
	$\frac{v_c}{v_s} = 0.90$	$\frac{v_c}{v_s} = 0.80$	$\frac{v_c}{v_s} = 0.71$	$\frac{v_c}{v_s} = 0.60$
0	0.90	0.80	0.71	0.60
1/20	0.94	0.86	0.78	0.68
1/15	0.96	0.88	0.80	0.71
1/10	0.99	0.92	0.85	0.76
1/7	1.00	0.97	0.91	0.83
1/5	1.00	1.00	0.99	0.92
1/4	1.00	1.00	1.00	1.00

4.4.3. Two-way reinforcement. Steel reinforcement in two or more directions complicates the interpretation of pulse velocity measurements. Corrections based on Tables III and IV may be calculated for simple well-defined systems of reinforcement but it may become impossible to make any reliable corrections for more complicated heavily reinforced concrete.

5. DETERMINATION OF DYNAMIC MODULUS OF ELASTICITY AND DYNAMIC POISSON'S RATIO OF CONCRETE

As discussed in Section 3.2, a measurement of pulse velocity at maximum signal amplitude provides a good approximation to the velocity of longitudinal waves in mass concrete provided the restrictions given in Section 4.3.2 are observed. The dynamic Young's modulus (E) of the concrete can be determined from this pulse velocity (v_m) and the dynamic Poisson's ratio (δ) by the following relation:

$$E = \frac{(1+\delta)(1-2\delta)}{(1-\delta)}\rho v_m^2 = f(\delta)\rho v_m^2 \qquad (5)$$

The dynamic Poisson's ratio of concrete over 14 days old containing natural river gravels is usually about 0.25 but variations within the range of 0.2 to 0.35 have been reported for concrete containing other types of aggregate. Over this range of variation the factor $f(\delta)$ in equation (5) varies from 0.90 to 0.63, and it is clearly desirable to have an independent measure of the dynamic Poisson's ratio for the particular type of concrete under test.

The dynamic Poisson's ratio is obtained from measurements on concrete test-beams of the pulse velocity v_m along the length l of the beam and the fundamental resonant frequency n of the beam in longitudinal mode of vibration (*). From these measurements the factor $f(\delta)$ is calculated by the relation:

$$f(\delta) = \frac{(2nl)^2}{(v_m)^2} \qquad (6)$$

The value of δ may be derived from $f(\delta)$ by table V.

TABLE V. — Relation between δ and $f(\delta)$

δ	$f(\delta)$
0	0
0.05	0.995
0.10	0.975
0.15	0.950
0.18	0.922
0.20	0.900
0.22	0.877
0.25	0.833
0.27	0.800
0.30	0.742
0.32	0.698
0.35	0.625
0.37	0.566
0.40	0.467
0.45	0.264

(*) Details for this measurement are given in the appropriate standard i.e. Recommendations of R.I.L.E.M. Working Group on Non-Destructive Testing of Concrete for Resonance Testing or in certain national standard specifications.

6. ESTIMATION OF COMPRESSIVE STRENGTH OF CONCRETE

The concrete compressive strength (R) may be determined from pulse velocity either by:

a) graphical correlations between v and R obtained on test specimens or by

b) known analytical correlations between v and R. In general, method 6a gives more reliable results than method 6b.

The pulse velocity may be measured either at fixed amplitude (i.e. $v = v_f$) or at maximum amplitude (i.e. $v = v_m$) provided one or the other is used consistently to test the structure and the test-specimens. The correlations between R and v_f and R and v_m will be different, and it seems likely that the former will be more sensitive to changes in R.

6.1. Preparation of correlation between pulse velocity and compressive strength from test-specimens

To obtain the graphical correlations referred to in 6a requires a minimum of 30 test-specimens having the same dimensions. An average value of pulse velocity and strength is obtained on a set of three specimens subjected to identical test conditions. Variations of strength and pulse velocity required for the correlation are introduced by altering the amount of water or the degree of compaction in each other set of three specimens. All the other characteristics of the concrete (i.e. amount and type of cement, amount, type and grading of aggregate, additives) the method of preparation, the curing conditions and age of test must be the same as in the corresponding precast unit or structure for which the in-situ strength is required.

The transit time of the ultrasonic pulse is measured across the test-specimen in a direction perpendicular to the casting direction of the concrete in the mould. There should be at least three positions of measurement spaced between the top and bottom of the test-specimen but not in the neighbourhood (within 20 mm) of the unmoulded (top) surface. The variation between the measured transit times (on single test specimen) should be within ± 5 % of the mean value, otherwise the test-specimen should be rejected.

The mean pulse velocity and mean strength obtained from each set of three similar test-specimens provides the experimental data to construct the graphical correlation curve between v and R. The co-ordinates of this curve are determined by any standard curve fitting procedure, and for an acceptable correlation curve 90 % of the experimental points should lie within ± 12 % of the strength at the measured value of pulse velocity.

6.2. Use of analytical correlations

It is often possible to fit an analytical expression to the correlation curve and the following have been employed:

$$R = av^b$$
$$R = ae^{bv}$$
$$R = av^2 + bv + c$$

Once an analytical correlation has been found for a particular type of concrete by the method of Section 6.1., subsequent checks require only a few test-specimens. If no test-specimens are available and the composition is unknown, it is possible to provide an estimate of the strength by assuming an analytical formula and obtaining the constants from tests on cores cut from the structure.

Estimates of the strength can be obtained for in-situ concrete using analytical relations in the following circumstances:—

a) When the composition of the in-situ concrete is known and there are at least three remaining test-specimens of the same age as the structure or alternatively at least three cores can be cut from the structure.

b) When the composition of the concrete is known and there are no remaining test-specimens of the original concrete but materials are available to make at least three new test-specimens.

c) When the composition of the concrete is unknown but at least three cores from the structure are available.

d) When only the composition of the concrete is known.

In general the estimate of strength obtained by correlation 6.2(a) is more reliable than 6.2(b) which in turn is more reliable than 6.2(c) or 6.2(d). The accuracy of the correlation 6.2(c) may be improved by first making a homogeneity survey of the structural concrete (see later); if it is relatively homogeneous, results from three cores are averaged; if there are wide variations in pulse velocity, groups of there cores are taken at two or more values of pulse velocity.

7. HOMOGENEITY OF CONCRETE

Inhomogeneities in the concrete within a structure cause variations in pulse velocity which in turn are related to variations in strength. Measurements of pulse velocity provide a means of studying the homogeneity, and, in such measurements, a system of measuring points must be chosen which covers uniformly the whole volume of concrete in the structure. The spacing between individual test points depends upon the size of the structure, the accuracy required, and the variability of the concrete. In a large structure of fairly uniform concrete, testing at the corners of a 1—m grid is often adequate but on small units or variable concrete a finer grid may be necessary.

The coefficient of variations (C_v) of strength in the structure may be defined as:

$$C_v = \frac{\sigma_R}{R_o} \qquad (7)$$

where σ_R is the standard deviation and R_o is the mean value of the compressive strengths obtained from the measured pulse velocities.

A useful approximation for C_v which can be derived directly from the measured pulse velocities is:

$$C_v = \frac{4\sigma_v}{v_o} \qquad (8)$$

where σ_v is the standard deviation of the measured values of pulse velocity and v_0 is the mean value.

C_v in equations (7) or (8) is a function of the path length because of variations produced by differences in the distribution of coarse aggregate. It is likely that the influence of aggregate distribution can be neglected when the path length is greater than 400 mm for maximum dimensions of the aggregate of 20-30 mm

8. FOLLOWING CHANGES IN THE PROPERTIES OF CONCRETE

Changes occurring in the properties of concrete with time either caused by the hardening process, by the influence of an aggressive environment or by overloading are determined by repeated measurements of pulse velocity. Changes in pulse velocity are indicative of changes in strength and they have an advantage in that the same test piece is retained throughout the investigation.

Pulse velocity measurements are particularly useful for following the hardening process, especially during the first 36 hours. Here, rapid changes in pulse velocity are associated with physico-chemical changes in the cement structure, and it is desirable to make measurements every hour or two. As the concrete hardens, the intervals between tests may be lengthened to one day at ages of 8 to 14 days and even longer if further tests are required. The pulse velocity in Portland-cement concrete increases very slowly beyond an age of about 28 days and strength prediction becomes more imprecise than at earlier ages.

Aggressive attack or damage to concrete by freezing and thawing or chemical action causes a reduction in pulse velocity. Progressive deterioration can be followed by making repetitive pulse velocity measurements, preferably across the direction of the test-piece where there is the highest ratio of exposed surface to thickness dimension and where the changes are likely to be most marked. Such tests are particularly useful for following the deterioration of structural concrete or for testing specimens in order to correlate them with the in-situ concrete. Although the ultrasonic pulse measurements can also be applied to specimens used in purely laboratory investigations, there are distinct advantages in using flexural resonance tests where possible.

9. DEFECTOSCOPY

The use of the ultrasonic pulse technique for locating flaws, voids or other defects in concrete is based on the negligible transmission of ultrasonic energy across a concrete-air interface. Thus any air-filled crack or void lying immediately between two transducers will obstruct the direct ultrasonic beam when its projected area is greater than the area of the transducers. When this happens the first pulse to arrive at the receiving transducer will be diffracted around the periphery of the defect and the transit time will be longer than in homogeneous concrete. Apart from the apparent decrease in pulse velocity the amplitude of the received pulse is usually less than in homogeneous concrete and the decrease is most marked for transducers which produce a well-defined beam i.e. those having a high resonant frequency and large cross-section.

9.1. Detecting large voids or cavities

Large voids or cavities can be detected when their projected area at right angles to the path of propagation is sufficiently extensive to give a significant change in the pulse transit time relative to the transit time in homogeneous concrete. The minimum change in pulse time for voids of the same projected area occurs when the void is midway between the transducers and it can be shown that:—

$$T_d = T_h \qquad \text{for } a \leqslant d \qquad (9)$$

$$\frac{T_d}{T_h} = \sqrt{1 + \frac{(a-d)^2}{L^2}} \qquad \text{for } a > d \qquad (10)$$

where a is the minimum transversal dimension of the projected area of the defect and d is the diameter of the transducer

T_d is the transit time across the centre of the defect

T_h is the transit time in homogeneous concrete.

It will be seen from equation (10) that over a path-length of 300 mm it would require a cavity with a minimum transverse dimension of 150 mm to produce an increase of transit time of 10 % when using transducers with a diameter of 25 mm.

Equation (9) represents cases where the projected area is smaller than the diameter of the transducer, and indicates that voids of this type cannot be detected. One such void is a long cylindrical cavity with its axis along or across the direction of propagation and its diameter smaller than that of the transducer.

9.2. Estimating the depth of a surface crack

It is sometimes required to estimate the depth of a crack which is visible at the surface of a concrete structure. An estimate of crack depth is obtained by comparing the transit times across the crack and in nearby homogeneous concrete from transducers applied to the concrete surface at the same distance apart. If the crack is spaced midway between the transducers the crack depth (c) is obtained as follows:—

$$c = b\sqrt{\frac{T_c^2}{T_L^2} - 1} \qquad (11)$$

where T_c^2 is the transit time across the crack

T_L^2 is the transit time along the surface of the same type concrete without defects

c is the depth of the crack

b is the distance of the nearest point of the active area of the transducer from the crack.

The depth of cracks will be underestimated when they become bridged by solid material or filled with water because transmission of the ultrasonic pulse then occurs.

9.3. Thickness of damaged layers

The thickness of a damaged surface layer of structural concrete can be estimated from ultrasonic measurements of transit times along the surface. The transmitting transducer is usually held in a fixed position and the receiver moved along the surface by fixed increments of distance. When the transducers are near together the pulse travels through the damaged concrete and the slope of the experimental line relating distance of separation of transducers (as ordinate) to the transit time (as abscissa) gives the pulse velocity in this surface layer. Beyond a certain distance of separation, the first pulse to arrive is refracted along the surface of the underlying undamaged concrete and subsequent experimental points lie on a line whose slope gives the pulse velocity in the undamaged concrete. The distance x_o at which the change of slope occurs together with the measured pulse velocities in the damaged and undamaged concreteenables an estimate of the thickness of the damaged layer to be found as follows:

$$\delta = \frac{x_o}{2}\sqrt{\frac{v_s - v_d}{v_s + v_d}} \qquad (12)$$

where v_d is the pulse velocity in the damaged concrete

v_s is the pulse velocity in the underlying sound concrete

δ is the thickness of the layer of damaged concrete.

This above method is applicable to extensive surface areas of fairly uniform thickness of damaged concrete. Localised areas of damaged or honeycombed concrete are more difficult to test, but it is possible to derive an approximate thickness of such localised poor quality material if both direct transmission and surface propagation measurements are made. The thickness may be calculated as follows:—

$$\delta = \mathrm{L}\left(\frac{\dfrac{\mathrm{T}}{\mathrm{T}_u} - 1}{\dfrac{v}{v_d} - 1}\right) \qquad (13)$$

where L is the path length through the thickness of the test-piece at right angles to the surface containing areas of damaged or honeycombed concrete.

T_u is the transit time measured through a section (thickness L) of undamaged concrete

T is the transit time measured through a section (thickness L) containing a thickness δ of damaged concrete

v_u is the pulse velocity in sound concrete $\left(v_u = \frac{\mathrm{L}}{\mathrm{T}_u}\right)$

v_d is the pulse velocity in damaged concrete for which an estimate is obtained from surface propagation measurements on an area of damaged or honeycombed material.

10. THE MEASURING APPARATUS

10.1. The electronic apparatus

The electronic apparatus for testing concrete by the ultrasonic pulse method should have the following characteristics:

a) It should be capable of measuring transit times to an accuracy of within ± 1 % over a range of 20 microseconds to 1 millisecond (or longer if path length greater than 4 m are to be tested).

b) the electronic excitation pulse applied to the ransmitting transducer should have a rise time of t not greater than one quarter of its natural period. This is to ensure a sharp pulse onset, and is especially important when method 3.2.(a) is used for the measurement of α.

c) the pulse repetition frequency should be low 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 receiver amplifier should have an upper frequency response of at least five times the natural frequency of the transducers. Some attenuation at low frequencies is permissible as a means of improving signal-to-noise ratio, but a flat response should be maintained down to about one-fifth of the natural frequency of the transducers.

The gain of the amplifier should be as large as possible consistent with a high signal-to-noise ratio, peak limiting is permissible.

There should be no attempt to improve the signal-to-noise ratio or artificially sharpen the received signal by adjusting the threshold response of the amplifier (i.e. no ' grasscutting ').

e) To ensure that transit times are measured correctly the received signal should be displayed for measurement on a cathode ray oscilloscope.

f) The apparatus should have a system for checking the accuracy of time measurement either by internal or external reliable electronic calibration, or by the use of stable standard prisms with accurately known pulse travel times.

g) The apparatus should maintain its performance over an ambient temperature range of — 10 °C to + 45 °C, at a relative humidity of up to at least 90 % and for variations in supply voltage of ± 10 %.

10.2. The transducers

10.2.1. Natural Frequency. The two transducers in use to any one time usually have natural frequencies which are approximately matched. The natural frequency of the transducers is usually within the range of 20-200 kHz, and the choice depends upon factors which were discussed earlier in Section 4 of these recommendations. Frequencies higher than 200 kHz are sometimes used but only rarely because the range of measurement is restricted by the increased attenuation in the concrete.

10.2.2. Transducer materials. Ferro-electric materials are usually employed in the transducers because of their high sensitivity and high internal capacitance. Details of specific materials are available from the various manufacturers, and, in this rapidly developing field, newer improved materials are always becoming available. The materials are polarised during manufacture and it should be noted that the sensitivity will be destroyed if the temperature exceeds a value specified by the manufacturer for each material: this temperature is usually in excess of 100 °C.

Ferro-electric materials operate in a similar way to piezo-electric crystals and an electrical charge applied between the polarised faces produces a corresponding mechanical displacement. To produce an ultrasonic pulse of usable amplitude from these materials it is usually necessary to apply a voltage pulse of 1 000 volts peak. The natural frequency of the sample depends upon its dimensions and its elastic properties; in the case of a disc the relevant dimension is its thickness although in thin discs natural frequencies of other modes sometimes predominate, especially after the signal passes through concrete.

Magneto-strictive materials are also used in transducers especially at frequencies under 50 kHz where they are relatively efficient. They are less influenced by temperature and are more robust than ferro-electric or piezo-electric materials. The best known magneto-strictive materials are nickel and some of its alloys, also certain ferrites. To obtain the ultrasonic pulse the material is polarized by a magnetic field obtained either from a permanent magnet or a coil carrying a constant current, and a pulsed magnetic field is generated by a coil carrying a pulsed current. These transducers operate at a much higher current and lower voltage than ferro-electric transducers and are not directly interchangeable with them.

10.2.3. Assembly of ferro-electric type materials. The transducer material is usually in the form of a disc with metal coated circular faces. The disc is mounted on a metal diaphragm and surrounded by a metal case for protection and electrical shielding. It is important that the disc be as closely coupled acoustically to the diaphragm as is possible. In some cases adhesive is used but experience suggests that this bond may deteriorate in time especially if the transducer is subject to rough usage. Another method is to attach one face of the transducer disc to the diaphragm by a couplant and to spring-load the back face. Silicone grease is one of the most stable couplants for this purpose although commercial vaseline, or oil can also be used. Rough usage or deterioration of the properties of the couplant causes a loss of overall sensitivity of the transducers, and it is desirable to have a simpleway of checking the overall performance of the transducer system: one such method is to measure the amplitude of the received signal when the two transducers are held at a fixed distance of separation in air. Loss of performance can invariably be traced to poor coupling within one transducer; the remedy is to clean the face of the disc and the inside of the diaphragm thoroughly and renew the couplant.

It should be noted that the transducer material is polarised in one direction, and in some cases the sensitivity of the transducer is higher if the transducer is mounted in this direction. It is thus desirable to check whether a change in the orientation of the two transducer discs causes any substantial change in sensitivity. It should also be noted that changing the polarity of one disc only will cause the phase of the received signal to change by 180°.

10.2.4. Assembly of magneto-strictive transducers. There are several types of magneto-strictive assemblies produced by different manufacturers for use as transducers. It should never be necessary to reassemble the transducer after it is received from the manufacturer.

10.2.5. Inherent time delay in the transducers. There is a small but significant time delay between the electrical shock excitation applied to the transmitting transducer and the electrical signal at the receiving transducer when the two transducers are held in contact. Part of this delay (i.e. the ' system-delay ') arises during transmission of the mechanical pulse through the two metal diaphragms and couplant, and most of the remainder occurs within the transducer material. In practice it is convenient to use the initial electrical shock as reference mark for measurements in concrete specimens, and it is therefore necessary to subtract the system delay from these measurements to obtain the transit time through the concrete.

The simplest method of measuring system delay is to measure it directly when the two transducers are held in contact. This is not always easy to do in practice because it is often difficult to produce a clean sharp reference mark from the shock excitation pulse, and any electrical breakthrough from this pulse makes accurate measurements difficult when the system delay is typically of the order of one microsecond. An alternative method is to make uncorrected time measurements through different lengths of metal cut from the same supply and to deduce the system delay from the results. Using billets of brass of length, 100, 200 and 300 mm by 100 mm diameter the system delay can be deduced to an accuracy of better than $\pm$ 0.2 microseconds, provided a damping material such as plasticene is wrapped around the cylindrical surfaces to reduce reverberation.

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