The dynamic testing of concrete by a supersonic method

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Essai dynamique du béton par une méthode supersonique [1]

Die dynamische Prüfung von Beton mittels einer supersonischen Methode [1]

The dynamic testing of concrete by a supersonic method [1]

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Introduction

In recent years, non-destructive methods of testing concrete have been developed in both Great Britain and America based on the measurement of the velocity of sound waves in the material. It has been found that the velocity is related to some of the other properties of concrete, and to its treatment after casting.

In America [2], a testing technique has been developed based on the measurement of the natural frequency of transverse vibration of concrete beams from which the velocity of sound in the material, and thence the elastic modulus, are deduced.

The advantages which are claimed for this method of test are :

The method is non-destructive and hence the same specimen may be employed to investigate the effects of factors such as ageing, frost damage, etc.;

Changes in the quality of the concrete may be related to changes in the dynamic elastic modulus;

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(2) THOMSON, W. T., *Measuring changes in physical properties of concrete by the dynamic method* (*American Society for Testing Materials*, Vol. 40, 1940, pp. 1113-1121).

OBERT, L. and W. I. DUVALL, *Discussion of dynamic methods of testing concrete with suggestions for standardisation* (*American Society for Testing Materials*, Vol. 41, 1941, pp. 1053-1071).

LONG, B. G., H. J. KURTZ and T. A. SANDERSON, *An instrument and a technic for field determinations of the modulus of elasticity and flexural strength of concrete (pavements)* (*Journal of the American Concrete Institute*, Vol. 16, No. 3, January, 1945, pp. 217-281).

A higher order of reproducibility of results is obtained compared with the cube compressive strength, which, hitherto, has been accepted as the main method of assessing concrete quality. As a result, fewer specimens are required for dynamic testing compared with cube tests;

The tests are simple and rapid in operation.

A disadvantage of this method is that it is restricted to specimens of a particular shape. Further, when the longitudinal sound wave velocity is measured on pavement slabs or mass concrete the dynamic modulus cannot be deduced without a knowledge of Poisson's ratio for the material. This is shown by the equations (1) and (2) below :

$$E = V^2 \rho \, (1 - \sigma^2) \text{ for pavements} \tag{1}$$

$$E = V^2 \rho \, \frac{(1 + \sigma)(1 - 2\sigma)}{(1 - \sigma)} \text{ for mass concrete} \tag{2}$$

where E = velocity of longitudinal waves
V = dynamic elastic modulus
ρ = density
σ = Poisson's ratio.

At the Road Research Laboratory, the aim of the investigation has been to devise a testing technique for determining the quality of concrete road slabs in situ, and, although this object has not yet been achieved, much useful data has been obtained relating the variation of the velocity of longitudinal pressure waves with the other properties of concrete. Information of this type would be necessary in any event in connexion with the testing of slabs in situ, since the quality of the concrete would have to be deduced from the dynamic measurements.

In the experiments described in this paper, measurements have been made of the longitudinal wave velocity in concrete beams, together with auxiliary experiments to determine the fundamental longitudinal resonance conditions for the same beams. From these data it was possible to determine the elastic modulus and hence compute Poisson's ratio.

The methods available for measuring the longitudinal wave velocity depend either on determining the wavelength of sustained vibrations of known frequency, or the measurement of the time taken for a pulse, produced either mechanically or electrically, to travel through a known distance of concrete. The latter method has received most attention because it is easier and quicker to use in practice, and apparatus has been constructed for measuring these times for mechanically or electrically produced pulses. The longitudinal wave velocity over the surface of large slabs of concrete can be measured by timing mechanically produced pulses, but this method is not capable of sufficient control or accuracy for use with smaller laboratory specimens. The general investigation of the variation of velocity with concrete quality has involved the testing of large numbers of laboratory specimens, and, for this purpose, the electrically produced pulse has been employed.

The measurement of the velocity of longitudinal waves in concrete, by a supersonic method

The velocity of longitudinal waves in concrete is measured by sending a short duration pulse into a concrete specimen and measuring the time taken for this pulse to traverse a known distance. The great advantage of the method is that it is not restricted to specimens of a certain shape but can be applied to any specimen where two flat opposite faces are available. In the use of the method on the cube and beam specimens normally employed in laboratory tests, the distance over which the pulse was timed was about 10 cm, and for concrete made from typical road mixes the time taken was about 20-25 microseconds. To differentiate between the various mixes it is essential, therefore, to have apparatus which is capable of measuring individual times accurately to a fraction of a microsecond and also to take a large number of similar observations from which to obtain a mean value. The apparatus specially designed to meet these requirements is shown schematically in fig 1.

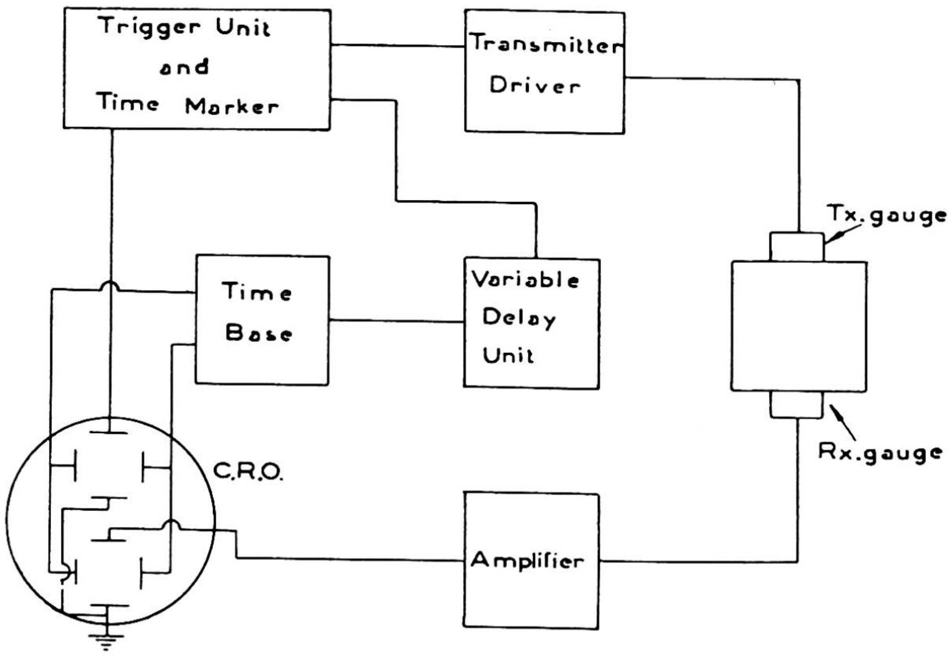

Fig. 1. Schematic diagram of supersonic pulsing apparatus.

The trigger unit supplies an electrical impulse of about 20 microseconds duration at a recurrence frequency of about 300 times per second which operates the time base *via* the delay unit so that the spots of the cathode ray tube are brightened and traverse the screen at some time variable, by means of a manually operated control on the delay unit, from about a microsecond to any chosen delay after the leading edge of the 20-microsecond pulse. The back edge of the 20-microsecond pulse is used to trigger a thyratron circuit (transmitter driver fig. 1) causing a short duration pulse to be applied to the piezo-electric crystal transmitter gauge which emits a short train of vibrations of supersonic frequency.

The vibrations after passing through the concrete are picked up by a receiving piezo-electric crystal gauge and, after amplification, the corresponding electrical signal is applied to the Y plate of the lower gun of the cathode ray tube. To the upper gun Y plate, timing pulses are applied direct from the crystal controlled circuits in the trigger unit giving timing marks on the top trace at intervals of 1.017 microseconds (small amplitude) and 10.17 microseconds (large amplitude).

If the transmitter and receiver gauges are held in direct contact, a signal appears on the lower trace when the time base operates with zero delay. The position of this signal is adjusted to coincide with a cursor line on the face of the screen and also with a large timing mark on the other trace. When the gauges are now placed on opposite sides of the specimen, the time of transmission of the supersonic pulse through the concrete may be measured by gradually turning the delay control and counting the number of time intervals passing the cursor line until the received signal appears on the lower trace under the cursor line. The operation is extremely rapid, and a high order of accuracy is possible, since individual times can normally be measured to within $\pm$ 0.2 microsecond.

The recurrence frequency of the trigger unit allows about 3 milliseconds between each cycle of events which is long in comparison of the time of transmission of the pulse through the specimen (normally less than 50 microseconds with distances less than 20 cm), and thus time is allowed during the resting period for reflections from the various boundaries to become of infinitesimally small amplitude before the next working stroke begins. For larger specimens it has been necessary on occasions to reduce the recurrence frequency to about 100 per second to obtain a reasonably linear trace before the onset of the signal.

It can be shown, theoretically, that, when supersonic waves are propagated through media, almost all the energy travels at right angles to the surface of the transmitter. The magnitude falls to zero at a semi angle θ given by :

$$\sin\theta = \frac{1.22\,c}{nd}$$

c being the longitudinal wave velocity in the media;
n the natural frequency of the transmitter;
d the diameter of the transmitter.

Thus, for a transmitter of given diameter, the directionality of the energy increases with increasing frequency. Unfortunately, the attenuation of the energy by the media also increases with the frequency, and concrete, due to its non-homogeneous nature, imposes a high attenuation on high frequency waves so that a frequency of 250 kc has been the highest gauge frequency used, in which case θ is about 40°. Lower natural frequency gauges, down to 40 kc, have been employed with increase of output and less attenuation, but the increased spread of the energy gives rise to increased amplitude of the reflections within the specimens necessitating a lower recurrence frequency.

Variations of the velocity in laboratory and road core specimens

The forms of the specimens used in most of the tests made up to the present had also to be suitable for measurement of the static quantity with which the longitudinal wave velocity was being compared, and were mainly 10-cm cubes or beams 10 cm square by 40 cm long or 15 cm square by 77 cm long, used subsequently for compressive cube strength and modulus of rupture determinations. With these specimens, measurements of the longitudinal wave velocity were made across the moulded faces of the concrete, intimate contact between the gauges and the concrete being facilitated by the use of a thin film of oil. It was impracticable to make routine measurements in a direction perpendicular to the top face of the specimens due to the uneven nature of the top surface which would have required special preparation to ensure sufficiently good contact between the gauges and the concrete. Since the gauges were about 3 cm diameter, it was possible to make nine separate observations across each pair of opposite moulded faces of a 10-cm cube specimen.

If the specimens contain large aggregate, as in the present case (ratio of size of aggregate/side of specimen = 1/5), the concrete is far from isotropic, and a large scatter may be anticipated between successive measurements. Analysis of the times of propagation over the 10-cm path indicated that the scatter was greater for some mixes than for others and also that the distribution was irregular as may be seen from fig. 2 which represents the analysis of observations on thirty cubes of a 1 : $2\frac{1}{2}$: 5/0.70 mix. In the cases where large scatter was observed a closer examination of the results showed that there were three definite groups corresponding to transmission times across sections near the top, the middle and the bottom of the cube. If the results used for the distribution curve of fig. 2 are separated into the three different groups the separate distribution curves are those given in fig. 3. It will be seen that the distribution curves of the transmission times in the top and bottom slices are almost identical in shape, but with different mean transmission times corresponding to a higher longitudinal velocity in the bottom slice. The distribution curve in the middle slice indicates a spread of results with standard deviation approximately equal to twice that in the top or bottom sections, as though it were composed of results from the other two groups. It is to be expected that the method of manufacture will influence the results; the 10-cm cubes used in all tests were made in steel moulds in two 5-cm lifts, the lower lift being compacted before the upper lift was placed in position. Thus measurements over the middle slice overlap the original join between the two lifts, which was caused to disappear by the final compaction, and this may explain the greater scatter of the results over the middle slice.

In almost every cube and beam specimen tested the mean longitudinal wave velocity is higher at the bottom of the specimen than at the top, the magnitude of the difference being dependent on the water/cement ratio as may be seen from fig. 4, which gives the mean results at an age of 28 days from eighteen water-saturated cubes from each of five different mixes with five water/cement ratios. In general the wetter mixes of each series tend to produce a greater degree of non-uniformity in the cube, except the wettest mix of each series where it is possible that only a small amount of punning was used to obtain compaction. It is conceivable that the discrepancy is due to segregation of the aggregate, and though this may be a contributory cause, particularly with the leaner mixes, a more likely explanation may be that a higher percentage of water voids are present near the top of the specimens due to water rising during manufacture. The latter explanation is supported by some previous results obtained by a sonic longitudinal resonance method on beams cut from a road slab when it was observed that the velocity of the longitudinal vibrational sound wave was related approximately inversely to the percentage voids.

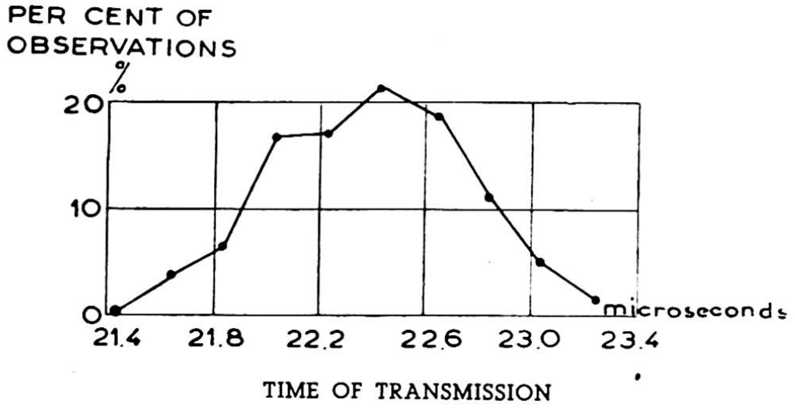

Fig. 2. Distribution of transmission times in concrete cubes.

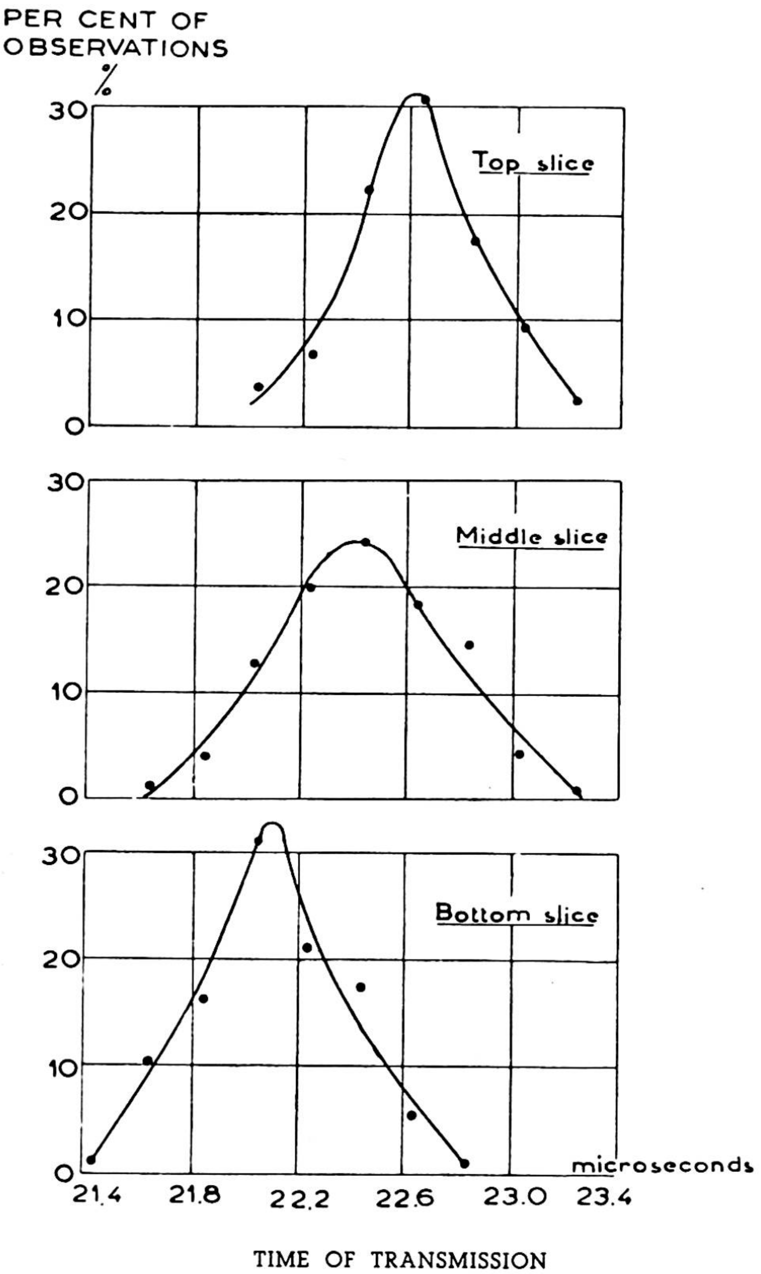

Fig. 3. Distribution of transmission times through three sections of concrete cubes.

The results quoted above serve to illustrate the scope of the supersonic method in the examination of laboratory specimens. Time has not permitted any further studies on the effect of different methods of specimen preparation and attention is now being devoted to the analysis of road cores.

When it was found that the longitudinal wave velocity was sensitive to void content, experiments were begun to investigate the possibility of using such a method in the routine analysis of road cores as an alternative to the analysis by density determinations of thin slices cut from the core, which is a long and costly procedure. Preliminary tests have been made on specially prepared oven-dried cores, and fig. 5 shows a comparison for one particular core, between the longitudinal wave velocity and compaction as measured by density analysis. When obtained from the road slab the core has rough cylindrical sides and therefore requires preparation before the velocity measurements can be made. In most preliminary tests flat parallel surfaces have been cut but further tests are being made to obtain a quicker method of preparation which will give adequate transmission without impairing the accuracy.

The variation of the longitudinal wave velocity in compacted concrete of different mix proportions and water/cement ratios

For the purpose of studying the variation of the longitudinal wave velocity in concrete of different mix proportions and water/cement ratios, use is made of the velocity obtained near the bottom of cube and beam specimens, since this, it may be assumed, is the nearest approach to fully compacted conditions. The extent and type of variation of this velocity in saturated specimens of concrete made with Ham River aggregate at 7 and 28 days is shown in figs. 6 and 7 respectively. These results represent the mean value from two series of beams, 15 cm square by 77 cm long, each beam being tested at different ages. The agreement between the beams made from the same mix was extremely good and in most cases the velocities agreed to within 1 per cent.

It will be seen that for each mix proportion the velocity decreases approximately linearly with increasing water/cement ratio, but mixes with higher aggregate content give a higher velocity at the same water/cement ratio. It is possible to draw a single curve through all the points at each age but the scatter would be extremely large. A better representa-

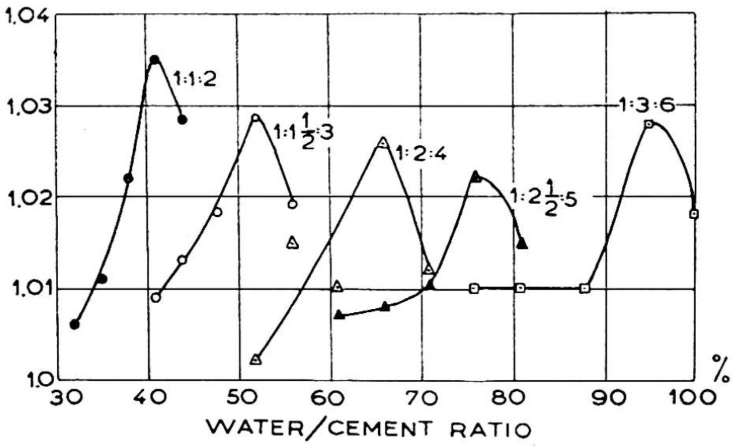

Fig. 4. Ratio of the longitudinal wave velocity near the bottom of a concrete cube to that near the top for different concrete mixes.

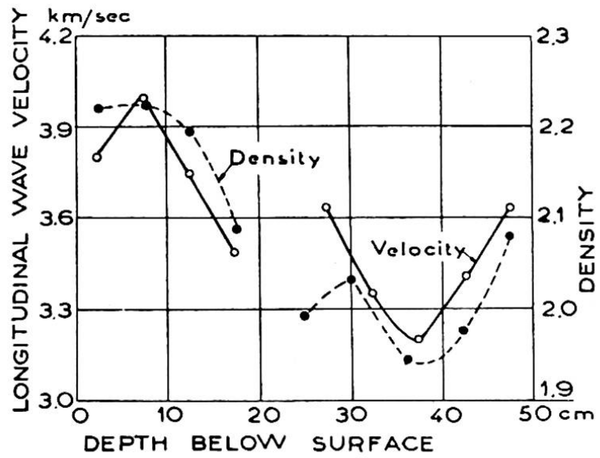

Fig. 5. Longitudinal wave velocity and density at various depth in a road slab.

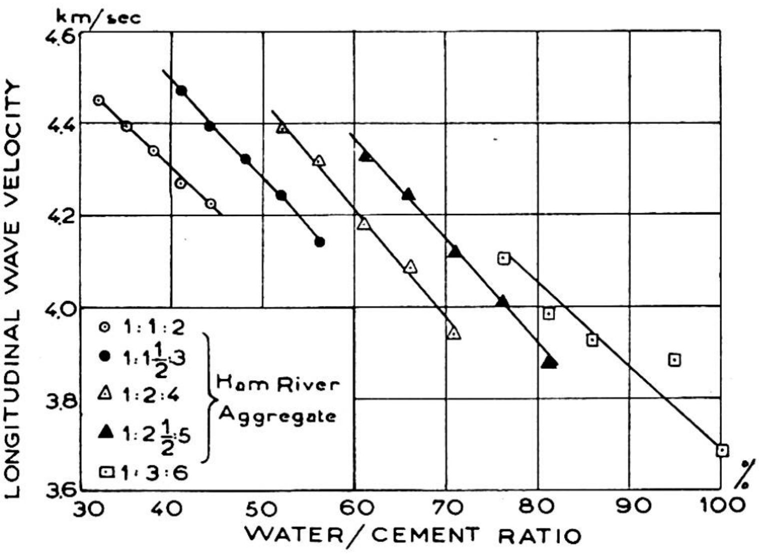

Fig. 6. Longitudinal wave velocity in concrete at an age of 7 days.

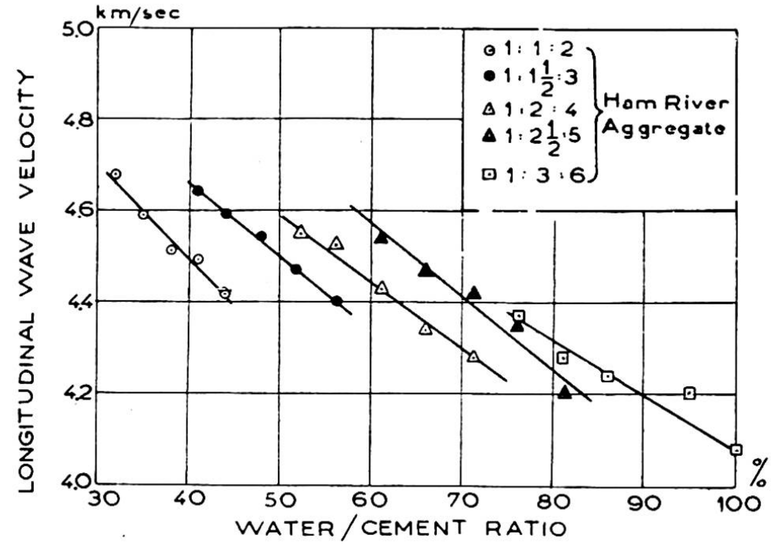

Fig. 7. Longitudinal wave velocity in concrete at an age of 28 days.

tion is that adopted in figs. 6 and 7 of a series of approximately parallel curves, one for each aggregate/cement ratio.

The increase of velocity between 7 and 28 days can be seen by a comparison of figs. 6 and 7, but results obtained on similar specimens at an age of three months showed little change from the 28-day results. Thus the main increase in the longitudinal wave velocity occurs prior to 28 days which is in agreement with results obtained using the resonance method when it was found that only small increases occurred in the dynamic modulus after an age of 28 days (2).

Variation of longitudinal velocity with static strengths

After the velocity measurements most of the water-saturated specimens were tested, statically, on the same day, the 10-cm cubes in compression and the 10-cm and 15-cm section beams in flexure by centre line and third line loading respectively.

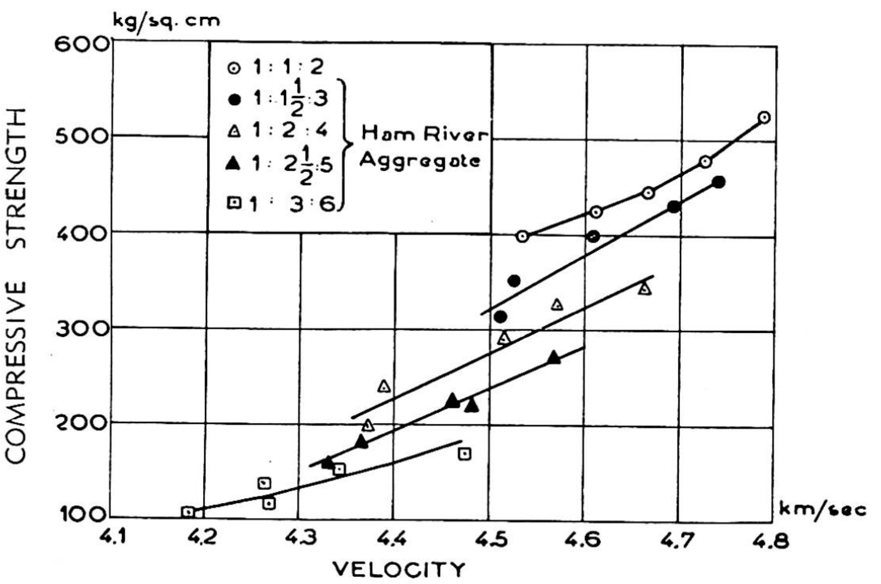

Fig. 8. Relation between the longitudinal wave velocity and the compressive cube strength.

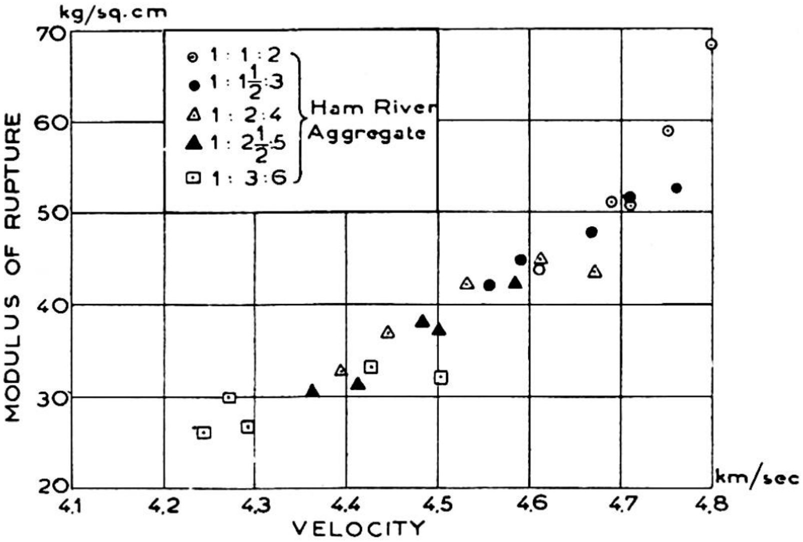

Fig. 9. Relation between the longitudinal wave velocity and the modulus of rupture (centre line loading).

The variation of the mean longitudinal wave velocity with compressive strength for cubes made from Ham River aggregate is shown in fig. 8. It will be seen that, for a particular mix, the increase in strength is accompanied by an increase in longitudinal wave velocity but the actual value of the velocity is also dependent on the aggregate-cement ratio.

In fig. 9 the mean velocity from three 10-cm section beams of each mix of the Ham River concrete is plotted against the modulus of rupture measured by centre line loading. It will be seen that the results fall on a single curve irrespective of aggregate content, but it should be noted that the modulus of rupture results for a particular mix showed considerable scatter so that the three beams tested were probably too few to obtain an accurate result.

Fig. 10 gives mean longitudinal wave velocity plotted against the modulus of rupture, measured by third line loading for three 15-cm section beams from two concrete mixes 1 : 1½ : 3 and 1 : 3 : 6 each with three water/cement ratios adjusted to give three different workabilities corresponding approximately to 0-, 5- or 15-cm slumps with Bridport, Enderby

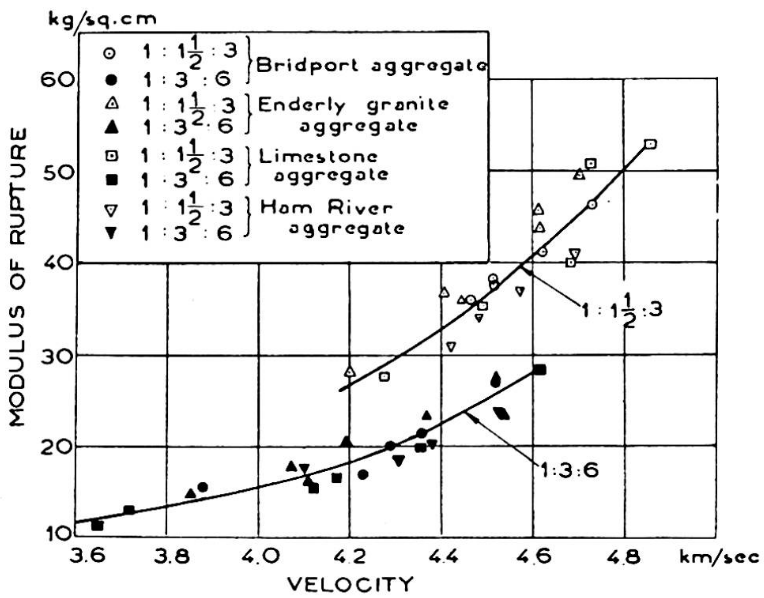

Fig. 10. Relation between the longitudinal wave velocity and the modulus of rupture (third line loading).

granite, Ham River and limestone aggregates. It will be seen that the relation between velocity and modulus of rupture appears to be independent of age and type of aggregate but to depend upon the aggregate/cement ratio. In these tests modulus of rupture values from beams of the same mix were more consistent and reproducible than those obtained previously from the smaller beams.

With the latter series of beams the tests were extended to include longitudinal resonance measurements from which the dynamic modulus may be calculated to a sufficient degree of accuracy from the equations

$$E = c^2 \rho \qquad (3)$$

$$c = \frac{2\,nl}{i} \qquad (4)$$

where c = the longitudinal vibrational sound velocity
ρ = the density of the concrete
n = the natural frequency of vibration in longitudinal resonance
i = the order of the harmonic (= 1 for fundamental)
l = the length of the beam (about 79 cm).

The variation of the dynamic modulus with the modulus of rupture is given in fig. 11; it will be seen that the relation between these quantities is also dependent on aggregate/cement ratio, and that there is a greater scatter of the results about the curves for each of the two mixes than for the longitudinal wave velocity-modulus of rupture curves.

Measurement of Poisson's ratio

Poisson's ratio may be obtained from observations of the longitudinal wave velocity (V) and the fundamental longitudinal resonance (n) on the same beam specimen when by equations (2), (3) and (4) :

$$\frac{V}{2\,nl} = \sqrt{\frac{1-\sigma}{(1-2\,\sigma)(1+\sigma)}} \qquad (5)$$

In order fully to justify the method measurements have been made on suitable metal beam specimens of known properties and the results were in very good agreement with values normally given (steel 0.28; brass 0.33).

Poisson's ratio has been determined from water-saturated beams at 28 days of 1 : $1\frac{1}{2}$: 3 and 1 : 3 : 6 mixes with different water/cement ratios and made with four different types of aggregate. Fig. 12 shows that there is an appreciable variation in Poisson's ratio with type and texture of the concrete and that the values obtained are somewhat higher than 1/6 which is often used [2]. Thus in calculating the dynamic modulus from equations (1) or (2) it is essential to know the value of Poisson's ratio otherwise it is possible to introduce appreciable errors by assuming a constant value.

Investigation of frost damage

A recent application of the supersonic method to concrete has been to investigate the development of cracks in laboratory specimens caused by successive freezing and thawing cycles. Velocity measurements have been made during one of the thawing cycles on cube specimens completely

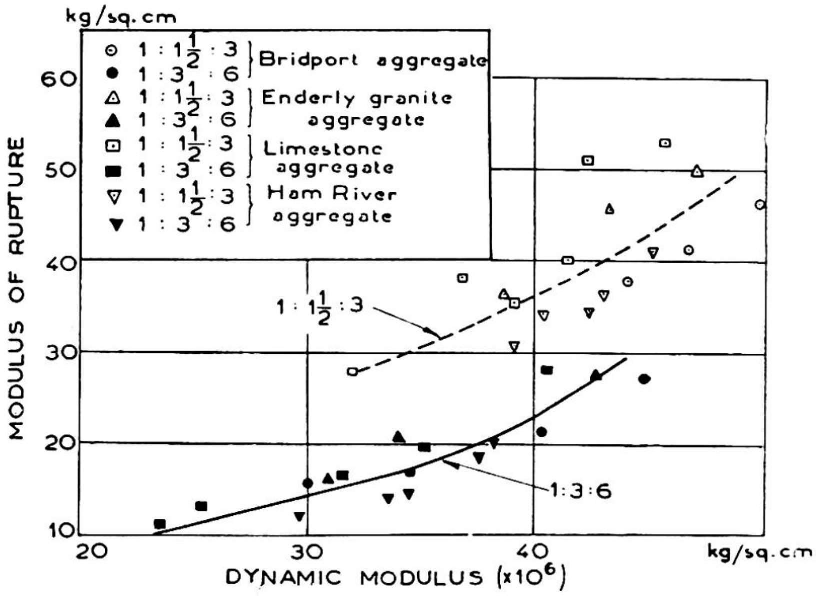

Fig. 11. Relation between the dynamic modulus and the modulus of rupture (third line loading).

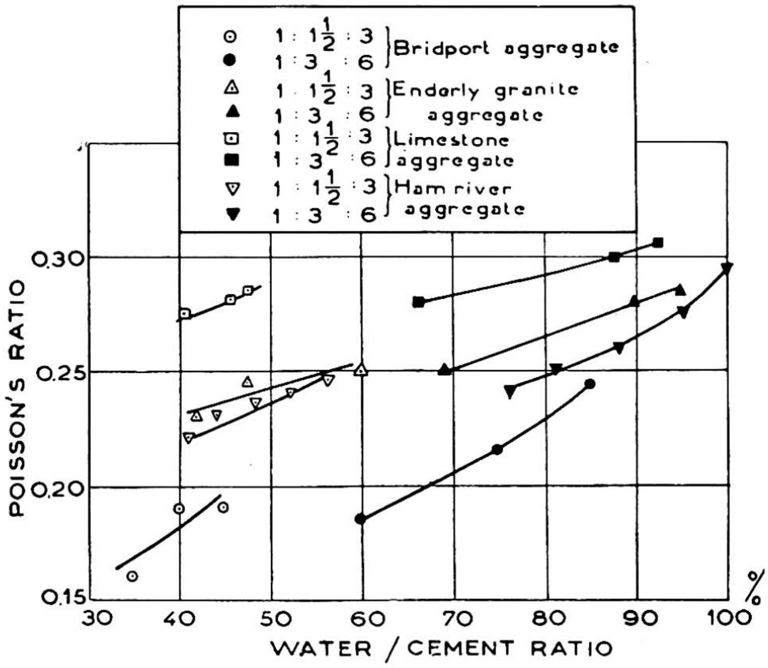

Fig. 12. Poisson's ratio of concrete made from different types of aggregate at an age of 28 days.

immersed in water after various numbers of freezing and thawing cycles. Table I illustrates the changes in velocity which occur at different positions on a cube.

Number of freezing and thawing cycles	Longitudinal wave velocity (km/sec)					
	Position 1	Position 2	Position 3	Position 4	Position 5	Position 6
0	4.50	4.47	4.47	4.45	4.43	4.43
5	4.36	4.33	4.34	4.27	4.27	4.24
10	4.24	4.20	4.21	3.67	3.51	3.35
15	4.16	3.96	4.00	3.21	2.67	2.30

TABLE I : *Variation of the longitudinal wave velocity in concrete during freezing and thawing tests*

It will be seen that the velocity decreases in a different manner at the different positions and whilst at position 1 the decrease after 15 cycles amounts to about 7 per cent, at position 6 the decrease is nearly 50 per cent. When large decreases in velocity occur the amplitude of the received signal is considerably reduced due to a greater attenuation of the supersonic pulse caused presumably by cracks opened up within the specimen.

The preliminary results obtained indicate that the method is likely to be of particular value in studying the internal rupture of superficially sound specimens.

The use of the longitudinal wave velocity as an index of concrete quality

It is not possible to obtain a unique figure to represent the quality of concrete : it is necessary to employ for its definition the results of physical tests which indicate the behaviour of the concrete under the relevant working conditions. Thus the quality of the concrete has often been based on its ultimate strength in compression or flexure and though neither quantity can be said to specify the concrete, they do provide a good indication of the quality of the mix. The inherent difficulty in determining the quality of concrete in situ lies mainly in the fact that test samples are not true samples of the mass of the concrete but are merely specially prepared samples of the concrete mix. Thus, if the concrete is poorly compacted, it is possible to obtain a poor quality concrete from a good quality mix, and in such cases strength tests on well compacted cubes from the same mix would not be representative of the concrete. It is considerations such as these which lead to the conclusion that a method applicable to the actual mass concrete is the only way to obtain reliable information as to its quality. There is obviously no type of strength test which will yield the requisite information on slabs in situ without damaging the slab, and it is therefore necessary to find a quantity which can be measured by non-destructive means and used as an index of quality. American workers have used the dynamic modulus for this purpose, but variations which have been found to occur in Poisson's ratio make the accurate determination of the modulus difficult except for laboratory specimens.

The longitudinal wave velocity is a quantity which can be determined directly in mass concrete and it is suggested that it can be used as an index of quality with certain limitations. For any concrete mix the longitudinal wave velocity can be used to indicate changes in quality of the concrete due to compaction or damage, but in order to relate, to a reasonable accuracy, the actual velocity results to values of the ultimate strength it is necessary to know the aggregate/cement ratio.

A great difficulty in applying the method to road slabs is to define the position of measurement on the slab. To determine the longitudinal wave velocity along the surface (2) does not give a representative value for the slabs as a whole but only for the relatively well compacted surface layers.

A method which has been tested entails the measurement of the thickness of the slab and also of the longitudinal wave velocity from observations on a pulse reflected from the bottom surface of the slab. The method presents numerous practical difficulties due to causes such as the back scatter of the energy from the inhomogeneities in the concrete and the interference by surface waves which make the relatively small-magnitude reflected pulse difficult to detect with certainty.

Another method has been suggested in which the velocity is measured at different depths in the slab between two small holes drilled through the concrete by a procedure similar to that used on laboratory specimens. This method would give useful information of the variation of concrete with depth but it has the disadvantage that some damage is done to the slab.

Further research is needed before non-destructive methods assume the nature of routine measurements on concrete in situ, but the importance of the results to be obtained makes the work of especial value.

Acknowledgements

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Résumé

Ce rapport donne la description d'une méthode qui a été utilisée pour déterminer la vitesse d'une onde longitudinale dans des éprouvettes de béton, en mesurant le temps nécessaire pour traverser une distance connue de béton par une onde à fréquence supersonique. Des résultats montrent la valeur spéciale de cette méthode pour l'étude des variations qui se produisent dans la composition de béton dans des éprouvettes de laboratoire.

La valeur de la vitesse d'une onde longitudinale comme indice de la qualité de béton est discutée à propos des essais exécutés sur diverses éprouvettes de béton soumises plus tard à des essais de compression et flexion, et aux déterminations de densité.

Zusammenfassung

Es wird eine Methode beschrieben, welche benutzt wurde, um die Longitudinalwellenlänge in Betonprobekörpern durch Messung der Zeit festzustellen, die ein Impuls supersonischer Frequenz braucht, um im Beton eine bestimmte Strecke zurückzulegen. Es werden Ergebnisse aufgezeigt, welche den besonderen Wert der Methode für das Studium von Unregelmässigkeiten in der Betonzusammensetzung innerhalb von Probekörpern demonstrieren.

Der Wert der Longitudinalwellenlänge als ein Gradmesser für die Qualität von Beton wird unter Berücksichtigung von Untersuchungen besprochen, die an verschiedenen Betonprobekörpern durchgeführt wurden, an denen nachher Druck- und Biegeproben und Dichtebestimmungen untersucht wurden.

Summary

A method is described which has been used to determine the velocity of longitudinal waves in concrete specimens by measuring the time taken for a supersonic pulse to travel through a known distance of concrete. Results are given which illustrate the use of the method for studying the variations occurring in concrete composition within laboratory specimens.

The value of the longitudinal wave velocity as an index of concrete quality is discussed with reference to tests made on a variety of concrete specimens subsequently subjected to compressive and flexural strength tests and density analysis.