8

The Ultrasonic Pulse Velocity Method

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The ultrasonic pulse velocity method has been used successfully to evaluate the quality of concrete for more than 60 years. This method can be used for detecting internal cracking and other defects as well as changes in concrete such as deterioration due to aggressive chemical environment and freezing and thawing. By using the pulse velocity method it is also possible to estimate the strength of concrete test specimens and in-place concrete.

The pulse velocity method is a truly nondestructive method, as the technique uses mechanical waves resulting in no damage to the concrete element being tested. A test specimen can be tested again and again at the same location, which is useful for monitoring concrete undergoing internal structural changes over a long period of time.

8.1 Historical Background

Concrete technologists have been interested in determining the properties of concrete by nondestructive tests for decades. Many test methods have been proposed for laboratory test specimens using vibrational methods beginning in the 1930s. Powers,[1] Obert,[2] Hornibrook,[3] and Thomson[4] were the first to conduct extensive research using vibrational techniques such as the resonant frequency method (see Chapter 7).

World War II accelerated research regarding nondestructive testing using stress wave propagation methods (see also Chapter 14 by Carino on stress wave propagation methods). The development of the pulse velocity method began in Canada and England at about the same time. In Canada, Leslie and Cheesman[5] developed an instrument called the soniscope. While in England, Jones[6] developed an instrument called the ultrasonic tester. In principle, both the soniscope and the ultrasonic tester were quite similar, with only minor differences in detail. Since the 1960s, pulse velocity methods have moved out of laboratories and to construction sites.[7] Malhotra[8] has compiled an extensive list of papers published on this subject. Many nations have adopted standardized procedures to measure pulse velocity in concrete.

8.2 Theory of Wave Propagation

Three types of propagating mechanical waves (also called stress waves) are created when the surface of a large solid elastic medium is disturbed by a dynamic or vibratory load: (1) compressional waves (also called longitudinal or P-waves), (2) shear waves (also called transverse or S-waves), (3) and surface waves (also called Rayleigh waves). The compressional waves propagate through the solid medium in a fashion analogous to sound waves propagating through air. Each wave type propagates with its characteristic velocity. For a given solid, compressional waves have the highest velocity and surface waves the lowest. In concrete, the velocities of the shear and surface waves are typically 60 and 55%, respectively, of the compressional wave velocity.[9] The particular velocity of a wave depends on the elastic properties and density of the medium. For elastic, homogeneous solid media the compressional wave velocity is given by the following:[9]

$$V = \sqrt{\frac{KE}{\rho}} \tag{8.1}$$

where

V = compressional wave velocity,
$K = (1 - \mu)/((1 + \mu)(1 - 2\mu))$
E = dynamic modulus of elasticity
ρ = density
μ = dynamic Poisson's ratio

The value of K varies within a fairly narrow range. For example, as μ increases from 0.15 to 0.25 (67% increase), the associated K value increases from 1.06 to 1.20 (12% increase). Thus, variations in E and ρ have a more significant effect on V than variations in μ. For concrete, V typically ranges from 3000 to 5000 m/s.

The frequency f and wavelength λ of propagating wave motion are related by the velocity of propagation: $V = f\lambda$. The frequency is reported in units of hertz (or cycles per second) and the wavelength in units of distance (e.g., mm). In a given medium, an increase in wave frequency therefore dictates a decrease in the wavelength, and vice versa. When a propagating wave pulse impinges on an interface with a medium having distinct material properties, a portion of the wave energy is scattered away from the original wave path (see also Chapter 14). For example, voids, cracks, and aggregate particles in concrete act to scatter some of the initial energy of the compressional wave pulse away from the original wave path. The magnitude of the scattering is especially intense if the wavelength of the propagating wave is the same size or smaller than the size of the scatterer, resulting in rapid wave attenuation.[10] For concrete, the upper limit of usable frequency is about 500 kHz as the associated wavelength is approximately 10 mm, which is in the size range of the coarse aggregate particles. As a result, the path length that can be effectively traversed at this upper limit of frequency before the wave pulse becomes completely scattered is only several centimeters. Greater path lengths can be traversed using lower frequencies (thus larger wavelengths): a frequency of 20 kHz can usually traverse up to 10 m of concrete.[10]

In the ultrasonic pulse velocity test method, an ultrasonic wave pulse through concrete is created at a point on the surface of the test object, and the time of its travel from that point to another is measured. Knowing the distance between the two points, the velocity of the wave pulse can be determined. Portable pulse velocity equipment is available today for concrete testing to determine the arrival time of the first wavefront. For most test configurations, this is the direct compressional wave, as it is the fastest wave.

8.3 Pulse Velocity Test Instrument

The test instrument consists of a means of producing and introducing a wave pulse into the concrete (pulse generator and transmitter) and a means of sensing the arrival of the pulse (receiver) and accurately measuring the time taken by the pulse to travel through the concrete. The equipment may also be connected to an oscilloscope, or other display device, to observe the nature of the received pulse. A schematic diagram is shown in Figure 8.1. A complete description is provided in ASTM Test Method C 597.[11]

Portable ultrasonic testing units are available worldwide. The equipment is portable, simple to operate, and may include a rechargeable battery and charging unit. Typically, pulse times of up to 6500 μs can be measured with 0.1-μs resolution. The measured travel time is prominently displayed. The instrument comes with a set of two transducers, one each for transmitting and receiving the ultrasonic pulse. Transducers with frequencies of 25 to 100 kHz are usually used for testing concrete. Transducer sets having different resonant frequencies are available for special applications: high-frequency transducers (above 100 kHz) are used for small-size specimens, relatively short path lengths, or high-strength concrete, whereas low-frequency transducers (below 25 kHz) are used for larger specimens and relatively longer path lengths, or concrete with larger size aggregates. These transducers primarily generate compressional waves at predominantly one frequency, with most of the wave energy directed along the axis normal to the transducer face. A commonly used instrument is shown in Figure 8.2.

8.4 The Pulse Velocity Method

The basic idea on which the pulse velocity method is established is that the velocity of a pulse of compressional waves through a medium depends on the elastic properties and density of the medium, as shown in Equation 8.1.

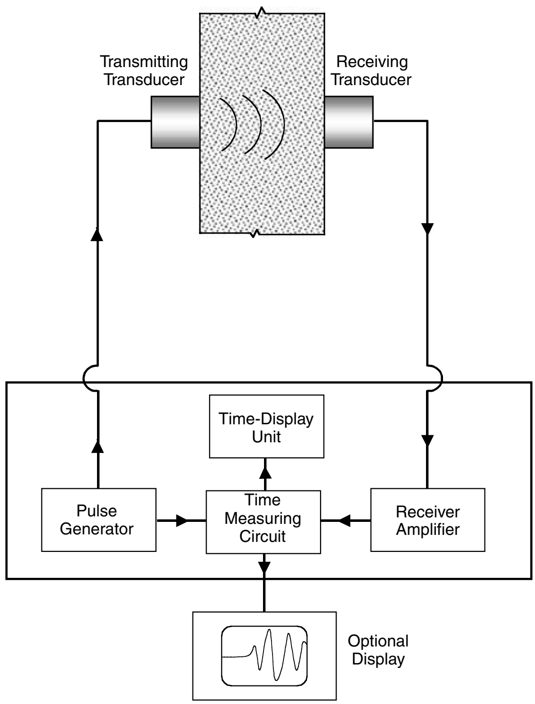

FIGURE 8.1 Schematic diagram of pulse velocity test circuit. (Adapted from Reference 11.)

FIGURE 8.2 Pulse velocity instrument. (Courtesy of James Instruments, Inc.)

The transmitting transducer of the pulse velocity instrument transmits a wave into the concrete and the receiving transducer, at a distance L, receives the pulse through the concrete at another point. The pulse velocity instrument display indicates the transit time, Δt, it takes for the compressional wave pulse to travel through the concrete. The compressional wave pulse velocity V, therefore, is

$$V = \frac{L}{\Delta t} \tag{8.2}$$

The compressional pulse transmitted through the concrete undergoes scattering at various aggregate–mortar boundaries. By the time the pulse reaches the receiving transducer it becomes transformed into a complex waveform, which contains multiply reflected compressional waves and shear waves. Of course, compression waves traveling the fastest arrive first at the receiver.

To transmit or receive the pulse, the transducers must be in full contact with the test object; otherwise an air pocket between the test object and transducer may introduce an error in the indicated transit time. This error is introduced because only a negligible amount of wave energy can be transmitted through air. Many couplants available in the market can be used to eliminate air pockets and to assure good contact; petroleum jelly has proved to be one of the superior couplants. Other couplants are grease, liquid soap, and kaolin-glycerol paste. The couplant layer should be as thin as possible. While applying constant pressure on the transducers, repeated readings at a particular location should be taken until a minimum value of transit time is obtained. If the concrete surface is very rough, thick grease should be used as a couplant. In some cases, the rough surface may have to be ground smooth, or a smooth surface may have to be established with the use of plaster of Paris or suitable quick-setting cement paste or quick-setting epoxy mortar. The leveling paste should be allowed to set before proceeding with the pulse velocity test. An exponential receiver probe with a tip diameter of only 6 mm may also be used to receive the pulse in very rough surfaces, e.g., locations where the surface mortar is scaled off due to fire or weathering action. It must be emphasized, however, that this probe is good only for receiving the signal. A smooth surface is still required for the transmitting transducer.

The pulse velocity for ordinary concrete is typically 3700 to 4200 m/s. Therefore, for a 300-mm path length, the travel time is approximately 70 to 85 μs. It is obvious that the instrument must be very accurate to measure such a short transit time. The path length should also be carefully measured. Because the pulse velocity method is a wave propagation technique, any sources creating even the slightest wave motion in the element under test (e.g., jackhammers) should be eliminated during the time of the test. Many other factors also affect the pulse velocity. They are discussed in detail in the next section.

There are three possible configurations in which the transducers may be arranged, as shown in Figure 8.3A to C. These are (1) direct transmission; (2) semidirect transmission; and (3) indirect or surface transmission. The direct transmission method, Figure 8.3A, is the most desirable and the most satisfactory

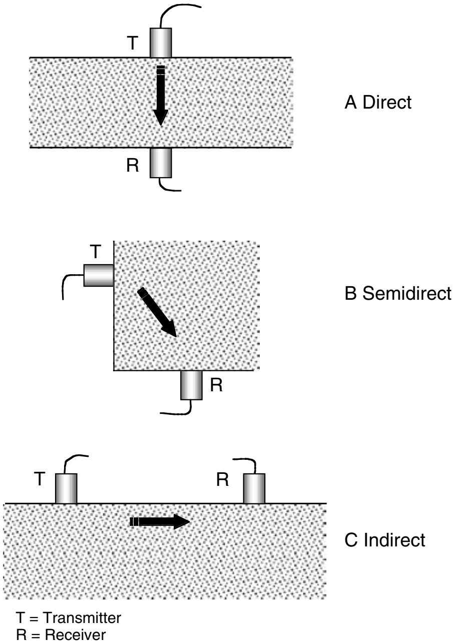

FIGURE 8.3 Pulse velocity measurement configurations. (A) Direct method. (B) Semidirect method. (C) Indirect surface method.

arrangement because maximum energy of the pulse is transmitted and received with this arrangement. The semidirect transmission method, Figure 8.3B, can also be used quite satisfactorily. However, care should be exercised that the transducers are not too far apart; otherwise the transmitted pulse might attenuate and a pulse signal might not be detected. This method is useful in avoiding concentrations of reinforcements. The indirect or surface transmission method, Figure 8.3C, is least satisfactory because the amplitude of the received signal is significantly lower than that received by the direct transmission method. This method is also more prone to errors and a special procedure may be necessary for determining the pulse velocity.[12] First, the location of the transmitting transducer is fixed and the receiver location is changed in fixed increments along a line, and a series of transit time readings are taken. The direct distance between the two transducers is plotted on the X-axis and the corresponding pulse transit time is plotted on the Y-axis (Figure 8.4). The inverse of the slope of this plot is the pulse velocity along the line.

When this surface method is used, the pulse propagates in the concrete layer near the surface. The near-surface concrete is sometimes of a composition slightly different from the concrete in the lower layer. For example, the concrete near the surface of a slab has higher amounts of fine materials than the concrete in the lower portion of the slab. Thus, velocities measured by the surface transmission method are typically lower than those measured with direct transmission. This behavior, however, can be turned into a means to detect and estimate the thickness of a layer of different quality material. A layer of lower quality concrete may occur due to improper construction practices (e.g., poor vibration and finishing, poor curing, cold joints due to delay, incorrect placement), damage due to weathering action (e.g., freezing and thawing, sulfate attack, and corrosion of reinforcement and other embedded items), and damage by fire. The layer thickness can be estimated by using the surface transmission procedure. When the two transducers are closer together, the fastest travel path is through the upper layer of concrete, and as the transducers are moved further apart, the fastest travel path is the combined path through both layers. The pulse velocity through the upper layer (V_1) and the lower layer (V_2) will be indicated on the plot by the different slopes of the two straight lines fitted to the data (Figure 8.4). The distance X in Figure 8.4 at which the change in these slopes occurs is measured and the thickness of the upper layer, t, is estimated from the following equation:[9]

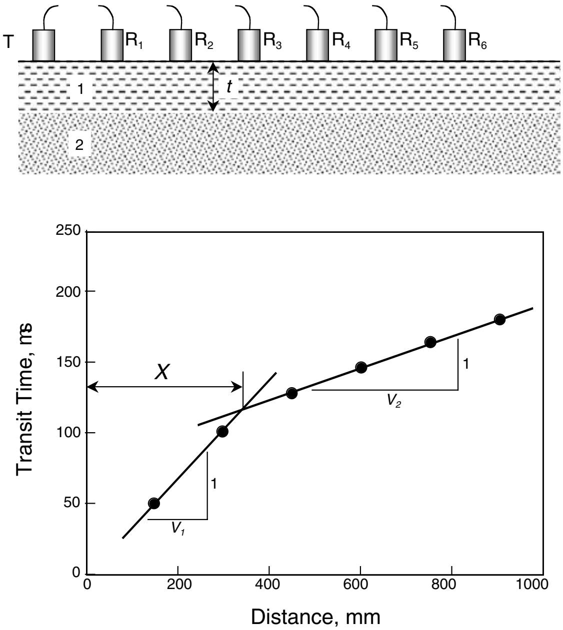

FIGURE 8.4 Use of surface method to determine depth of deterioration, *t*.

$$t = \frac{X}{2}\sqrt{\frac{V_2 - V_1}{V_2 + V_1}} \tag{8.3}$$

This method is only suitable when the upper layer (the poor-quality layer) is distinct, is of reasonably uniform thickness, and $V_2 > V_1$. Benedetti proposed a more realistic model for the interpretation of surface velocity measurements, which assumes a linear distribution of elastic modulus within a fire-damaged layer.[13]

8.5 Factors Affecting Pulse Velocity

Although it is relatively easy to conduct a pulse velocity test, it is important that the test be conducted such that the pulse velocity readings are reproducible and that they are affected only by the properties of the concrete under test rather than by other factors. The factors affecting the pulse velocity can be divided into two categories: (1) factors resulting directly from concrete properties; and (2) other factors. These influencing factors are discussed below.

8.5.1 Effects of Concrete Properties

8.5.1.1 Aggregate Size, Grading, Type, and Content

Many investigators have found that the pulse velocity is affected significantly by the type and amount of aggregate.[14–19] In general, the pulse velocity of cement paste is lower than that of aggregate. Jones[18] reported that for the same concrete mixture and at the same compressive strength level, concrete with rounded gravel had the lowest pulse velocity, crushed limestone resulted in the highest pulse velocity, and crushed granite gave a velocity that was between these two. On the other hand, type of aggregate had no significant effect on the relationship between the pulse velocity and the modulus of rupture. Additional test results by Jones,[10] Bullock and Whitehurst,[14] and Kaplan[20] indicate that at the same strength level the concrete having the higher aggregate content gave a higher pulse velocity. The effects of varying

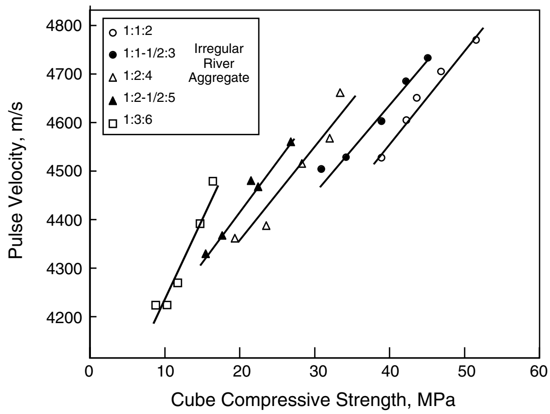

FIGURE 8.5 Effect of cement:fine aggregate:coarse aggregate proportions on the relationship between pulse velocity and compressive strength. (Adapted from Reference 10.)

the proportion of coarse aggregate in a concrete mixture on the pulse velocity vs. compressive strength relationship are shown in Figure 8.5.[10] The figure shows that for a given value of pulse velocity, the higher the aggregate–cement ratio, the lower the compressive strength.

8.5.1.2 Cement Type

Jones[18] reported that the type of cement did not have a significant effect on the pulse velocity. The rate of hydration, however, is different for different cements and it will influence the pulse velocity. As the degree of hydration increases, the modulus of elasticity will increase and the pulse velocity will also increase. The use of rapid-hardening cements results in higher strength for a given pulse velocity level.[21]

8.5.1.3 Water–Cement Ratio

Kaplan[20] studied the effect of water- cement (*w/c*) ratio on the pulse velocity. He has shown that as the *w/c* increases, the compressive and flexural strengths and the corresponding pulse velocity decrease assuming no other changes in the composition of the concrete.

8.5.1.4 Admixtures

Air entrainment does not appear to influence the relationship between the pulse velocity and the compressive strength of concrete.[18] Other admixtures will influence the pulse velocity in approximately the same manner as they would influence the rate of hydration. For example, the addition of calcium chloride will reduce the setting time of concrete and will increase the rate by which the pulse velocity increases.

8.5.1.5 Age of Concrete

The effect of age of concrete on the pulse velocity is similar to the effect on the strength development of concrete. Jones[18] reported the relationship between the pulse velocity and age. He showed that velocity increases very rapidly initially but soon flattens. This trend is similar to the strength vs. age curve for a particular type of concrete, but pulse velocity reaches a limiting value sooner than strength. He further concluded that once the pulse velocity curve flattens, experimental errors make it impossible to estimate the strength with accuracy.[10]

8.5.2 Other Effects

8.5.2.1 Transducer Contact

The influence of improper transducer contact was discussed in Section 8.4. If sufficient care is not exercised in obtaining a good contact (e.g., inconsistent pressure applied to transducers), an incorrect pulse velocity reading may result.

8.5.2.2 Temperature of Concrete

Temperature variations between 5 and 30∂C have been found to have an insignificant effect on the pulse velocity.[21] For temperatures beyond this range, the corrections in Table 8.1 are recommended.[22]

8.5.2.3 Moisture and Curing Condition of Concrete

The pulse velocity for saturated concrete is higher than for air-dry concrete. Moisture generally has less influence on the velocity in high-strength concrete than on low-strength concrete because of the difference in the porosity.[21] A 4 to 5% increase in pulse velocity can be expected when dry concrete with high w/c ratio is saturated.[10] Kaplan[23] found that the pulse velocity for laboratory-cured specimens were higher than for site-cured specimens. He also found that pulse velocity in columns cast from the same concrete were lower than in the site-cured and laboratory-cured specimens.

8.5.2.4 Path Length

Theoretically the path length traveled by the wave and the frequency of the wave (which is the same as the frequency of the transducer) should not affect the propagation time; therefore, they should not affect the pulse velocity. However, in practice, smaller path lengths tend to give more variable and slightly higher pulse velocity because of the inhomogeneous nature of concrete.[10] RILEM[24] has recommended the following minimum path lengths:

1. 100 mm for concrete having maximum aggregate size of 30 mm
2. 150 mm for concrete having maximum aggregate size of 45 mm

8.5.2.5 Size and Shape of a Specimen

In most cases, the pulse velocity is not dependent on the size and the shape of a specimen. However, Equation 8.1 is valid only for a medium having an infinite extent. This requirement is easily satisfied for a finite-dimension test specimen by requiring that the smallest lateral dimension of the specimen be greater than the wavelength of the pulse. For concrete having a pulse velocity of about 3700 m/s and for a transducer frequency of 54 kHz, the wavelength is about 68 mm. Therefore, a specimen made from this concrete, when tested with a transducer having a frequency of 54 kHz, should have a minimum lateral dimension of 70 mm. If the least lateral dimension of this specimen is less than 70 mm, then Equation 8.1 may not be an accurate relationship, especially for longer path lengths. For such situations, it would be advisable to use a higher-frequency transducer, thus reducing the wavelength and the corresponding least lateral dimension requirement. The maximum size aggregate should also be smaller than the wavelength; otherwise, the wave energy will attenuate to the point that no clear signal may be detected at the receiving transducer. RILEM[24] recommendations for least lateral dimension and corresponding maximum size aggregate are given in Table 8.2.

8.5.2.6 Level of Stress

Pulse velocity is generally not affected by the level of stress in the element under test. However, when the concrete is subjected to a very high level of static or repeated stress, say, 65% of the ultimate strength or greater, microcracks develop within the concrete, which will reduce the pulse velocity considerably.[25,26]

TABLE 8.1 Corrections for Pulse Velocity Due to Temperature Changes

	Correction (%)	
Concrete Temperature (∂C)	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

Source: From BS 1881 Part 203, 1986.

TABLE 8.2 Frequency of Transducer vs. Least Lateral Dimension

Minimum Frequency of Transducer (kHz)	Smallest Lateral Dimension (or Max. Size Aggregate) (mm)	Range of Path Length (mm)
60	70	100–700
40	150	200–1500
20	300	>1500

Source: From RILEM Recommendation NDT1, Paris, Dec. 1972.

8.5.2.7 Presence of Reinforcing Steel

One of the most significant factors that influences the pulse velocity of concrete is the presence of steel reinforcement. The pulse velocity in steel is 1.4 to 1.7 times the pulse velocity in plain concrete. Therefore, pulse velocity readings in the vicinity of reinforcing steel are usually higher than that in plain concrete. Whenever possible, test readings should be taken such that the reinforcement is avoided in the wave path. If reinforcements cross the wave path, correction factors should be used. The correction factors that are used are those recommended by RILEM[23] and British Standards.[22] Appendix 8.1 provides specific information about the correction factors. Chung[27,28] has demonstrated the importance of including bar diameters as a basic parameter in the correction factors. However, the RILEM recommendations involve only two basic parameters: the pulse velocity in the surrounding concrete and the path lengths within the steel and concrete. Bungey[29] also provides correction factors that include bar diameters. It should be emphasized, however, that in heavily reinforced sections it might not be possible to obtain accurate measurements of the concrete pulse velocity.

8.6 Standardization of the Pulse Velocity Method

Many nations have developed standardized procedures to measure pulse velocity. Several standards are compared by Komlos et al.[30] In the United States, ASTM Committee C09 initiated the development of a standard for pulse velocity in the late 1960s. A tentative standard was issued in 1968. A standard test method was issued in 1971 and no significant changes have been made in the standard since then.[11] The Significance and Use statement of the test method, as given in the ASTM C 597-02, is as follows:[11]

> The pulse velocity, V, of longitudinal stress waves in a concrete mass is related to its elastic properties and density according to the following relationship (see also Equation 8.1):
>
> $$V = \sqrt{\frac{E(1-\mu)}{\rho(1+\mu)(1-2\mu)}} \tag{8.4}$$
>
> where
>
> E = dynamic modulus of elasticity
> μ = dynamic Poisson's ratio
> ρ = density
>
> This test method is applicable to assess the uniformity and relative quality of concrete, to indicate the presence of voids and cracks, and to evaluate the effectiveness of crack repairs. It is also applicable to indicate changes in the properties of concrete, and in the survey of structures, to estimate the severity of deterioration or cracking.* When used to monitor changes in condition over time, test locations are to be marked on the structure to ensure that tests are repeated at the same positions.

*Naik, T.R. Evaluation of an 80-Year-Old Concrete Dam, paper presented at the ACI meeting in Seattle, WA, October 1987 (available from the UWM Center for By-Products Utilization, University of Wisconsin–Milwaukee).

The degree of saturation of the concrete affects the pulse velocity, and this factor must be considered when evaluating test results. In addition, the pulse velocity in saturated concrete is less sensitive to changes in its relative quality.

NOTE 1 — The pulse velocity of saturated concrete may be up to 5% higher than in dry concrete.

The pulse velocity is independent of the dimensions of the test object provided reflected waves from boundaries do not complicate the determination of the arrival time of the directly transmitted pulse. The least dimension of the test object must exceed the wavelength of the ultrasonic vibrations.

[NOTE 2 is omitted because it is not relevant to the significance and use of the pulse velocity method.]

The accuracy of the measurement depends upon the ability of the operator to determine precisely the distance between the transducers and of the equipment to measure precisely the pulse transit time. The received signal strength and measured transit time are affected by the coupling of the transducers to the concrete surfaces. Sufficient coupling agent and pressure must be applied to the transducers to ensure stable transit times. The strength of the received signal is also affected by the travel path length and by the presence and degree of cracking or deterioration in the concrete tested.

NOTE 3 — Proper coupling can be verified by viewing the shape and magnitude of the received waveform. The waveform should have a decaying sinusoidal shape. The shape can be viewed by means of outputs to an oscilloscope or digitized display inherent in the device.

The results obtained by the use of this test method are not to be considered as a means of measuring strength nor as an adequate test for establishing compliance of the modulus of elasticity of field concrete with that assumed in the design. The longitudinal resonance method in Test Method C 215 is recommended for determining the dynamic modulus of elasticity of test specimens obtained from field concrete because Poisson's ratio does not have to be known.

NOTE 4 — When circumstances permit, a velocity-strength (or velocity-modulus) relationship may be established by the determination of pulse velocity and compressive strength (or modulus of elasticity) on a number of samples of a concrete. This relationship may serve as a basis for the estimation of strength (or modulus of elasticity) by further pulse-velocity tests on that concrete. Refer to ACI 228.1R for guidance on the procedures for developing and using such a relationship.

The procedure is applicable in both field and laboratory testing regardless of size or shape of the specimen within the limitations of available pulse-generating sources.

Since the pulse velocity in steel could be up to double that in concrete, the pulse velocity measured in the vicinity of the reinforcing steel will be higher than in plain concrete of the same composition. Where possible, avoid measurements close to steel parallel to the direction of pulse propagation.

8.7 Applications

The pulse velocity method has been applied successfully in the laboratory as well as in the field.[31–48] Furthermore, it can be used for quality control, as well as for the analysis of deterioration. Figure 8.6 illustrates the application of the pulse velocity method on a concrete structure.

8.7.1 Estimation of Strength of Concrete

The pulse velocity method may provide a means of estimating the strength of both *in situ* and precast concrete although there is no physical relation between the strength and velocity. The strength can be estimated from the pulse velocity by a pre-established graphical correlation between the two parameters, an example of which is shown in Figure 8.7. The relationship between strength and pulse velocity is not unique, and is affected by many factors, e.g., aggregate size, type, and content; cement type and content;

FIGURE 8.6 Application of pulse velocity technique on a concrete structure. (Courtesy of James Instruments, Inc.)

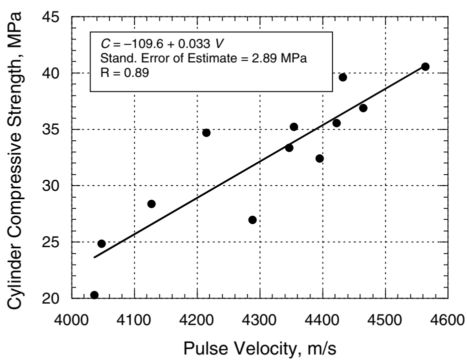

FIGURE 8.7 Example strength vs. velocity relationship for estimation of strength of concrete.

water–cement ratio; and moisture content. The effect of such factors has been studied by many researchers.[15,17,20,23] They have clearly pointed out that no attempts should be made to estimate compressive strength of concrete from pulse velocity values unless similar correlations have been previously established for the type of concrete under investigation. RILEM,[24] the British Standard,[22] and American Concrete Institute (ACI)[49] provide recommended practices to develop the relationship between pulse velocity and compressive strength, which can be later used for estimating the *in situ* strength based on the pulse velocity. Phoon et al.[50] recently proposed a probabilistic model to predict compressive strength from ultrasonic pulse velocity. By using the model together with field data, a consistent statistical quality assurance criterion may be established.

8.7.2 Establishing Homogeneity of Concrete

The pulse velocity method is suitable for the study of homogeneity of concrete, and, therefore, for relative assessment of quality of concrete. Heterogeneity is defined as interior cracking, deterioration, honeycombing, and variations in mixture proportions. Heterogeneities in a concrete member will cause variations in the pulse velocity. For example, the diffraction of a wave pulse around an internal air void will cause an increase in the time of propagation for an assumed path through the void center. Thus, the apparent velocity will decrease. However, only large voids, generally larger than the transducer contact face, will cause measurable reduction in velocity.[10] Also, *in situ* concrete strength varies in a structure because of the variations in source and proportions of materials, uniformity of mixing, and due to inadequate or variable consolidation. The pulse velocity method is highly effective in establishing comparative data and for qualitative evaluation of concrete. For obtaining these qualitative data, a system of measuring points, i.e., a grid pattern, may be established. Depending on the quantity of the concrete to be evaluated, the size of the structure, the variability expected, and the accuracy required, a grid of 300 mm spacing, or greater, should be established. Generally about 1 m spacing may be adequate depending on the thickness of the element being tested. Other applications of this qualitative comparison of *in situ* or test specimen concrete are (1) to check the variation of density of concrete to evaluate the effectiveness of consolidation; (2) for locating areas of honeycombed concrete; and (3) localizing internal cracks and voids.

Researchers[18,34–37,51,52] have reported results of carefully conducted surveys for determining the homogeneity of concrete in various types of structures. Of many such surveys carried out on existing structures, one that deserves mention is that reported in 1953 by Parker[34] of the Hydro-Electric Power Commission of Ontario, Canada. The survey was made on a dam built in 1914. A total of 50,000 readings were taken, most of them with 300-mm spacings. The pulse velocities measured on the structure ranged from below 1525 to over 5185 m/s, and these values were used, with success, to determine areas of advanced deterioration. Rhazi et al.[51] report the use of multiple velocity data to map subsurface anomalies within a concrete gravity retaining wall built in the 1940s. Olson and Sack[52] report the use of multiple velocity data to successfully assess the condition of larger concrete structures. Some thousands of pulse velocity measurements have been made on 29 concrete dams during the period of 1948 to 1965. McHenry and Oleson[37] cite ten of these case histories in which velocity measurements have been a valuable supplement to other observations for settling questions regarding repair or maintenance of dams.

8.7.3 Studies on the Hydration of Cement

The pulse velocity method has the advantage that it is truly nondestructive. Therefore, changes in the internal structure of concrete can be monitored on the same test specimen. Many researchers have published information on successful application of the pulse velocity method for monitoring the setting and hardening process of cement paste, mortar, and concrete.[7,18,38–42,53,54] The method is particularly useful for detecting changes during the first 36 h after adding water to the concrete mixture. A very significant practical use of the method is the evaluation of the rate of setting for different types of cements or admixtures to be used for a given project.

Whitehurst[41] reported results of tests on 102 ¥ 102 ¥ 406-mm concrete prisms, using various types of cement. The concretes used had zero slump and, immediately after casting, the end plates of the forms were removed. Pulse velocity tests using the soniscope were made periodically, from shortly after the specimens were cast until 8 h or more had elapsed. Initial velocities of the order of 1220 m/s were observed, and during the first few hours the velocities increased at a rapid rate. After periods varying from $4^{1}/_{2}$ to $8^{1}/_{2}$ h, the rate of increase suddenly changed and continued at a much slower pace. The point at which this occurred was taken as the time of setting of concrete. The results of Whitehurst,[41] together with those reported by Cheesman,[42] are shown in Figure 8.8.

8.7.4 Studies on Durability of Concrete

Aggressive environments will damage the structure of concrete and decrease the pulse velocity. Deterioration caused by freezing and thawing, sulfate exposure, alkali-silicate reactivity, and corrosion of embedded items can be detected by the pulse velocity method and have been studied by various investigators.[5,18,38,43,55,56] Progressive deterioration of either a test specimen or *in situ* concrete can be monitored by conducting repetitive tests on the same concrete element. Deterioration of concrete due to fire exposure has also been investigated by the pulse velocity method.[13,28,44]

8.7.5 Measurement of Surface Crack Depth

This aspect of the pulse velocity technique has been studied by various researchers.[5,45–48] As indicated earlier, the ultrasonic pulse transmits a very small amount of energy through air. Therefore, if a pulse

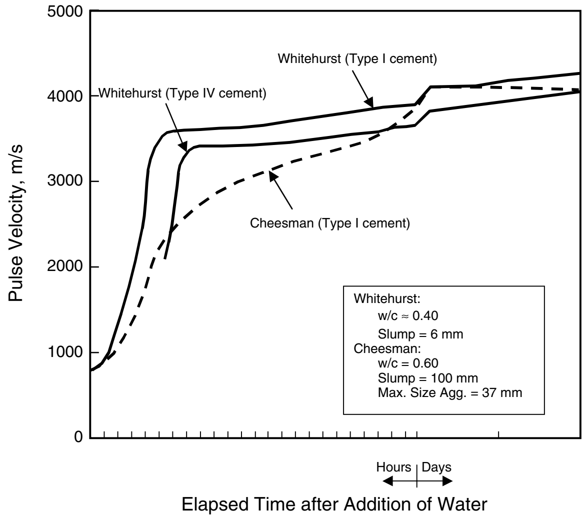

FIGURE 8.8 Relationship between pulse velocity and setting of concrete. (Adapted from References 41 and 42.)

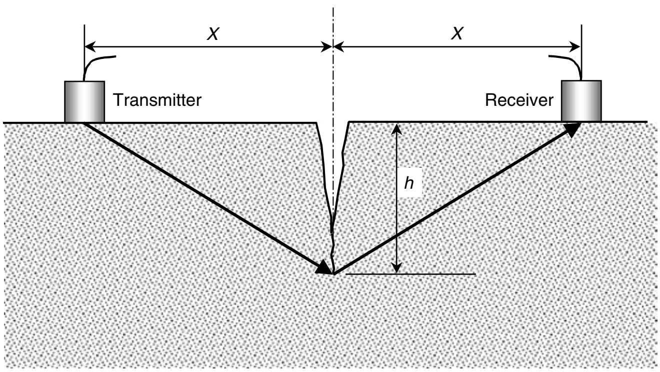

FIGURE 8.9 Scheme for measurement of surface crack depth, *h*.

traveling through the concrete comes upon an air-filled crack or a void whose projected area perpendicular to the path length is larger than the area of the transmitting transducer, the pulse will diffract around the defect. Thus, the pulse travel time will be greater than that through similar concrete without any defect. The pulse velocity method, therefore, is effective in characterizing surface cracks. It should be pointed out that the application of this technique in locating flaws has serious limitations. For example, if cracks and flaws are small or if they are filled with water or other debris thus allowing the wave to propagate through the flaw, or if the crack tip is not well defined, the pulse velocity will not significantly decrease, implying that no flaw exists.

The depth of an air-filled surface crack can be estimated by the pulse velocity method as shown in Figure 8.9. The depth, *h*, is given by Equation 8.5:

$$h = \frac{X}{T_2}\sqrt{T_1^2 - T_2^2} \tag{8.5}$$

where

X = distance to the transducer from the crack (note that both transducers must be placed equidistant from the crack)

T_1 = transit time around the crack
T_2 = transit time along the surface of the same type of concrete without any crack (note that the surface path length for T_1 and T_2 must be equal)

It should be pointed out that for Equation 8.5 to be valid, the crack must be perpendicular to the concrete surface. A check should be made to determine if the crack is perpendicular to the surface or not. This can be done as follows.[24] Place both transducers equidistant from the crack and obtain the transit time. Move each transducer, in turn, away from the crack. If the transit time decreases, then the crack slopes toward the direction in which the transducer was moved.

8.7.6 Determination of Dynamic Modulus of Elasticity

The velocity of a compressional wave traveling through an elastic material is uniquely defined by the elastic constants and density of the material by wave propagation theory (see Equation 8.1). Therefore, it is possible to compute the modulus of elasticity of a material if the ultrasonic pulse velocity is measured where the values of Poisson's ratio and density are known or assumed. This approach has an advantage over other standardized techniques, which make use of vibration frequencies, in that the testing is not restricted to specially shaped laboratory specimens. Several researchers report the estimation of dynamic (low-strain) modulus of elasticity from pulse velocity measurements in concrete.[5,7,31,32] Nevertheless, the estimation of the dynamic modulus of elasticity in concrete from ultrasonic pulse velocity measurements is not normally recommended for two reasons: (1) the error resulting from inaccurate estimation of Poisson's ratio is not insignificant and (2) Equation 8.1 is appropriate for homogeneous materials only, leaving the validity for inhomogeneous composite materials, such as concrete, in doubt.[31,57] Usually, the dynamic modulus of elasticity estimated from pulse velocity measurements is higher than that obtained from vibration measurements, even when the value of Poisson's ratio is known.[31]

8.8 Advantages and Limitations

The pulse velocity method is an excellent means for investigating the uniformity of concrete. The test procedure is simple and the available equipment in the market is easy to use in the laboratory as well as in the field.

The testing procedures have been standardized by ASTM and other organizations, and test equipment is available from several commercial sources. With the availability of small portable digital instruments, which are relatively inexpensive and easy to operate, ultrasonic testing adds a new dimension to quality control of concrete in the field.

Ultrasonic pulse velocity tests can be carried out on both laboratory-sized test specimens and concrete structures. This fact, combined with the knowledge that ultrasonic techniques provide an effective means of delineating both surface and internal cracks in concrete structures, enhances the usefulness of these tests.

Inasmuch as a large number of variables affect the relations between the strength parameters of concrete and its pulse velocity, the use of the latter to estimate the compressive and/or flexural strengths of concrete is not recommended unless previous correlation testing has been performed.

Appendix 8.1: 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 compressional pulse velocity in steel is 1.4 to 1.7 times that 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 on 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.[22,24,29]

Axis of Reinforcing Bar Perpendicular to Direction of Propagation

The 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 Q_i ($i = 1$ to n) directly in the path of the pulse, with their axes perpendicular to the path of propagation (see Figure 8.10A), then[22]

$$\frac{V_c}{V} = 1 - \frac{L_s}{L}\left(1 - \frac{V_c}{V_s}\right) \tag{8.6}$$

where

V = the pulse velocity in the reinforced concrete, i.e., the measured pulse velocity
V_c = the pulse velocity in the plain concrete
V_s = the pulse velocity in the steel
L = the total path length

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

Values of V_c/V are given in Table 8.3 for different amounts of steel in three types of concrete, which could be rated as very poor, fair, and very good materials, respectively.

In practice V_c/V is likely to be slightly higher than values given in Table 8.3 because of misalignment of the reinforcing bars and because only a small fraction of the pulse energy will actually traverse the full diameter of each bar.

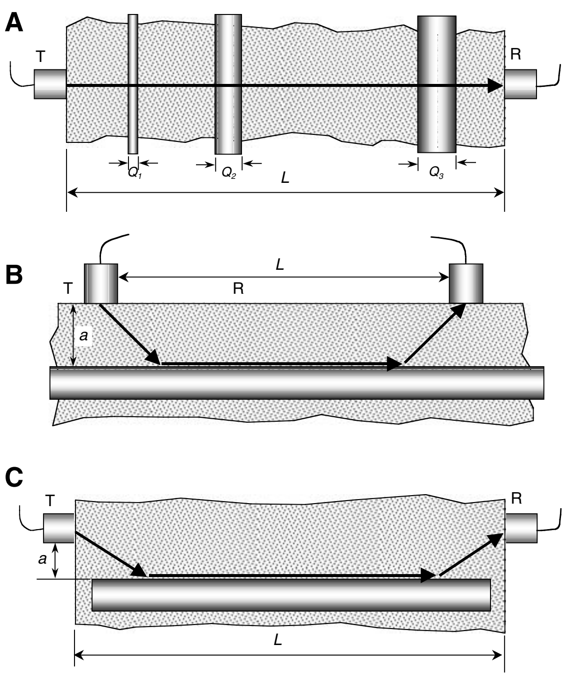

FIGURE 8.10 Measurements on reinforced concrete. (A) Reinforcing bar perpendicular to direction of propagation. (B) Reinforcing bar parallel to test surface. (C) Reinforcing bar parallel to direction of propagation.

TABLE 8.3 Influence of Steel Reinforcement — Line of Measurement Perpendicular to Axis of Bar

$$\frac{V_c}{V} = \frac{\text{pulse velocity in plain concrete}}{\text{measured pulse velocity in reinforced concrete}}$$

L_s/L	Very poor quality, $V_c = 3000$ m/s	Fair quality, $V_c = 4000$ m/s	Very good quality, $V_c = 5000$ 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

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 Figure 8.10B or C is[22]

$$T = \frac{L}{V_s} + 2a\sqrt{\frac{V_s^2 - V_c^2}{V_s V_c}} \tag{8.7}$$

for

$$\frac{a}{L} \le \frac{1}{2}\sqrt{\frac{V_s - V_c}{V_s + V_c}} \tag{8.8a}$$

There is no influence of the steel when[22]

$$\frac{a}{L} > \frac{1}{2}\sqrt{\frac{V_s - V_c}{V_s + V_c}} \tag{8.8b}$$

The difficulty of applying Equations 8.7 and 8.8 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 in the steel bar. The value for V_s is likely to be between about 5900 m/s (i.e., the compressional wave velocity in steel) and 5200 m/s (i.e., the bar velocity* in steel).

Corrections to the measured pulse velocity in the direction parallel to the reinforcement are given in Table 8.4. This table also indicates that, for bars that 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.

Two-Way Reinforcement

Steel reinforcement in two or more directions complicates the interpretation of pulse velocity measurements. Corrections based on Table 8.3 and Table 8.4 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.

*A guided wave is likely to set up and to propagate along the length of a long cylindrical bar. This “bar wave” has a lower velocity than the compressional wave.

TABLE 8.4 Influence of Steel Reinforcement — Line of Measurements Parallel to Axis of Bar

$$\frac{V_c}{V} = \frac{\text{pulse velocity in plain concrete}}{\text{measured pulse velocity in reinforced concrete}}$$

a/L	$\frac{V_c}{V_s} = 0.90$	$\frac{V_c}{V_s} = 0.80$	$\frac{V_c}{V_s} = 0.71$	$\frac{V_c}{V_s} = 0.60$
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

References

1. Powers, T.C., Measuring Young's modulus of elasticity by means of sonic vibrations, *Proc. ASTM*, 38(Part II), 460, 1938.
2. Obert, L., Sonic method of determining the modulus of elasticity of building materials under pressure, *Proc. ASTM,* 39, 987, 1939.
3. Hornibrook, F.B., Application of sonic method to freezing and thawing studies of concrete, *ASTM Bull.,* 101, 5, 1939.
4. Thomson, W.T., Measuring changes in physical properties of concrete by the dynamic method, *Proc. ASTM,* 40, 1113, 1940.
5. Leslie, J.R. and Cheesman, W.J., An ultrasonic method of studying deterioration and cracking in concrete structures, *ACI J. Proc.,* 46(1), 17, 1949.
6. Jones, R., *The Application of Ultrasonic to the Testing of Concrete,* Research, London, 1948, 383.
7. Whitehurst, E.A., *Evaluation of Concrete Properties from Sonic Tests,* ACI Monograph 2, American Concrete Institute, Detroit, MI, 1966, 94 pp.
8. Malhotra, V.M., *Testing Hardened Concrete: Nondestructive Methods,* ACI Monograph 9, American Concrete Institute, Detroit, MI, 1976.
9. ACI Committee 228, *Nondestructive Test Methods for Evaluation of Concrete in Structures,* ACI 228.2R-98, American Concrete Institute, Farmington Hills, MI, 1998.
10. Jones, R., *Non-Destructive Testing of Concrete*, Cambridge University Press, London, 1962.
11. ASTM Test Designation C 597-02, Standard Test Method for Pulse Velocity through Concrete, *Annual Book of ASTM Standards*, Vol. 04.02, West Conshohocken, PA, 2003.
12. Qixian, L. and Bungey, J.H., Using compression wave ultrasonic transducers to measure the velocity of surface waves and hence determine dynamic modulus of elasticity for concrete, *Constr. Build. Mater.*, 10(4), 237, 1996.
13. Benedetti, A., On the ultrasonic pulse propagation into fire damaged concrete, *ACI Struct. J.*, 95(3), 259, 1998.
14. Bullock, R.E. and Whitehurst, E.A., Effect of certain variables on pulse velocities through concrete, *Highway Res. Board Bull.,* 206, 37, 1959.
15. Sturrup, V.R. Vecchio, R.J., and Caratin, H., *Pulse Velocity as a Measure of Concrete Compressive Strength,* ACI SP 82-11, American Concrete Institute, Farmington Hills, MI, 1984, 201.
16. Swamy, N.R. and Al-Hamed, A.H., The use of pulse velocity measurements to estimate strength of air-dried cubes and hence *in situ* strength of concrete, Malhotra, V.M., Ed., ACI SP 82, American Concrete Institute, Farmington Hills, MI, 1984, 247.
17. Anderson, D.A. and Seals, R.K., Pulse velocity as a predictor of 28 and 90 day strength, *ACI J.,* 78, 116, 1981.

18. Jones, R., Testing of concrete by an ultrasonic pulse technique, RILEM Int. Symp. on Nondestructive Testing of Materials and Structures, Paris, Vol. 1, Paper No. A-17 January 1954, 137. *RILEM Bull.*, 19(Part 2), Nov. 1954.
19. Popovics, S., Rose, J.L., and Popovics, J.S. The behavior of ultrasonic pulses in concrete, *Cem. Concr. Res.*, 20, 259, 1990.
20. Kaplan, M.F., The effects of age and water to cement ratio upon the relation between ultrasonic pulse velocity and compressive strength of concrete, *Mag. Concr. Res.*, 11(32), 85, 1959.
21. Jones, R. and Facaoaru, I., Recommendations for testing concrete by the ultrasonic pulse method, *Mater. Struct. Res. Testing* (Paris), 2(19), 275, 1969.
22. BS 1881, Part 203, Recommendations for Measurement of Velocity of Ultrasonic Pulses in Concrete, British Standards Institution, London, 1986.
23. Kaplan, M.F., Compressive strength and ultrasonic pulse velocity relationships for concrete in columns, *ACI J.,* 29(54-37), 675, 1958.
24. RILEM Recommendation NDT 1, Testing of concrete by the ultrasonic pulse method, Paris, Dec. 1972.
25. Popovics, S. and Popovics, J.S., Effect of stresses on the ultrasonic pulse velocity in concrete, *RILEM Mater. Struct.*, 24, 15, 1991.
26. Wu, T.T and Lin, T.F., The stress effect on the ultrasonic velocity variations of concrete under repeated loading, *ACI Mater. J.*, 95(5), 519, 1998.
27. Chung, H.W., Effect of embedded steel bar upon ultrasonic testing of concrete, *Mag. Concr. Res.* (London), 30(102), 19, 1978.
28. Chung, H.W. and Law, K.S., Diagnosing *in situ* concrete by ultrasonic pulse technique, *Concr. Int.,* 42, Oct. 1983.
29. Bungey, J.H., *The Influence of Reinforcement on Ultrasonic Pulse Velocity Testing*, Malhotra, V.M., Ed., ACI SP 82, American Concrete Institute, Farmington Hills, MI, 1984, 229.
30. Komlos, K., Popovics, S., Nurnbergerova, T., Babal, B., and Popovics, J.S., Ultrasonic pulse velocity test of concrete properties as specified in various standards, *Cem. Concr. Composites*, 18, 357, 1996.
31. Philleo, R.E., Comparison of results of three methods for determining Young's modulus of elasticity of concrete. *ACI J.,* 26(5), 461, 1955. Discussions, 472-1, Dec. 1955.
32. Goodell, C.E., Improved sonic apparatus for determining the dynamic modulus of concrete specimens, *ACI J.,* 27(47-4), 53, 1950.
33. Galan, A., Estimate of concrete strength by ultrasonic pulse velocity and damping constant, *ACI J.,* 64(64-59), 678, 1967.
34. Parker, W.E., Pulse velocity testing of concrete, *Proc. ASTM,* 53, 1033, 1953.
35. Whitehurst, E.A., Soniscope tests concrete structures, *ACI J. Proc.,* 47(6), 433, 1957.
36. Breuning, S.M. and Bone, A.J., Soniscope applied to maintenance of concrete structures, *Proc. Highway Res. Board,* 33, 210, 1954.
37. McHenry, D. and Oleson, C.C. Pulse velocity measurements on concrete dams, in *Trans. 9th Int. Congr. on Large Dams,* Istanbul, 1967, Q34, R5, V. 3, 73.
38. Chefdeville, J., Application of the method toward estimating the quality of concrete, *RILEM Bull.* 15, Paris, Special Issue-Vibration Testing of Concrete, Part 2, Aug., 59. 1953.
39. Van der Winder, N.G.B. and Brant, A.W., *Ultrasonic Testing for Fresh Mixes,* Concrete, Cement and Concrete Association, Wexham Springs, U.K., 1977, 25.
40. Woods, K.B. and McLaughlin, J.F., Application of pulse velocity tests to several laboratory studies of materials, *Highway Res. Board Bull.,* 206, 1959.
41. Whitehurst, E.A., Use of soniscope for measuring setting time of concrete, *Proc. ASTM,* 51, 1166, 1951.
42. Cheesman, W.J., Dynamic testing of concrete with the soniscope apparatus, *Proc. Highway Res. Board,* 29, 176, 1949.
43. Neville, A.M., A study of deterioration of structural concrete made with high alumina concrete, *Proc. Inst. Civ. Eng.* (London), 25, 287, 1963.

44. Zoldners, N.G., Malhotra, V.M., and Wilson, H.S., High-temperature behavior of aluminous cement concretes containing different aggregates, *Proc. ASTM,* 63, 966, 1963.
45. Sturrup, V.R., Evaluation of pulse velocity tests made by Ontario hydro, Bull. 206, Highway Research Board, 1959, 1.
46. Jones, R., A method of studying the formation of cracks in a material subjected to stress, *Br. J. Appl. Phys.* (London), 3, 229, 1952.
47. Knab, L.J., Blessing, G.V., and Clifton, J.R., Laboratory evaluation of ultrasonics for crack detection in concrete, *ACI J.,* 80, 17, 1983.
48. Rebic, M.P., The distribution of critical and rupture loads and determination of the factor of crackability, *ACI J.,* 80, 17, 1983.
49. ACI Committee 228, *In-Place Methods to Estimate Concrete Strength*, ACI 228.1R-95, American Concrete Institute, Farmington Hills, MI, 1995.
50. Phoon, K.K., Wae, T.H. and Loi, C.S., Development of statistical quality assurance criterion for concrete using ultrasonic pulse velocity method, *ACI Mater. J.*, 96(5), 568, 1999.
51. Rhazi, J. Kharrat, Y., Ballivy, G., and Rivest, M., Application of acoustical imaging to the evaluation of concrete in operating structures, S. Pessiki and L. Olson, Eds., ACI SP 168, American Concrete Institute, Farmington Hills, MI, 1997, 221.
52. Olson, L.D. and Sack, D.A., Nondestructive evaluation of concrete dams and other structures, *Proc. SPIE* (The International Society for Optical Engineering), 2457, 113, 1995.
53. Keating, J., Hannant, D.J., and Hibbert, A.P., Correlation between cube strength, ultrasonic pulse velocity and volume change for oil well cement slurries, *Cem. Concr. Res.*, 19, 714, 1989.
54. Sayers, C.M. and Dahlin, A., Propagation of ultrasound through hydrating cement pastes at early times, *J. Adv. Cem. Based Mater.*, 1, 12, 1993.
55. Bungey, J.H., Ultrasonic testing to identify alkali-silica reaction in concrete, *Br. J. NDT*, 33(5), 227, 1991.
56. Selleck, S.F., Landis, E.N., Peterson, M.L., Shah, S.P., and Achenbach, J.D., Ultrasonic investigation of concrete with distributed damage, *ACI Mater. J.*, 95(1), 27, 1998.
57. Neville, A.M., *Properties of Concrete*, 4th ed., John Wiley & Sons, New York, 1996, 63.