HIGHWAY RESEARCH BOARD
Bulletin 206

Effects of Concrete Characteristics on the Pulse Velocity--a Symposium

National Academy of Sciences—
National Research Council
publication 639

HIGHWAY RESEARCH BOARD

Bulletin 206

Effects of Concrete Characteristics on the Pulse Velocity--a Symposium

PRESENTED AT THE
Thirty-Seventh Annual Meeting
January 6-10, 1958

1959

Washington, D. C.

Department of Materials and Construction

R. R. Litehiser, Chairman
Engineer of Tests, State Highway Testing Laboratory
Ohio State University, Columbus

CONCRETE DIVISION

K. F. Wendt, Chairman
Dean of Engineering
University of Wisconsin, Madison

R. T. Healy, Vice Chairman
Engineer of Materials
Connecticut State Highway Department, Portland

COMMITTEE ON DYNAMIC TESTS OF CONCRETE

R. E. Philleo, Chairman
Office of the Chief of Engineers
Civil Works Engineering Division, Department of the Army

Truman R. Jones, Jr., Associate Research Engineer, Texas Transportation Institute, Texas A and M College, College Station
Clyde E. Kesler, Department of Theoretical and Applied Mechanics, University of Illinois, Urbana
B. R. Laverty, Senior Civil Engineer, Southern California Edison Company, Los Angeles
John F. McLaughlin, Joint Highway Research Project, Purdue University, Lafayette, Indiana
Bryant Mather, Waterways Experiment Station, Jackson, Mississippi
R. C. Meyer, State Highway Commission of Kansas, Topeka
Leonard J. Mitchell, Engineering Laboratory Division—Concrete Branch, U. S. Bureau of Reclamation, Denver
Leonard Obert, Chief, Applied Physics Laboratory, Bureau of Mines, College Park, Maryland
C. C. Oleson, Principal Research Engineer, Portland Cement Association, Chicago
Gerald Pickett, Professor of Mechanics, University of Wisconsin, Madison
Thomas Reichard, Building Technology Division, National Bureau of Standards
V. R. Sturrup, Assistant Engineer, Hydro-Electric Power Commission of Ontario, Toronto
Rudolph C. Valore, Director of Research, Texas Industries, Inc., Dallas
E. A. Whitehurst, Director, Tennessee Highway Research Program, University of Tennessee, Knoxville

Contents

Evaluation of Pulse Velocity Tests Made by Ontario Hydro

V. R. STURRUP, Research Division, The Hydro-Electric Power Commission of Ontario

The soniscope was developed primarily as a non-destructive meth-of for following the cracking behaviour in concrete gravity dams by pulse velocity techniques. Internal cracks are detected by an abnormal increase in transmission time and/or reduction in pulse amplitude. The depths of surface cracks are determined by measuring the time required for a pulse of sound to travel around these cracks. Subsequently, a relationship was established between pulse velocity and the quality of concrete which has made it possible to assess the relative condition of structures. Consequently, having established datum pulse velocity measurements, the progress of deterioration in both field structures and laboratory specimens is followed by repetitive tests. While no well-defined correlation between pulse velocity and 28-day strength has been established as yet by this laboratory, the soniscope has been used to some extent to follow strength development of concrete at early ages. Limited success was also achieved in using pulse velocity techniques to study the setting behaviour of concrete.

Like most test equipment, the soniscope is subject to certain limitations and possible errors. Knowledge of these should not discourage its use but provide a better understanding of the apparatus and thereby permit a more intelligent interpretation of results. Pulse velocity is found to increase when specimens are saturated and a further significant increase in velocity is observed when these specimens are frozen. Large quantities of reinforcing steel near and parallel to the transmission path, also influence the results of pulse velocity measurements. The best assurance for reducing the possible errors to a minimum and obtaining the most from the equipment, is a competent operator capable of using sound judgement in the interpretation of the results.

THE SONISCOPE has been used by the Ontario Hydro for the evaluation of the condition of concrete structures for the past several years. This instrument was developed primarily as a rapid, non-destructive method for detecting the presence of internal cracks and to measure the depth and follow the behaviour of surface cracks in mass concrete structures. Subsequently, it was discovered that pulse velocity varied in different locations of a structure and from specimen to specimen in laboratory concrete. From this was established a general relationship between pulse velocity and quality which has been used extensively in the evaluation of concrete structures, for outlining areas of probable deterioration as well as to follow the advance of such deterioration by repetitive measurements.

The soniscope has been adequately described in earlier papers (1, 2) and the purpose of this paper is to present a general review of the application and interpretation of pulse velocity measurements as conducted by Ontario Hydro. In addition to crack investigations and the assessment of quality and deterioration, attempts have been made to correlate pulse velocity with compressive strength and to follow the setting behaviour and strength development of fresh concrete. In addition, limited data are presented concerning the effect of certain variables and possible errors on pulse velocity measurements. It is hoped that the data presented will contribute in some small way to the general fund of knowledge and assist in a better understanding of the apparatus and interpretation of results.

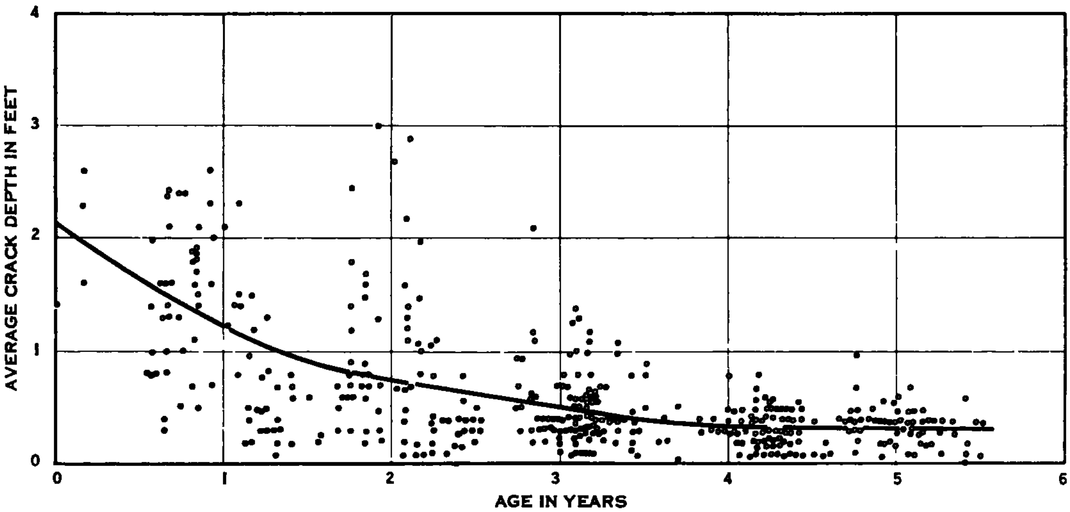

Figure 1. Crack depth vs age.

Measurement and Detection of Cracks

In view of the Ontario Hydro's technique of placing concrete in lifts up to 50 ft, a practice viewed with mixed feelings by other organizations, an extensive investigation was undertaken to study the cracking behaviour of their mass concrete structures. Leslie and Cheesman (1) found that high frequency sound would not cross an air-filled crack and thereby established the basic principle of crack detection by ultrasonics. Accordingly, large internal cracks could be detected by an abnormally long transmission time and/or a large decrease in the amplitude of the sound pulses. Likewise, by measuring the time required for sound to travel around a surface crack and the pulse velocity in adjacent, sound concrete, the depth of a surface crack could be determined.

Before adopting the pulse velocity method for crack depth determinations, the results were compared with measurements on the same cracks by the dye-injection method. Good correlation was obtained between the two methods and because of speed and convenience, crack depth measurements have since been made exclusively with the soniscope.

Since early 1949, periodic surface crack surveys have been conducted on all of the Commission's new gravity structures. The main cracks studied were those appearing on the downstream face of the dams and these measurements were taken by a man lowered down the face of the dam in a bosun's chair. Attempts were also made to measure cracks appearing in the inspection tunnels but due to the concentration of steel in these regions, the measurements were of doubtful validity.

In general, cracks examined shortly after form removal were found to have an average depth of 2 ft. However, repetitive measurements disclosed that these became gradually shallower with time until after a period of 5 years, when they averaged only 4 in. in depth (Fig. 1).

Concurrent with the surface crack surveys, pulse velocity measurements were made through the interiors of the dams to establish whether or not they were free of internal cracks. Due to the limiting range of the soniscope (50 ft), however, these measurements were restricted to about the upper third of most structures. Although the inspection tunnels provided limited access to the lower and more critical portions near the foundation, these regions could not be completely studied. This restriction was overcome at one location by drilling two vertical 6-in. holes 40 and 80 ft from the upstream face of the dam. Two special transducers that would operate in these holes were constructed thereby permitting pulse velocity measurements to be made the total depth of the dam. These measurements disclosed only a relatively small zone immediately below one construction joint suggestive of thermal cracking but not considered as a threat to the stability of the structure.

No claims are made for high precision, particularly with the measurement of crack depths, since it must be assumed that (a) the path of the crack is normal to the surface of the concrete and (b) no foreign substance is bridging the gap between the walls of the crack. It is felt, however, that the apparatus will differentiate between deep and shallow cracks as well as detect internal cracks large enough to cause significant increases in the transmission time or abnormal reduction in pulse amplitude. On the basis of the soniscope investigations on these structures, therefore, it was concluded that there were no cracks that posed a threat to the stability of the structures and that surface cracks tend to become shallower with time and after a period of three to four years they average less than half a foot in depth.

Condition Surveys of Structures

The soniscope has been used in assessing the condition of many of the Commission's structures as well as some owned by other organizations. Situations that required investigation have included frost damage at early ages, exposure to fire and natural deterioration resulting over a period of years. The most extensive survey undertaken was on a slab and buttress dam built in 1914. Pulse velocity measurements were made on every foot of all slabs and buttresses resulting in over 48,000 test points. With this close spacing of readings, it was possible to plot velocity "contours" and thereby outline and classify the zones of deterioration.

The pulse velocity readings were grouped into four ranges: under 5,000, 5,000 - 10,000, 10,000 - 12,000, and over 12,000 fps. Low velocity areas, those in which the values fell below 10,000 fps are shown in Figure 2. Since low velocity measurements do not reveal the exact nature of the trouble but may reflect either a low modulus in the material or a long transmission path introduced by internal cracking, 2-in. diameter cores were removed from the structure for additional study. The locations selected for sampling were chosen to permit comparisons of zones representing the full range of pulse velocity values. Compressive strength values were made on all

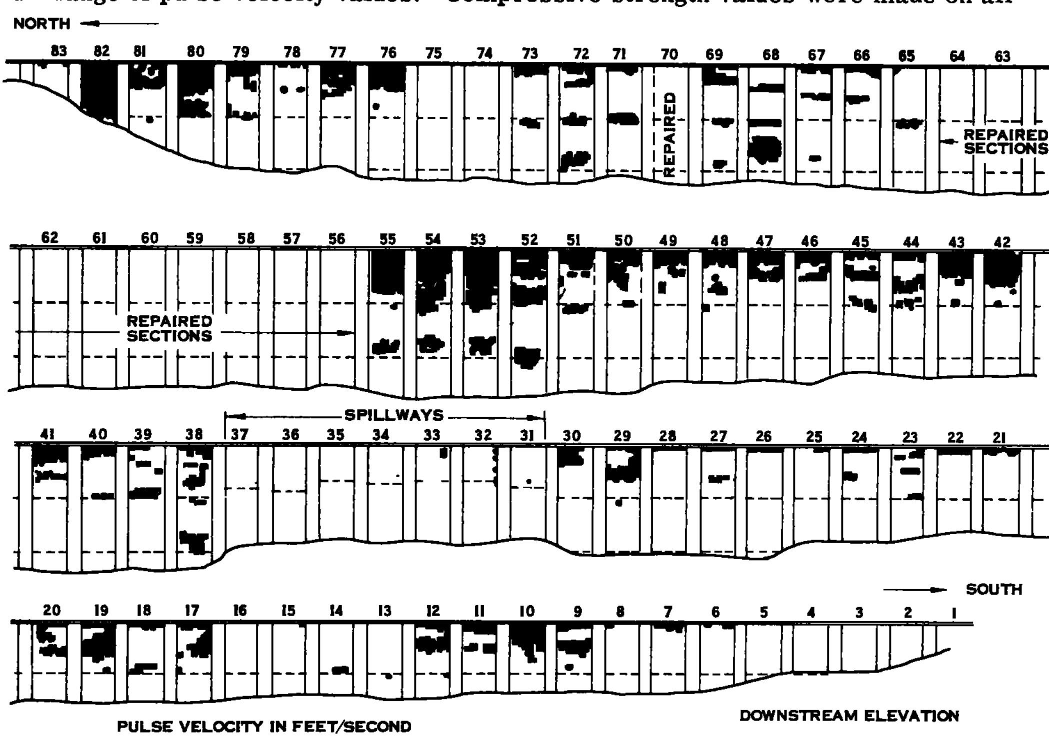

Figure 2. Soniscope tests on slab and buttress dam.

specimens of suitable length; however, due to the poor condition of the concrete in the low velocity regions, it was not possible to obtain suitable test specimens in such zones. Thus, while a pulse velocity-strength relationship was obtained (Fig. 3) this was confined to concrete above 2, 000 psi and 10, 000 fps, the range of relatively good concrete and where strength discrimination is difficult. On the other hand, drilling observations and core recovery correlated very well with pulse velocities. In areas where the velocity was below 5,000 fps, concrete was weak and could not be cored and no samples were obtained. Between 5,000 and 10,000 fps, only three cores suitable for testing were recovered. The core recovery corresponding to velocities above 12,000 fps was extremely good.

As a further evaluation of the soniscope, pulse velocity measurements were compared with an index of drilling resistance. During the coring operation, drilling resistance was arbitrarily assessed and divided into three categories, high, medium and low. Each hole was rated in accordance with the number of inches of the three types of resistance encountered in twelve inches of drilling. Data for holes not drilled the full 12 in. were suitably adjusted. High resistance was arbitrarily established as three units of resistance per inch and medium and low resistance two and one units, respectively. Ratings therefore, ranged from a low of 12 for 12 in. of low resistance to 36 for 12 in. of high resistance. The ratings were plotted against the corresponding pulse velocity readings for the concrete in-situ (Fig. 4). It was noted that a reasonable correlation was obtained.

Subsequent to the initial survey, 6 slabs were selected for repetitive measurement to provide a general picture of the progress of deterioration. In the over-all analysis of the results, over a period of 5 years, limited extensions of the low velocity zones were observed (Fig. 5) as well as a progressive reduction in pulse velocity. Apart from this general trend, a point-by-point study of the measurements revealed a number of discrepancies due in part to possible misalignment of the transducers, incorrect calculation of path length and normally poor reproducibility in deteriorated concrete. These sources of possible error are covered more completely in a later section.

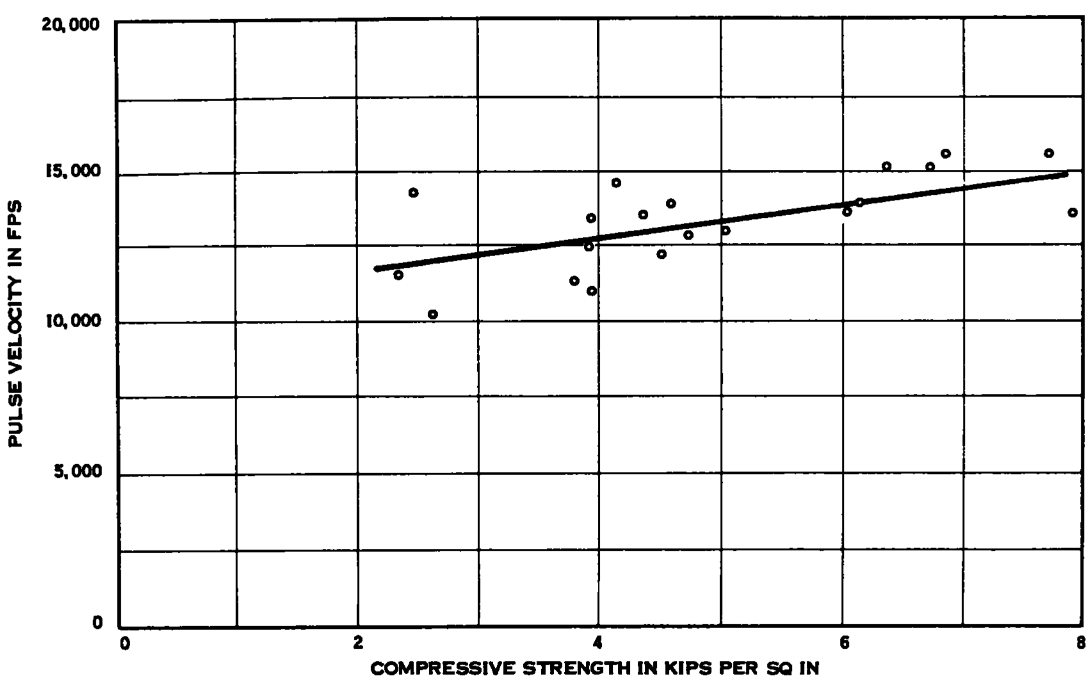

Figure 3. Pulse velocity vs compressive strength for 2-in. diameter cores from 40 year old dam.

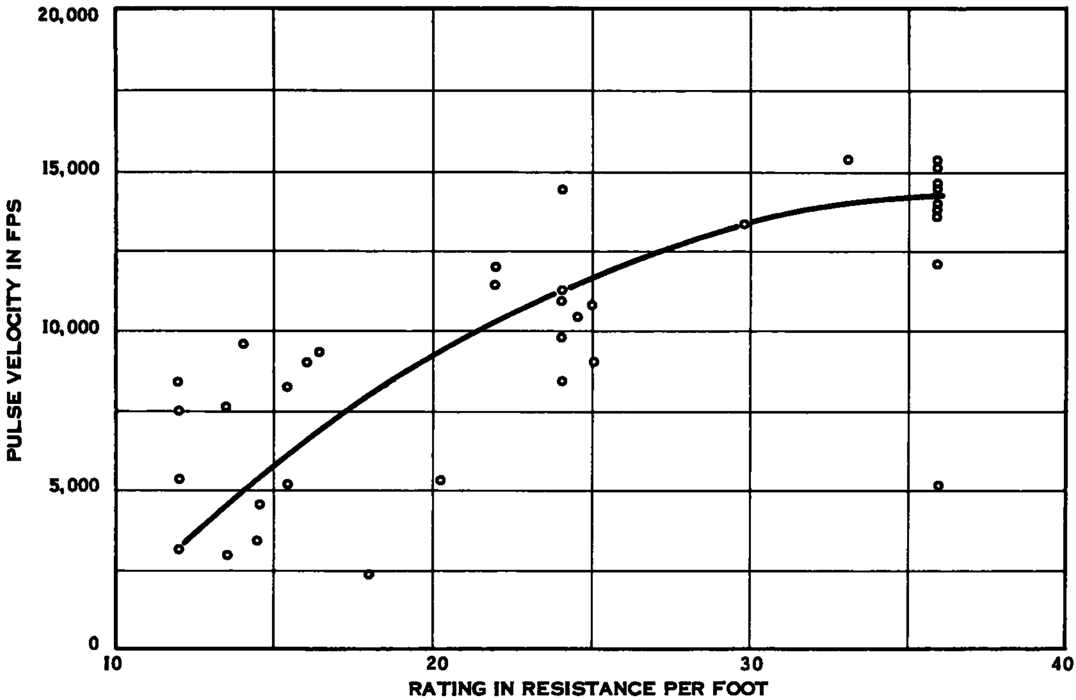

Figure 4. Pulse velocity vs drilling resistance in 40 year old dam.

Strength Development

Early re-use of formwork or discontinuance of curing and protective measures are often necessary from an economic point of view. The rate at which concrete develops strength is generally the limitng factor in such operations. Accordingly, the ability to follow non-destructively the strength development in a structure is often desirable.

Such a problem arose recently in connection with the tunnel concreting at the Commission's new Sir Adam Beck Generating Station at Niagara Falls, Ontario. There it

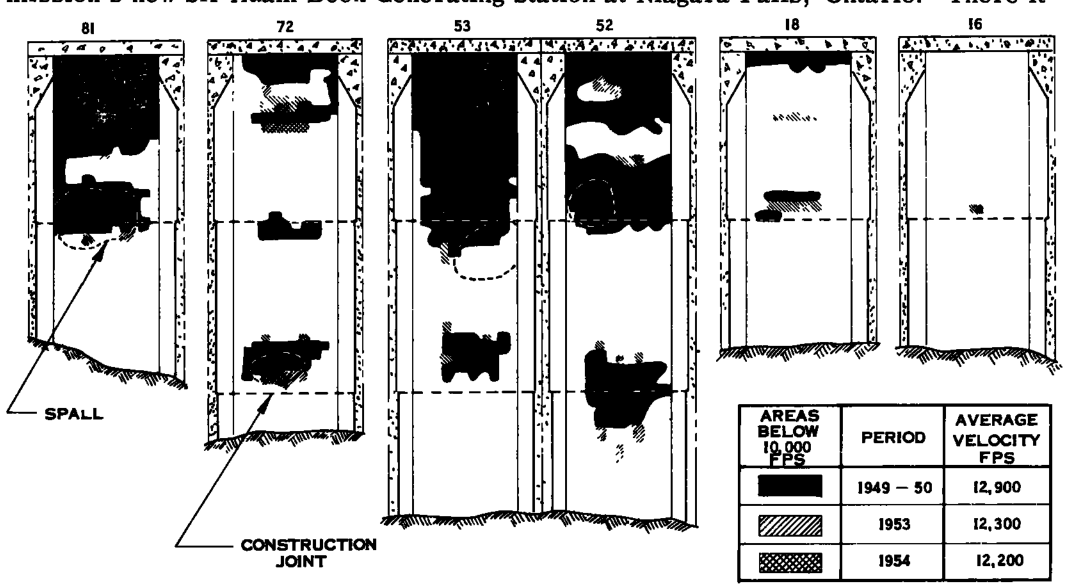

Figure 5. Soniscope tests on slab and buttress dam.

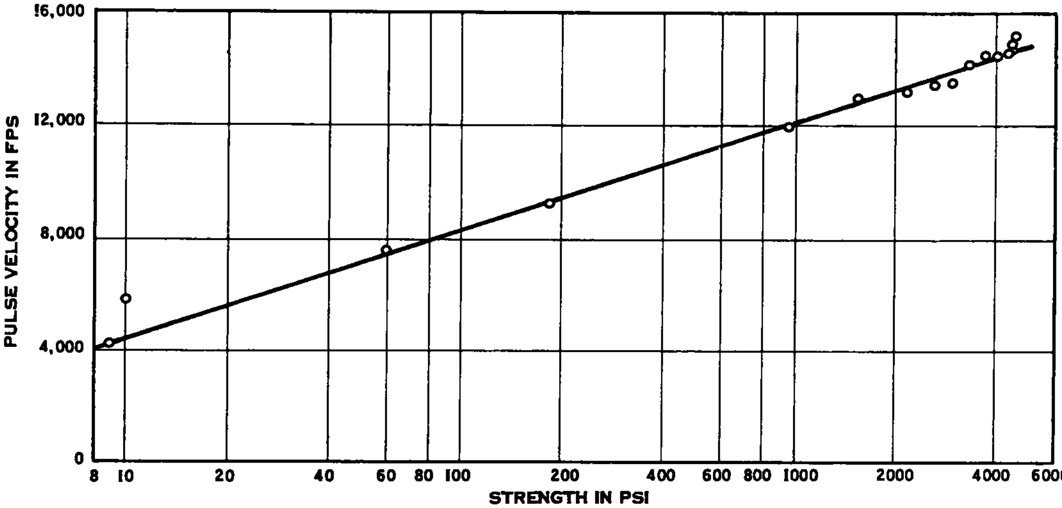

Figure 6. Pulse velocity vs strength, aluminous cement concrete.

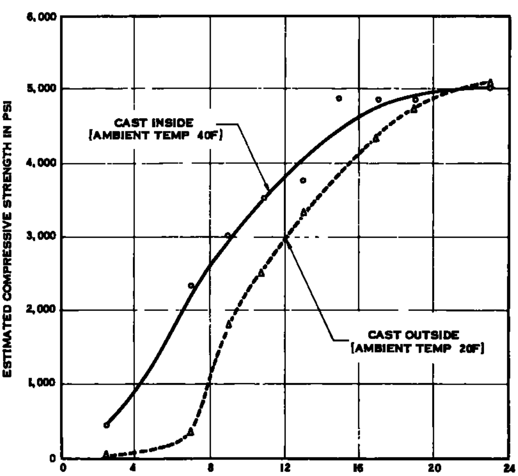

Figure 7. Estimated strength vs age, aluminous cement concrete (mixed and placed at 50 F).

was required that the concrete attain adequate strength to permit stripping of the steel forms at the age of twelve hours. During the test program, considerable data were obtained relating pulse velocity and strength. These data were previously reported by Parker (4) who demonstrated that this relationship between pulse velocity and strength would be practical at levels below 1,000 or 1,500 psi where variations would not be likely to exceed a few hundred pounds per square inch. At the higher strengths, however, the possible errors could exceed 1,000 psi and such variation would be too large to predict strength with sufficient accuracy.

In a later investigation (5), the soniscope was used to study means of facilitating winter construction of tower footings in remote northerly locations. Preliminary tests in the laboratory established the pulse velocity-strength relationship shown in Figure 6 for an aluminous cement concrete using job materials. Two test slabs, using these materials, were cast and cured under field conditions. Both slabs were protected by insulation but one was cast inside a tent where the average foundation temperature was 40 F while the other was cast outside where the foundation temperature averaged 20 F. For comparison, companion slabs, using a high-early-strength cement and 2 percent calcium chloride, were similarly prepared and cured. From the pulse velocity measurements on the aluminous cement specimens, which were started as early as 3½ hours after casting, the age-strength relationship shown in Figure 7 was established. However, it was not possible to transmit through the HES specimens under these conditions, until they had reached an age of 18 hr. Further indication of the superiority of the aluminous cement in this application was provided by an examination of specimens removed from the slabs 4 days after casting. This revealed that fractures, which occurred in the specimens during removal, were confined to the mortar in the HES concrete but in the aluminous cement concrete were also through the aggregate. Portions of rock adhering to the bottom of the latter specimens also illustrated the excellent bond that existed between the concrete and the foundation.

This last example has demonstrated a practical application of the soniscope in providing quantitative data on the behaviour of these materials under actual field conditions where other testing methods would have been impossible and only limited qualitative information could have been obtained.

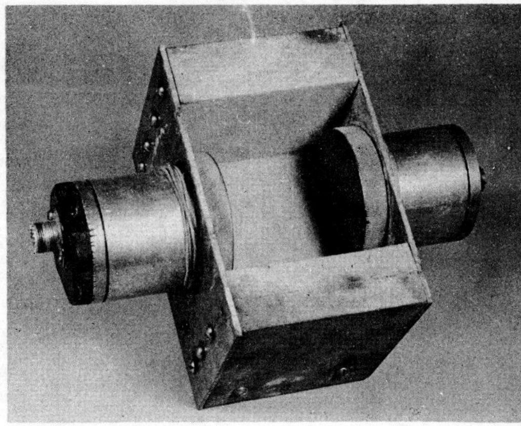

Figure 8. Specimen mould for studying setting behaviour of concrete.

Pulse Velocity vs Strength

The previous investigations, while demonstrating reasonably good correlation between pulse velocity and strength at early ages, have also shown that pulse velocity is an insensitive index of strength at higher levels. Further confirmation of this was provided by soniscope measurements on more than 200 standard test specimens immediately before they were tested in compression. Although a relationship did exist, it was not sufficiently precise to allow the accurate prediction of compressive strength.

In condition surveys of structures in service, most soniscope operators have been requested, at one time or another, to predict the compressive strength of the concrete on the basis of pulse velocity measurements. This, of course, is generally impossible, not only because of the relatively poor relationship between pulse velocity and strength in in mature concrete but also the effect of the various ingredients of the concrete on these properties. Similarly, it has been shown that pulse velocity measurements are greatly influenced by either a cracking condition in the structure or a low modulus concrete, whereas compressive strength is a poor indication of these conditions.

Setting Behaviour of Concrete

In view of the relationship established between pulse velocity and age of concrete by these previous tests, as well as work done by Whitehurst (6), Jones (7) and others, it seemed only natural that pulse velocity techniques should be used to study the setting behaviour of concrete. Although the accuracy of soniscope measurements decreases as the path length is shortened, early tests showed that a short path length is necessary in plastic concrete due to the high attenuation of the signal strength. Hence, a special mold (Fig. 8) was made for such studies. This consisted of rubberized cork sides and steel end plates in which the transducers were set. It was therefore possible to make pulse velocity measurements immediately after the concrete was placed. This procedure did, however, limit the number of specimens that could be tested at any one time. Figure 9 shows the velocity vs age relationship for several batches of a high early strength concrete mix. It was observed that the pulse velocity remained steady at values between 1, 000 and 2, 000 fps for approximately 1½ hr and then, at a time closely coinciding with the time of set (Vicat) of the cement, abruptly began to increase at a constant rate. Eventually another change in slope of the curve was observed, but this was gradual, often poorly defined and varied from specimen to specimen. While these tests seem to give a good picture of the actual hardening process in the concrete they do dispel any idea that "final set" is a well-defined condition.

Effect of Reinforcing Steel

Since the velocity of sound in steel is somewhat higher than in concrete there is naturally speculation as to the effect of steel in the proximity of the transmission path on the apparent pulse velocity. Limited studies were made on a 6-, 12-, 20-in. block of concrete with a 1-in. diameter steel bar parallel to and 3 in. from the 6-, 12-in. face. The velocities of sound in the steel and concrete were measured and the shortest periods

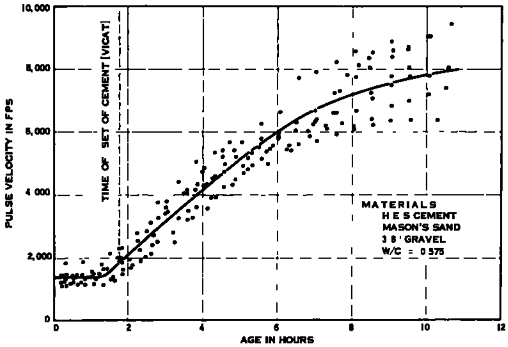

Figure 9. Study of setting behaviour of HES concrete by pulse velocity technique.

for traversing the block were calculated for various positions of the transducers. Measurements were then made and the results compared with the theoretical curves (Fig. 10). Although these tests showed such excellent correlation between the actual and theoretical behaviour, similar tests on a precast concrete slab with ½-in. diameter bars showed negligible effect when transmissions were parallel to and within an inch of the steel. When one transducer was located directly on the steel, or when transmissions were diagonally across its path only slight effects were observed. Similarly, in tests on concrete piers in the field, it was not possible to detect the presence of ¼-in. diameter stirrups by an increase in pulse velocity. On the other hand, attempts to ascertain the depth of cracks in inspection tunnels were nullified by the concentration of reinforcement in these regions.

Although the determining factor is the bond between the concrete and the steel, certain obvious conclusions were drawn from these experiences. These are, that the effect of steel on pulse velocity measurements depends upon the proximity of the steel to the transmission path, the size and concentration of the reinforcing, the distance between transducers and, of course, the relative velocities in concrete and steel. Although light reinforcement seems to have negligible effect upon pulse velocity measurements, in view of the many uncertainties, it is advisable to avoid where possible transmissions close and parallel to the direction of steel particularly in heavily reinforced structures.

Effect of Moisture Content on Pulse Velocity

In order to evaluate the quality of the concrete in one of the Commission's gravity structures, 6-in. cores were removed for study. Laboratory tests included soniscope measurements on 6-, 12-in. specimens in both the dry and saturated conditions. With a few exceptions, the results showed increases in pulse velocity, when the specimens were saturated, by amounts varying from 6 to 22 percent. The average increase was

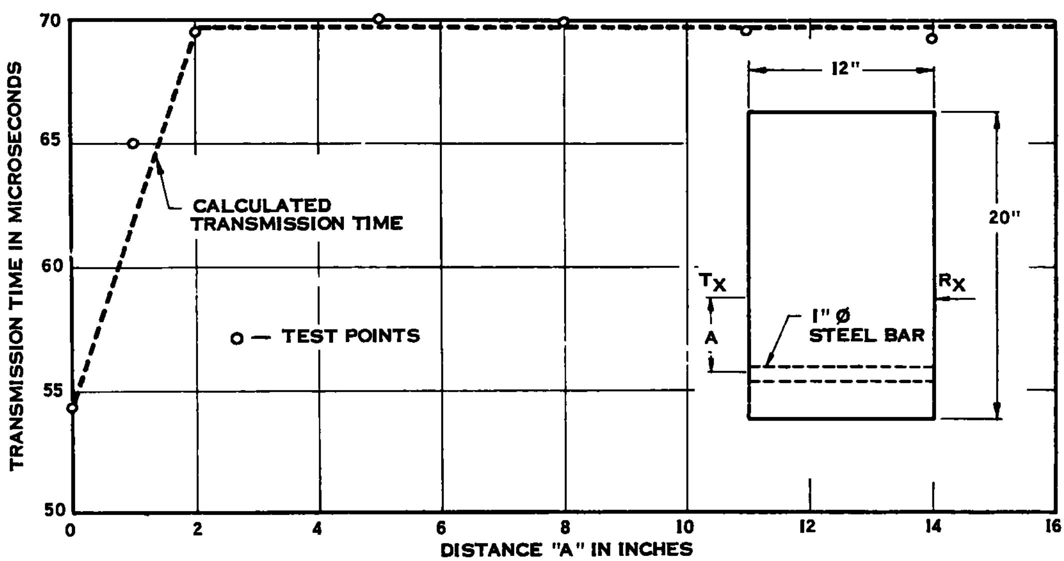

Figure 10. Effect of reinforcing steel on pulse velocity measurements.

TABLE I

EFFECT OF FREEZING
ON
PULSE VELOCITY AND RESONANT FREQUENCY
OF GREEN CONCRETE

CONDITION	AGE AT INITIAL FREEZING IN HOURS					
	NON-AIR-ENTRAINED			AIR-ENTRAINED		
	24	48	72	24	48	72
A ... PULSE VELOCITY IN FPS						
BEFORE FREEZING	12,700	14,200	14,700	11,000	13,100	13,500
6 HRS. IN FREEZER	17,000	17,500	17,100	16,000	15,900	15,700
23 HRS. IN FREEZER	17,500	17,300	17,600	16,200	16,000	16,100
AFTER THAWING – 7 HRS. AT 73F	12,600	14,100	14,700	11,700	13,000	13,400
B ... RESONANT FREQUENCY IN CPS						
BEFORE FREEZING	1510	1760	1850	1380	1600	1720
6 HRS. IN FREEZER	2190	2240	2220	2060	2070	2060
23 HRS. IN FREEZER	2260	2290	2260	2100	2070	2090
AFTER THAWING – 7 HRS. AT 73F	1600	1750	1810	1480	1600	1700

approximately 12 percent. It was first suspected that perhaps the larger increases were associated with higher absorption and/or voids content of the specimens. However, a comparison of these properties with the increase in pulse velocity showed no coherent relationship. Although, the effect of moisture content of concrete must obviously be taken into account in analysing pulse velocity data, its magnitude cannot be predicted with certainty. However, in order to reduce the variability in laboratory specimens, it is customary to carry out comparative measurements in the saturated condition, a practice followed by most organizations for resonance testing, which is similarly affected by the moisture content of the specimen. In surveys of small structures such as tower footings, the attempt to repeat measurements is made at the same time of year. In large masses of concrete, it is felt that moisture content will change very slightly and the variation would therefore be less important.

Recently, soniscope measurements were made on a 4-, 6-ft slab, 6 in. deep that had been allowed to dry. Due to an abnormal amount of interference on the screen, it was not possible to define the first received pulse properly. However, when the slab was again saturated, the interference was eliminated and velocity measurements were readily obtained. Similar interference has been encountered in relatively dry cores and discarded durability specimens. The problem was diagnosed as a case where reverberations were set up in the dry concrete due to the relatively high pulse repetition rate (100 per second). This problem was subsequently overcome by reducing the pulse repetition rate in the instrument to 50 per second. While this information may be of little technical importance, it has been included for the benefit of those who may have experienced similar difficulties.

Effect of Freezing Concrete on Pulse Velocity

Several specimens of both air- and non-air-entrained concretes were made and frozen at different ages, viz, 24, 48 and 72 hours. Both pulse velocity and resonant frequency measurements were made, immediately before freezing, 6 and 23 hours after freezing and 7 hours after thawing (Table 1). Pulse velocity and resonant frequency values increased appreciably with 6 hr freezing, and a further slight increase was

TABLE II

EFFECT OF FREEZING
ON
PULSE VELOCITY AND RESONANT FREQUENCY
OF DETERIORATED CONCRETE

CONDITION	SPEC. NO. 1	SPEC. NO. 2	SPEC. NO. 3	SPEC. NO. 4
A ... PULSE VELOCITY				
DRY [167 DAYS IN LAB. AIR]	4700	7300	8500	9400
SATURATED [48 HRS. IN WATER AT 73F]	9400	10,200	11,900	12,200
FROZEN [21 HRS. AT 0F	15,800	16,200	16,200	16,200
THAWED [23 HRS. IN WATER AT 73F]	9000	10,400	11,400	12,000
B ... RESONANT FREQUENCY				
DRY [167 DAYS IN LAB. AIR]	1480	1190	1090	940
SATURATED [48 HRS. IN WATER AT 73F]	1360	1240	1040	1100
FROZEN [21 HRS. AT 0F]	2070	2060	2070	2000
THAWED [23 HRS. IN WATER AT 73F]	1520	1220	980	1060

observed after the additional 17 hr at below freezing emperatures. Of particular interest was the fact that although the younger specimens had lower intitial velocity and frequency values than the older specimens, after 23 hr in the frozen condition the values were approximately the same in all specimens, regardless of age. Also, when the specimens were thawed, the pulse velocity and resonant frequency returned to the values observed immediately before freezing.

Similar tests were made on specimens of hardened concrete that had failed in the freezing and thawing tests and were considered to represent various degrees of deterioration. After a period of several months in laboratory air, these specimens were saturated, frozen and subsequently thawed. Pulse velocity and resonant frequency measurements were made on each specimen in the dry, saturated, frozen and thawed conditions (Table 2). As expected, the velocity increased after the concrete was saturated but the resonant frequency increased in two specimens and decreased in the others. When frozen, however, both the pulse velocity and resonant frequency values increased appreciably and were again approximately equal for all specimens regardless of the level of these values before freezing. Upon subsequent thawing, the values dropped to a level varying only slightly from those observed in the earlier saturated, unfrozen condition. Apparently, the cracks and discontinuities of the deteriorated concrete, which normally act as sound barriers, when filled with ice, increase the rigidity of the specimen and the concrete behaves like a homogeneous material. Consequently, there is a danger of erroneous conclusions when pulse velocity measurements are made on a deteriorated structure in which the concrete is in a saturated and frozen state.

Detection of Small Voids in Concrete

In order to assess the ability of the soniscope to detect small voids or other inclusions, several blocks of concrete were cast in which miscellaneous objects were buried. Without previous knowledge by the operator of either the nature or the location of these objects, soniscope measurements were made on each block and zones having doubtful properties were outlined. Abnormal responses were observed in regions which were later revealed to contain pockets of aggregate and pieces of insulating board; it was not possible, however, to locate several lengths of ½-in. diameter steel conduit (Fig. 11). This is probably due to a combination of the normal variability of pulse velocity in concrete and the fact that the sound pulses are not sufficiently directional and could therefore travel around the smaller voids without a detectable increase in the transmission time. However, it must be realized that the soniscope was developed primarily as a field tool for assessing massive concrete structures and the frequency, transducer size and range were designed accordingly. Although it has on occasion been suitably adapted for testing small specimens it does suffer certain limitations in the shorter path length. However, with certain modifications some of the shortcomings may be overcome.

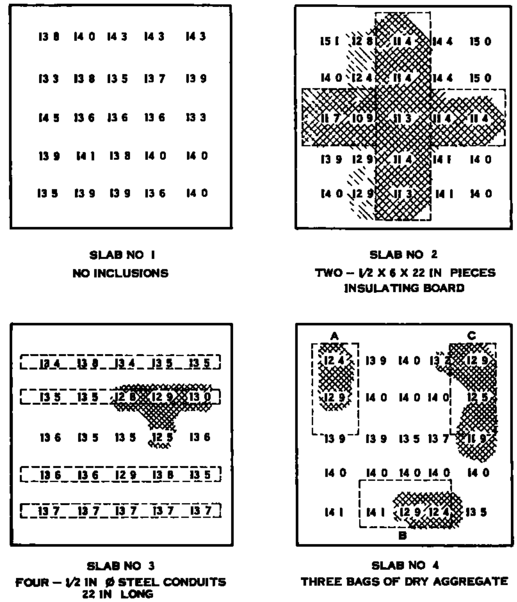

Figure 11. Detection of voids in concrete blocks. Figures shown are pulse velocity x 10^3 through 8 in. of concrete showing normal variation in uniform concrete (slab No. 1) and the effects of various discontinuities (slabs No. 2, 3 and 4).

Possible Errors in Soniscope Testing

Like most test equipment, the soniscope is not without limitations and is subject to certain testing errors. In general, the magnitude of the error or errors is dependent upon the transmission path, and may be negligible in the long path lengths but could be appreciable in the shorter distances. However, even in the latter case, the possible errors can be limited by thoughtful planning and exercising certain precautions in testing.

In the survey on the slab and buttress dam, described earlier, some difficulty was encountered in maintaining alignment of the transducer since the transmitter had to be lowered into the headpond by ropes. Since the slab varied in thickness from 11 to 27 in., if the transmitter were off by as little as six inches, errors up to 14 percent could be introduced. It was found, however, that misalignment of the transducers could often be detected when an appreciable and unexpected increase in transmission time was observed and particularly if there was no corresponding effect upon the pulse amplitude. To reduce the possibilities of errors caused by the transmitter drifting from its test point, periodic checks were made by moving the receiver until the position of minimum transmission time was obtained. By these precautions, it was estimated that errors due to misalignment alone were kept below 7 percent.

Changes in the pulse velocity of the concrete in the dam, after an interval of four years, are illustrated in Figure 12. Apart from deterioration that had taken place during this period, misalignment of the transducers along with operator and random errors undoubtedly account for part of the variations. The large discrepancies in the zones of originally low velocity, however, are mainly due to pulses in cracked or deteriorated concrete being ill-defined in any case. Mather (8) also observed that reproducibility is poor in concrete of this quality. Low amplitude and/or poorly defined pulses are often in themselves an indication of low quality concrete although they do complicate attempts to establish trends in deterioration. In this concrete, however, it was estimated that over the 4-yr interval, the average pulse velocity decreased by 480 fps and 750 fps, respectively, in the low and high velocity regions.

Incorrect measurement of the transmission path is a further source of error that is difficult to assess. Such errors may be introduced where the path length must be calculated or scaled from construction drawings or merely by inaccurate measurements. If the error is large, it may be detected by the experienced operator by readings that

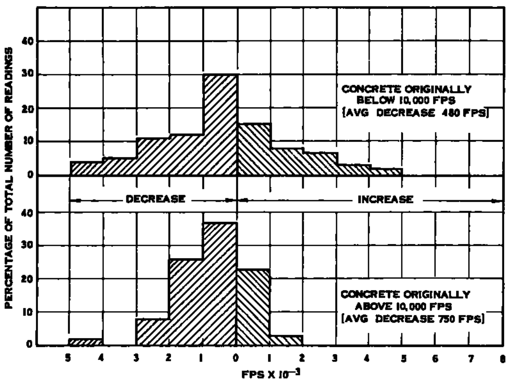

Figure 12. Changes in pulse velocity in a 40 year old dam from 1949 to 1953.

are obviously inconsistent with amplitude of the pulses and the apparent quality of the concrete.

Many errors could be introduced into pulse velocity measurements by inexperienced or disinterested personnel handling the equipment. Obviously, the only way to overcome this problem, is to use conscientious operators who are fully aware of the implications and are willing to put forth a little extra effort to produce consistent results. In order to reduce errors resulting through the incorrect reduction of results, special data sheets, in which the calculations follow a systematic order, have been found particularly helpful.

From past experience the following sequence has been established and proven to be of considerable assistance in preparing for a series of soniscope measurements. The set is permitted to warm up for a period of 10 to 20 minutes before tests are commenced, after which it is calibrated on all ranges to be used and suitably adjusted if required. With the time dial set to zero, the strobe and the transmitted pulse are aligned. Since it has been found that the polarity of the first received pulse may be either positive or negative, depending upon the transducer combination, it is advisable to establish this polarity by transmitting through a few feet of air prior to beginning the tests. Zero error, or the transducer delay time, is determined by holding the transmitter and receiver in contact and measuring the delay time. In this operation it may be necessary to reduce the output of the transmitter to its minimum to prevent overloading the circuit and hence avoid erroneous results. The transducer delay should be recorded and must be subtracted from all subsequent measurements. If tests with the soniscope continue for an extended time, periodic checks of the calibration and the transducer delay time are recommended to determine any shift in the relative position of the traces.

Concluding Comments

The Ontario Hydro has found pulse velocity testing with the soniscope the best method to date for assessing the quality of concrete in place. The depth of surface cracks has been measured with what is considered to be a reasonable degree of accuracy. Successful transmissions through mass concrete blocks are considered indicative of freedom from internal cracks. Although the soniscope has been used to follow the strength development of concrete, the accuracy with which strength can be estimated from pulse velocity values is limited; however, under certain conditions, this may be adequate. In condition surveys there is no attempt, at the present, to reduce pulse velocity to other properties (e.g. compressive strength or modulus of elasticity) but base assessment on the measurements themselves particularly when datum readings are available. Undoubtedly, if a relationship could be established between strength and velocity, the value of the soniscope would be increased appreciably.

Like most other test equipment, the soniscope is not without limitations, and perhaps these may have been over-emphasized. However, this is not intended to induce a lack of confidence in the apparatus but to provide a better understanding and perhaps a more intelligent interpretation of the results. Undoubtedly, the best assurance for reducing the possible errors to a minimum and obtaining the most from the equipment is a competent operator capable of using sound judgement in his interpretation of the results.

REFERENCES

1. Leslie, J. R. , and Cheesman, W. J., "An Ultrasonic Method of Studying Deterioration and Cracking in Concrete Structures." Journal, Am. Concrete Inst., Vol. 21, No. 1 (September 1949); p. 17, Proceedings, Vol. 46 (1950).
2. Leslie, J. R., "Pulse Techniques Applied to Dynamic Testing." Proceedings, Am. Soc. Testing Mats., Vol. 50, p. 1314 (1950).
3. Young, R. B., "A Device for Determining the Depth of Surface Cracks in Concrete." Journal, Am. Concrete Inst., (April 1944); Proceedings, Vol. 40, p. 401 (1944).
4. Parker, W. E., "Pulse Velocity Testing of Concrete." Proceedings, Am. Soc. Testing Mats., Vol. 53, p. 1033 (1953).
5. Chapin C. L., and Lemire, W. A. R., "Aluminous Cement in Winter Line Construction." Hydro Research News, Vol. 8, No. 2, p. 9 (April-June 1956).
6. Whitehurst, E. A. "Use of the Soniscope for Measuring Setting Time of Concrete." Proceedings, Am. Soc. Testing Mats., Vol. 51, p. 116 (1951).
7. Jones, R., "The Testing of Concrete by an Ultrasonic Pulse Technique." Proceedings, HRB, Vol. 32, p. 258 (1953).
8. Mather, Bryant, "Comparative Tests on Soniscopes." Proceedings, HRB, Vol. 33, p. 217 (1954).

Application of Pulse Velocity Tests to Several Laboratory Studies of Materials

K. B. WOODS, Director, Joint Highway Research Project and Head, School of Civil Engineering; and
J. F. McLAUGHLIN, Research Engineer, Joint Highway Research Project and Assistant Professor of Highway Engineering,
Purdue University, Lafayette, Indiana

This paper reviews the research conducted by various investigators at Purdue University in which the soniscope has had a primary role. It is the purpose in this report to summarize data published previously in greater detail, to omit much of the procedures, and to concentrate on the function of the soniscope in its various application to the study of materials.

Three separate laboratory investigations are reviewed. In the first, the soniscope was used to measure the setting time of concrete. Four cements (ASTM types I, II, III and IV) were used to make concretes of a rather stiff consistency. Velocity tests were made periodically from soon after the specimens were cast until at least 8 hr had elapsed. It was concluded that for the specimens tested the setting time of concrete could be determined by the pulse velocity technique.

In another investigation, the pulse velocity technique was compared to the resonant frequency technique as a means of following the deterioration of concretes subjected to alternate freezing and thawing. In addition, two of the test series included dynamic determinations of Poisson's ratio which, in turn, were used to calculate E-values from the pulse velocity tests. These values are compared with values obtained from resonant frequency tests. It was concluded that the velocity tests were less sensitive than resonant frequency measurements as a measure of the deterioration of the concrete specimens.

The last investigation considered was one in which the soniscope was used to measure the progressive deterioration of lime-stabilized soils subjected to alternate freezing and thawing. In this case, the technique employed seemed to be an adequate measure of deterioration. The changes in velocity that were noted seemed highly indicative of changes in the quality of the specimens tested.

●IN FEBRUARY, 1950, plans for the construction of a soniscope were prepared by E. A. Whitehurst, then a member of the staff of the Joint Highway Research Project of Purdue University, and were approved by the Advisory Board of that organization. Construction of the instrument followed and by September of that year the soniscope was available for testing. Upon its completion, Purdue University became the fifth organization known to own such a device, the others being the Hydro-Electric Power Commission of Ontario, the Portland Cement Association, the University of California, and Kansas State College.

In the years following, the soniscope was used in a variety of experimental investigations dealing with highway pavements and materials (1, 2, 3). It is the purpose of this paper to review and summarize the pertinent parts of several of these investigations and to illustrate the application of the soniscope or the pulse-velocity technique in a variety of situations.

This paper is based on three published papers and many unpublished reports which were written by present and former members of the staff of the Joint Highway Research Project, School of Civil Engineering, Purdue University. The authors wish to acknow-

ledge the work of E. A. Whitehurst, D. W. Lewis, G. M. Batchelder, and E. J. Yoder. These men conducted the investigations and reported the results which are herein summarized.

MEASURING SETTING TIME OF CONCRETE[1]

There is an obvious need for a method of determining the setting time of concrete. A needle penetration test such as is applied to neat-cement paste cannot be readily adapted to concrete because of the large range in particle size of the ingredients.

There have been several references in the literature concerning the possibility of measuring changes in the condition of green concrete through the use of a dynamic method of test. Specific mention has been made of measuring the velocity with which an energy pulse travels through the concrete. Jones (4), in 1949, reported making such tests on laboratory specimens using equipment built in the Road Research Laboratory, England. He stated, however, that below ages of 10 hr, considerable difficulty was experienced in obtaining an adequate signal through the concrete. This study by Jones and an additional study made by Arndt (5) suggested the study.

The purpose of this study was to investigate the possibility of determining the setting time of concrete by measurement of pulse velocities through the still plastic material. No effort was made to investigate the several variables which influence the time of setting of concrete. In so far as possible, these variables were minimized except where necessary to provide sufficient range in setting times to permit a satisfactory evaluation of the proposed test method.

In order to introduce into the study some element which would cause the time of set of the concretes to vary, preferably in some predetermined manner and still keep all mixes as uniform as possible, it was decided that the mix design and method of handling should be kept constant and one of the constituents of the mix should be varied. Since various portland cements conforming to ASTM types I, II, III, and IV could be procured, the type of cement used was, in most cases, the variable between batches.

Most of the concrete mixtures contained 6 bags of cement per cu yd of concrete and were designed to have a nominal water-cement ratio of 0.40 by weight. The use of very stiff (0 to $^{3}/_{8}$ in. slump) mixes permitted the early removal of the end plates of the specimen molds, thus obtaining access to the ends of the beams for testing purposes. Two mixes of a somewhat wetter consistency ($6^{1}/_{2}$ and $2^{1}/_{2}$ in. slump) were also included.

Specimens were cast into 4- by 4- by 16-in. beams. Nine beams were cast from each 1.5-cu ft batch; three triple-section molds were employed. Specimens were molded, generally, in accordance with the ASTM requirements for the molding of laboratory specimens. Because of the unusual stiffness of the plastic concrete, extensive rodding was required. The top surfaces of the beams were finished with a dampened wooden float, an operation which was rather difficult. Despite considerable effort to achieve well-compacted specimens, some honeycombing was noted in most cases.

The forms used were so constructed that single plates at each end served as the end plates for all three beams. Shortly after the floating of the specimen surfaces was completed, these end plates were removed. Pulse velocity tests were begun on the beams as soon as possible after the removal of the end plates. Initial velocity tests were made on the specimens in the first mold from 2 to 4 hr after the concrete was mixed, depending upon the type of cement used. Earlier tests were attempted but were found to be unsatisfactory. Once a satisfactory test was accomplished, the beams were tested repeatedly, usually at intervals of $^{1}/_{2}$ hr.

It had been suggested that the vibrations passed through the specimen in testing, though of a minute nature, might have some material effect upon the concrete. To check this hypothesis only the specimens cast in the first mold were tested throughout the entire setting period. Those in the second mold were subjected to their first velocity tests approximately 3 hr after those in the first mold, after the setting process was well under way. Tests were not begun on the beams in the third mold until it was felt that the final set had occurred. Only a few tests were made on these specimens.

---

[1] Abstracted from reference 1.

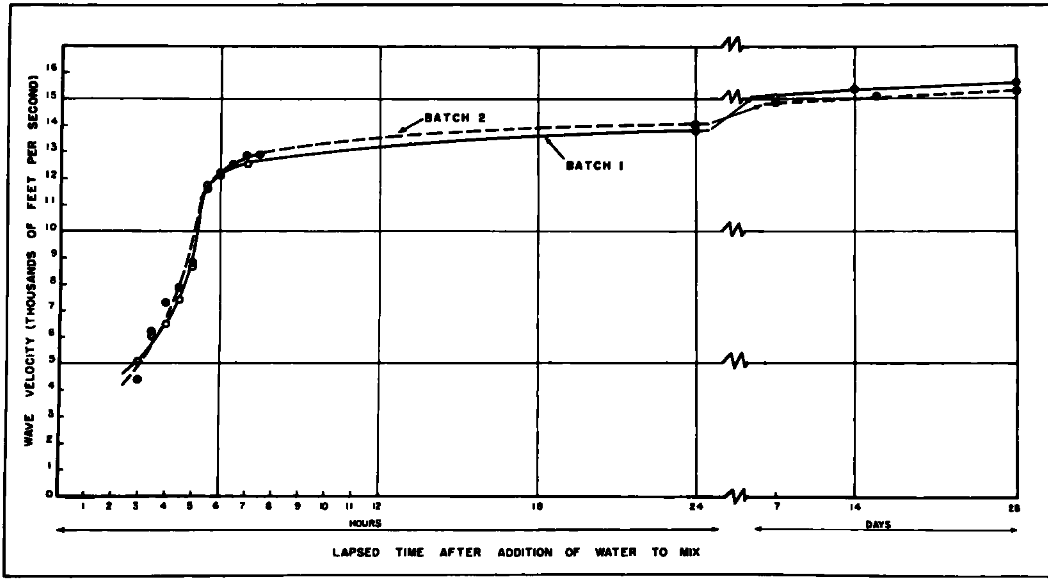

Figure 1. Average wave velocities through concrete made from Type I cement.

The half-hour velocity tests were continued until the specimens were 8 to 9 hr old and appeared to have reached final set. The beams were then allowed to remain over night in the forms. On the following morning, when the concrete was approximately 24-hr old, velocity tests were made on all nine of the specimens, the forms were stripped, and the beams were moved to the moist room. Additional velocity tests were made when the specimens reached ages of 7, 14 and 28 days.

Discussion of Results

In all cases it was found that the pulse velocity through the specimens increased at a rapid rate during the first few hours after the concrete was mixed. Figures 1 and 2

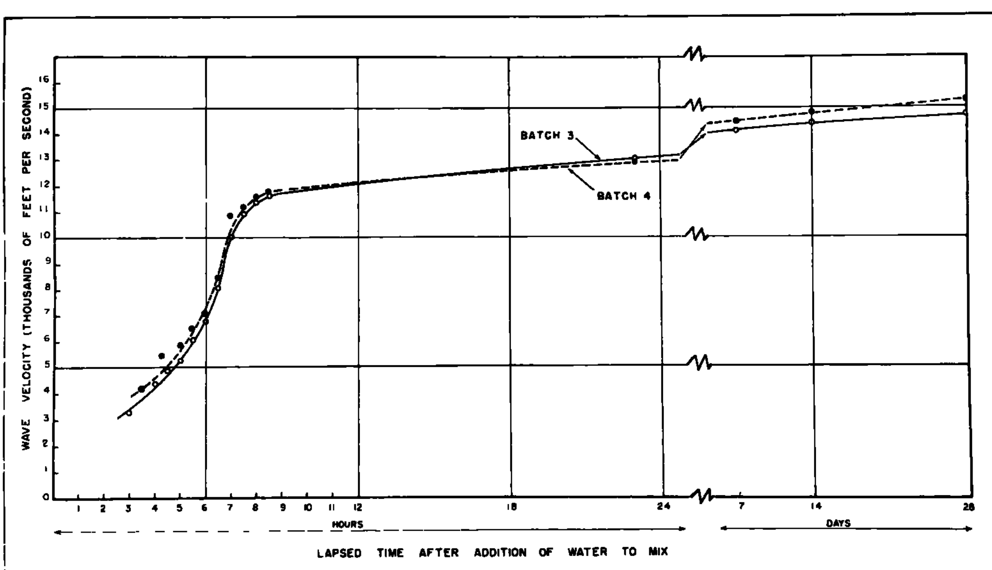

Figure 2. Average wave velocities through concrete made from Type II cement.

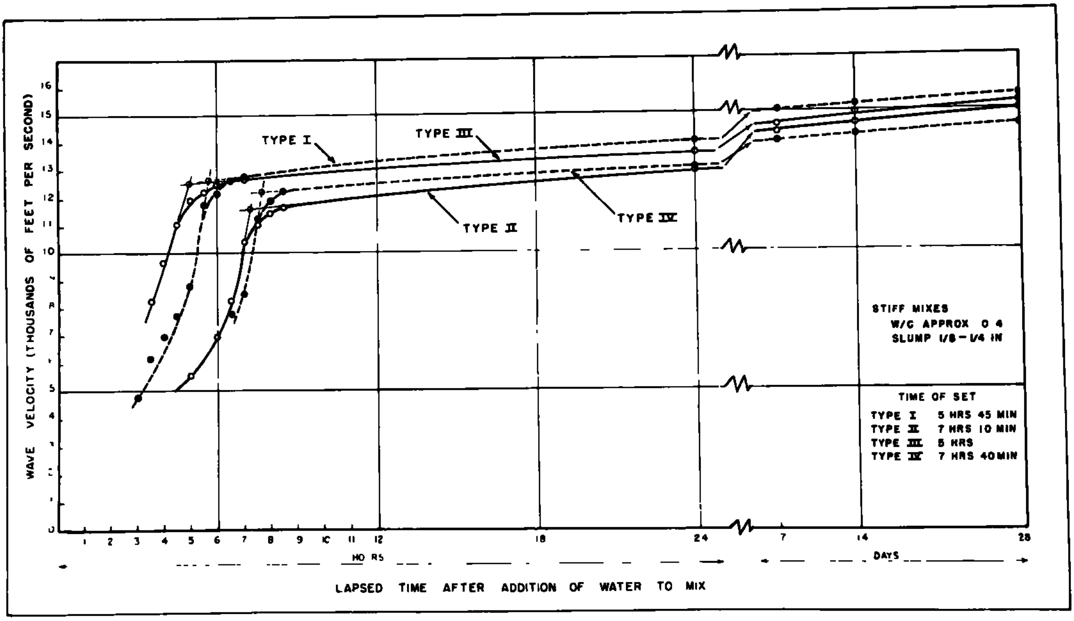

Figure 3. Comparison of wave velocities through concretes made from Types I, II, III, & IV cements, stiff mixes.

show the results of tests on mixes containing Types I and II cements, respectively. The results from Types III and IV were similar.

Each point on the graphs represents the average of test values for the three beams cast in the first mold. It may be noted that velocity when first measured was in the range of 3,000 to 6,000 ft per sec. From this initial value it increased at an accelerating rate for several hours. At the end of some period of time, the rate of change in velocity decreased sharply during a relatively brief interval. Velocities then continued to increase at a slow rate throughout the duration of the tests. Only very small differences were observed between the three companion specimens in any given mold.

It seems desirable, especially for the evaluation of accelerating or retarding admixtures, to designate a specific time as the time of set. From a study of the data it appeared that the time which could be most consistently reproduced was that designated by the intersection of lines drawn tangent to the curve before and after the interval during which the rate of change in velocity decreased sharply. Figure 3 shows a comparison of results of velocity tests on concretes made from the four cements used in this study. The tangents have been drawn to indicate the time of set. A comparison of the setting times so determined with the setting time of the cement alone, as determined by the Gillmore needle, is shown in Table 1.

Some additional tests were made on concretes having a nominal water-cement ratio of 0.5 and which were considerably wetter than those so far discussed. It was found that results similar to those obtained with the stiff mixes were obtained.

Conclusions

From the results of the tests, it was concluded, at least for specimens of laboratory size, that the setting time of concrete may be determined by observing the rate of change of the velocity with which small vibrations are propagated through the specimen. Time of set is taken as the time at which this rate of change decreases suddenly. If the velocity is measured periodically and plotted versus elapsed-time-after-mixing, this time may be determined by locating the point of intersection of tangents drawn to the curve immediately prior to and after the period during which the decrease occurs.

The soniscope appears to be a suitable instrument for measuring the desired velocities.

TABLE 1
COMPARISON OF SETTING TIME OF CONCRETE AND CEMENT

Type Cement	Time of Set	
	Concrete	Cement
Type I	5 hr, 45 min	5 hr, 45 min
Type II	7 hr, 10 min	6 hr, 50 min
Type III	5 hr	4 hr, 15 min
Type IV	7 hr, 40 min	8 hr

The test is rather difficult to perform because of the very weak signals received during the setting period. With a little experience, however, an operator is able to achieve reliable and reproducible results. It should be noted that the increase in velocity is generally so great immediately prior to the setting of the concrete that the change could scarcely be missed, even if the accuracy of measurement were poor.

The method is probably no more precise than are the needle tests for setting time of cement, since the phenomenon of final set is not an instantaneous process. The method does, however, provide a means of quantitatively evaluating the setting time of concrete.

COMPARISON OF DYNAMIC METHODS OF TESTING CONCRETES SUBJECTED TO FREEZING AND THAWING[2]

In recent years, dynamic techniques have been widely used in concrete testing, particularly in connection with durability studies. Dynamic testing techniques are divided into two general methods, one based upon determination of the fundamental resonant frequency of vebration of a specimen and the other upon measurement of the velocity of a compressional wave through the material. Many investigations of these techniques and their application to concrete have been made in the past. Correlations of changes in the dynamic modulus of elasticity with the deterioration of concrete subjected to freezing and thawing and with changes in the flexural strength have been made by several investigators. As a result, the test is widely used in durability testing of concrete. The method is restricted to tests on specimens with uniform cross-sections.

Investigations using velocity measurements, which are not affected by specimen shape and can be used in the field, apparently were started by Long and Kurtz (6). Later reports by Long, Kurtz, and Sandenaw (7) and West (8, 9) gave test results of a similar nature involving measurement of the transit time of a single impact pulse through the concrete between two pickups.

This paper reports the results of laboratory tests to compare the resonant frequency and velocity test techniques for determining the deterioration of laboratory specimens of concrete subjected to freezing and thawing, and to compare the actual moduli of elasticity values computed from the results obtained by the two test methods. Theoretically, the same results should be obtained from tests on the same specimens by the two methods.

Two series of tests were conducted. The first, designated as series A, involved transverse resonant frequency and velocity tests on three concretes (two mixes of each). Comparisons of test results were made on the basis of changes in velocity squared and in the dynamic modulus of elasticity calculated from the transverse frequency during freezing and thawing. In series B, tests were run on two concretes (one mix of each). Longitudinal, transverse, and torsional frequencies were determined and velocities measured in this series. Values of the modulus of rigidity and Poisson's ratio were obtained, and moduli of elasticity were computed from the longitudinal and transverse frequencies and from the velocities.

All specimens were cured for 28 days completely immersed in water at 70 F, except those from mix 1, series B, which were cured only 21 days. At the end of the curing period, three beams from each mix in series A and eleven from each mix in series B were subjected to alternate freezing and thawing. The cycle consisted of a 16-hr freezing period and an 8-hr thawing period. Freezing was done in air at -18 F in a walk-in freezer; thawing was in running tap water at 55 F. Resonant frequency and velocity

[2] Abstracted from reference 2.

tests were made periodically during freezing and thawing. At the end of the testing, beams were broken in flexure.

Series A. During the freezing-and-thawing tests on series A specimens, periodic measurements were made of velocity and transverse resonant frequency on each specimen. Modulus of elasticity values were calculated from the transverse frequencies, using the equations given in ASTM C 215-52T, Tentative Method of Test for Fundamental Transverse and Torsional Frequencies of Concrete Specimens. Poisson's ratio was assumed to have a value of $1/6$.

Series B. More complete dynamic tests were conducted on the specimens in series B, where longitudinal, transverse and torsional resonant frequencies and velocities were measured. Modulus of elasticity, modulus of rigidity, and Poisson's ratio values were determined for each test.

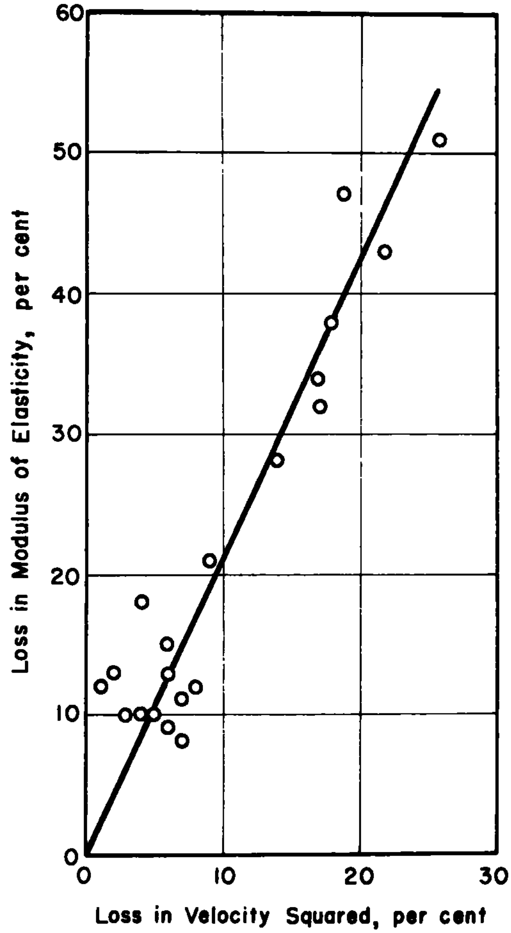

Figure 4.

Discussion of Results

Series A. Since no attempt was made in this series of tests to determine the value of Poisson's ratio, modulus of elasticity values were not calculated from the velocity measurements. Instead, the results of the tests were compared on the basis of the relative changes in dynamic modulus of elasticity (based on transverse frequency) and in velocity squared. It may be shown that the square of the velocity is directly proportional to the modulus of elasticity. Therefore, changes in velocity squared, calculated as percentages of the original value, would be the same as the percentage changes in modulus of elasticity. This assumes that Poisson's ratio, whatever its value may be, remains constant during the freezing-and-thawing cycles.

The results of the tests in series A are shown in Figure 4, where changes in the transverse modulus of elasticity are plotted against changes in the velocity squared. Each plotted point shows the average value obtained from tests on six specimens, three from each of two mixes, after varying numbers of cycles of freezing and thawing.

The average line for the data shown in Figure 4 does not indicate the equal changes in modulus of elasticity and in velocity squared that had been expected. Instead, the percentage change in modulus of elasticity is approximately twice as great as the change in velocity squared. The data, then, show that velocity measurements were only about one half as sensitive as transverse resonant frequency tests as a measure of the deterioration of these concretes during freezing and thawing.

Original velocity measurements on these specimens showed a range of values from 14,700 to 15,860 ft per second. Velocities during the freezing-and-thawing tests were never less than 12,000 ft per second, although decreases in dynamic modulus of elasticity ranged up to 50 percent.

No reason was apparent for the lack of correlation of the values obtained in this test series. Among the possible explanations considered were:

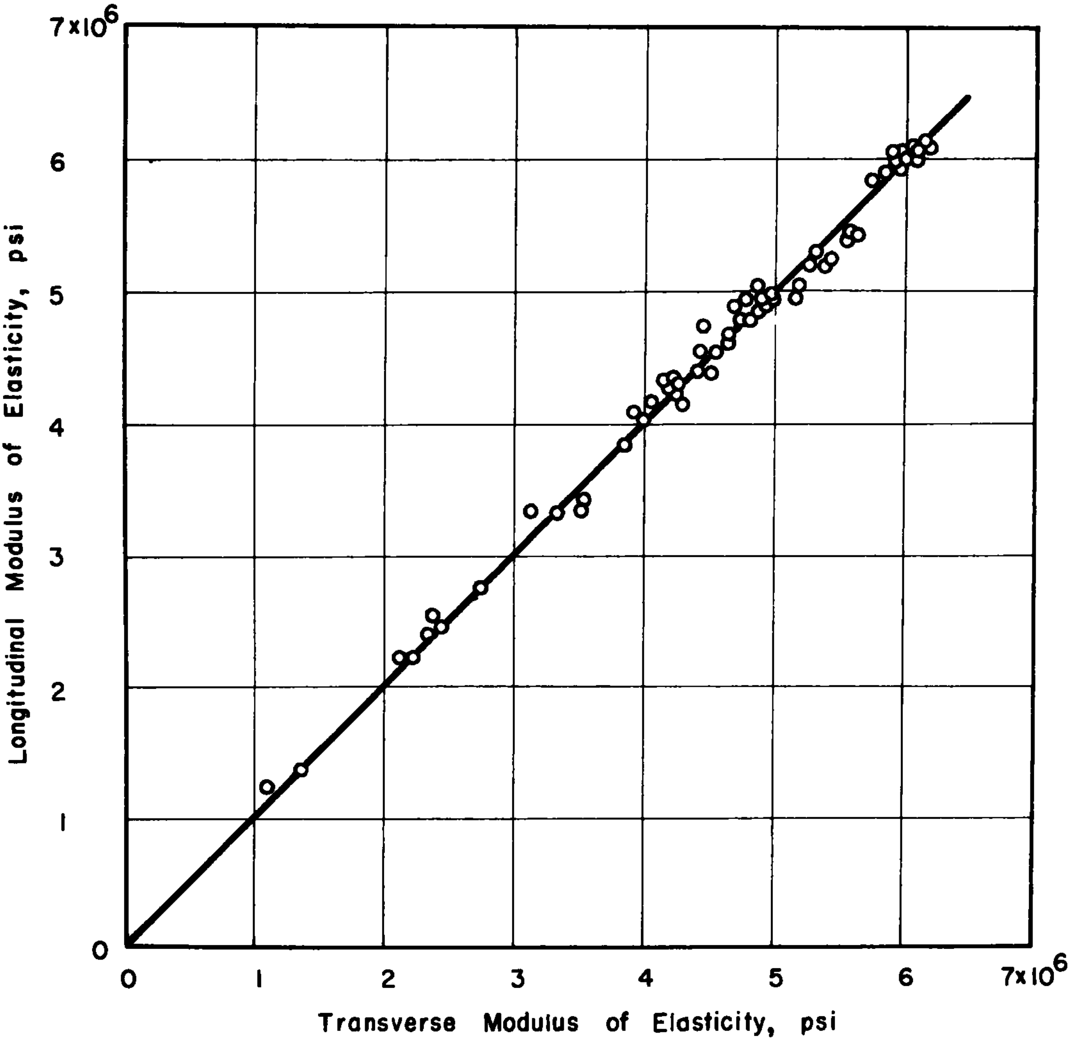

Figure 5.

1. Poisson's ratio may not remain constant as deterioration progresses. If Poisson's ratio increased with deterioration of the concrete, the effect would be to decrease the modulus of elasticity value calculated from the velocity, thus making changes from the original value greater.

2. The concrete may not be sufficiently homogeneous, especially along the "line path" over which velocity tests are conducted, for the equations relating modulus of elasticity to velocity to be applicable. In this case, correlation of the modulus of elasticity values from resonant frequency and velocity tests would be poor even in initial tests before any weathering cycles were started.

3. The possibility exists that the resonant frequency values are dependent upon the "average" condition of the specimen, while the velocity is measured along a single line. The compressional waves used in the velocity test would tend to travel through the soundest material in the specimen, and the results would not reflect the average condition of the concrete.

Series B. The tests conducted in series B were designed to determine the changes, if any, in Poisson's ratio during freezing and thawing and to compare actual values of

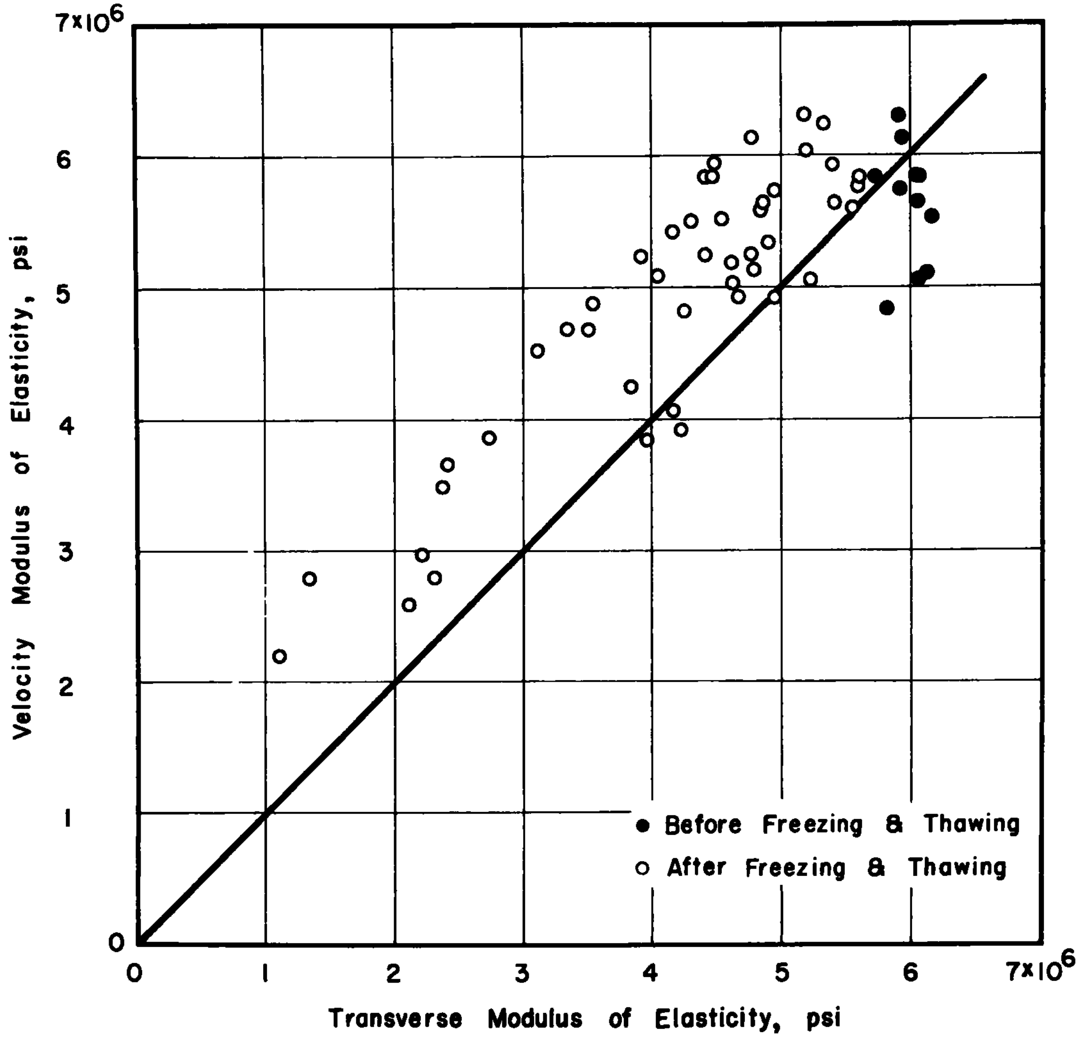

Figure 6.

the modulus of elasticity calculated from the velocity with the values obtained from the resonant frequencies.

Comparison of Moduli of Elasticity from Longitudinal and Transverse Frequencies. Only the transverse frequencies are ordinarily obtained in routine dynamic testing. Therefore, it was of interest to compare the modulus of elasticity values so obtained with those calculated from the fundamental longitudinal frequencies. These values for mix 1 are plotted in Figure 5. Each plotted point represents one test on a single specimen. Excellent correlation is shown, the values lying on or very close to the line of equal values drawn on the graph. Values obtained for mix 2 showed a similarly close correlation.

Comparison of Moduli of Elasticity from Transverse Frequency and Velocity. In Figure 6 data from the same specimens in mix 1, showing the relationship of the moduli of elasticity calculated from transverse frequency and velocity, are plotted. As in Figure 5 the curve shown is the theoretical line of equal values. It is readily apparent that the theoretical relationship does not hold, even though Poisson's ratio was determined for each test and was used in calculating the moduli of elasticity values. There is a definite general trend for the values computed from velocity measurements to be con-

TABLE 2

INITIAL MODULUS OF ELASTICITY VALUES, SERIES B, MIX 2

Beam	Modulus of Elasticity, psi Transverse	Velocity	Percent Difference
No. 1	4.77×10^6	5.16×10^6	+8
No. 2	4.66	4.82	+3
No. 3	4.84	4.20	-13
No. 4	5.04	4.11	-18
No. 5	4.51	4.12	-9
No. 6	4.53	4.22	-7
No. 7	4.65	4.25	-7
No. 8	4.49	4.30	-4
No. 9	4.77	5.16	+8
No. 10	4.93	4.98	+1
No. 11	4.99	4.97	0
Average	4.74	4.57	-3.6

siderably higher than those computed from transverse frequency. It is significant, however, that a somewhat better correlation is shown for the original values; that is, those measured before freezing-and-thawing tests were started. Actually, these original values calculated from velocity tend to be lower than those from transverse frequency. After freezing and thawing, the reverse is true. This shows the same trend previously noted in test series A; that is, the change in modulus of elasticity calculated from velocity undergoes less change as the concrete deteriorates than does the value obtained from resonant frequency.

In mix 2, all values of modulus of elasticity were closely grouped, with little deterioration taking place. The initial values for the eleven specimens are shown in Table 2. The values computed from velocity range from 8 percent higher to 18 percent lower than those from transverse frequency. Changes in these values were, in general, small during freezing and thawing. The reasonably good correlation noted for the initial values seemed to hold for this concrete mix throughout the tests, probably because of the small changes that took place.

It should be noted that the equation which was used to convert velocity to dynamic modulus of elasticity is one that Long, Kurtz and Sandenaw (7) recommended for mass concrete but which Leslie and Cheesman (10) recommended for all concrete, including laboratory specimens. This equation is:

$$E = \frac{V^2 \rho (1 + \mu)(1 - 2\mu)}{(1 - \mu)}$$

where:

E = modulus of elasticity
V = compressional wave velocity
ρ = density of concrete
μ = Poisson's ratio

Changes in Velocity Squared and Dynamic Modulus of Elasticity Calculated from Velocity. The changes in velocity squared and in modulus of elasticity calculated from velocity, shown in Table 3, do not correspond well with the changes in the other dynamic moduli. The tendency, although not so pronounced, is the same as that encountered in test series A. The losses in velocity squared are less than the losses in the moduli of elasticity calculated from resonant frequencies (a greater percentage of the original value is retained).

Mix 2 data, shown in Table 4, indicate a much closer correlation of changes in the velocity values with changes in the other dynamic moduli. Apparently the closeness of the correlation is affected by the amount of deterioration that takes place. In the case of mix 2, there is little choice between velocity squared and modulus of elasticity calculated from velocity. Velocity squared does, however, tend to be a little closer to the other values after 15 cycles of freezing and thawing.

The results obtained in these tests indicate no benefits from determining Poisson's ratio and calculating values of modulus of elasticity from velocity measurements. Instead, the velocity values themselves appear to be a better measure of concrete deterioration than does the modulus of elasticity values calculated from velocity. These results confirm the opinion expressed by Whitehurst (1) that velocity measurements should be used as such, without attempting to calculate the dynamic modulus of elasticity.

Actual velocity values obtained for the specimens in test series B (other data shown in Tables 3 and 4) varied from 15,470 ft per second initially to 9,920 ft per second after weathering for mix 1; and from 14,200 to 13,350 ft per second for mix 2.

Changes in Poisson's ratio. The data in Table 3 show a definite trend in the values of Poisson's ratio, which decreased markedly as deterioration of the concrete took place. It should be noted that the change is in the opposite direction from that required to improve the correlation of the dynamic moduli changes from resonant frequency and velocity measurements. The effect of the variation in Poisson's ratio is to cause differences in the relative changes in velocity squared and in modulus of elasticity calcu-

TABLE 3

DYNAMIC TEST VALUES DURING FREEZING AND THAWING, SERIES B, SPECIMENS 1 AND 2, MIX 1

Number of Cycles of Freezing and Thawing	Dynamic Moduli and Velocity Squared, Percent of Original Value					Poisson's Ratio
	Longitudinal Modulus of Elasticity	Transverse Modulus of Elasticity	Modulus of Rigidity	Velocity Squared	Velocity Modulus of Elasticity	
0	100	100	100	100	100	0.30
1	88	90	90	96	102	0.27
2	82	82	85	94	106	0.24
4	76	75	80	82	94	0.24
6	68	70	72	79	90	0.24
10	56	57	58	70	82	0.23
15	44	42	45	56	63	0.25
20	40	39	42	48	55	0.23
25	36	36	39	41	48	0.23
36	21	20	24	33	43	0.15

TABLE 4

DYNAMIC TEST VALUES DURING FREEZING AND THAWING, SERIES B, SPECIMENS 1 AND 2, MIX 2

Number of Cycles of Freezing and Thawing	Dynamic Moduli and Velocity Square, Percent of Original Value					Poisson's Ratio
	Longitudinal Modulus of Elasticity	Transverse Modulus of Elasticity	Modulus of Rigidity	Velocity Squared	Velocity Modulus of Elasticity	
0	100	100	100	100	100	0.29
1	94	92	94	96	92	0.30
2	92	92	93	98	95	0.29
4	93	93	94	97	96	0.28
6	91	92	93	95	94	0.28
10	91	91	91	95	97	0.27
15	92	92	92	91	91	0.28
20	93	92	92	92	90	0.29
25	94	92	92	90	86	0.30
35	95	93	92	91	86	0.30
50	94	93	92	87	85	0.31

lated from velocity. The changes in Poisson's ratio cannot account for the discrepancies in results noted above in the series A tests.

The changes in the calculated values of Poisson's ratio are caused by the difference between the changes in longitudinal modulus of elasticity and in modulus of rigidity. Although the percentage difference in the changes in these values is quite small, it is consistent. The change in modulus of rigidity is slightly less than the change in modulus of elasticity, resulting in an apparent decrease in Poisson's ratio. Although the significance of this change is difficult to determine, it seems reasonable that actual measurements of Poisson's ratio would be superior to the use of assumed values for calculation of modulus of elasticity from velocity determinations. Use of the measured values, however, causes greater discrepancies between changes in the velocity and resonant frequency moduli than does the assumption of a constant Poisson's ratio during the weathering tests.

The values of Poisson's ratio for mix 2 (Table 4) remained relatively constant during the freezing-and-thawing cycles. It appears probable that this is due to the small amount of deterioration that took place in this concrete mix. Since no great changes took place in the other characteristics of the concrete, Poisson's ratio might be expected to undergo but little change.

Summary

1. In general, no benefit is derived from calculating modulus of elasticity values from velocity measurements. When the concrete undergoes extensive deterioration, the changes in velocity squared form a more accurate indication of concrete deterioration than does such a modulus of elasticity.
2. If the modulus of elasticity is calculated from velocity, the equation recommended by Leslie and Cheesman should be used. Although inaccurate for the deteriorated concrete tested, this equation results in better correlation with resonant frequency moduli than do the other equations that have been suggested for velocity modulus of elasticity.
3. Velocity measurements are less sensitive to deterioration than are resonant frequency determinations. Decreases in resonant frequency moduli may be twice as great as the decreases in velocity moduli as the concrete deteriorates.
4. Measurements of longitudinal, transverse, or torsional resonant frequencies are equally useful and sensitive in tracing the deterioration of concrete specimens.
5. Poisson's ratio showed a definite decrease in the nondurable concrete as the weathering cycles progressed. This change is responsible for the differences noted between changes in velocity squared and in the modulus of elasticity calculated from the velocity.
6. It appears probable that the lack of correlation between changes in resonant frequency and velocity moduli, when the concrete deteriorates, is due to failure of the velocity measurements to indicate the average condition of the specimen. The pulse path in the velocity measurements would probably be through the soundest concrete in the interior of the specimen, and the results would indicate only the condition of the best portion of the concrete. An average condition for the entire mass of concrete should be indicated by the resonant frequency tests in which the whole specimen is vibrated.

DURABILITY TESTS ON LIME-STABILIZED SOILS[3]

The purpose of this study was threefold: first, to determine the durability characteristics of lime-soil mixtures as affected by such variables as soil texture, soil density, and quantity of lime; second, to determine the effect of moist curing on the unconfined compressive strength and durability of lime-soil mixtures; and third, to explore the suitability of dynamic testing techniques for evaluating the performance of such mixtures.

Abstracted from reference 3.

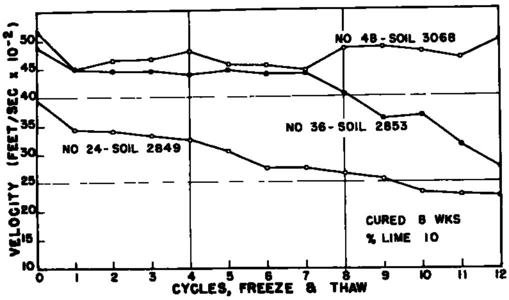

Figure 7. Influence of soil type on durability.

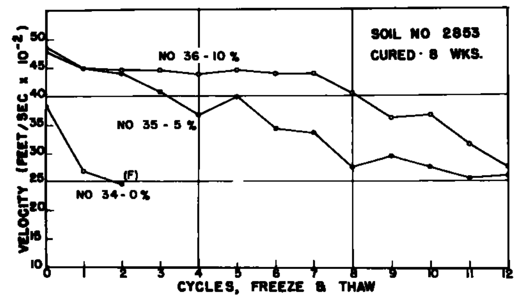

Figure 8. Influence of percent admixture on durability.

Three different soils were used in this investigation. Soil 2849 was a silty clay of Wisconsin glacial age, a calcareous drift soil typical of that overlying a large portion of the central states. Soil 2853 was an Illinoian drift soil. The third soil, 3068, was a pit-run gravel with all material larger than 1/4-in. discarded.

The effects of the several variables upon strength were evaluated by unconfined compression tests. Relative durability was determined by freezing-and-thawing and velocity tests. Curing times ranged from 1 to 36 weeks and the quantity of lime from 0 to 10 percent by weight. Some tests were made on specimens of varying density.

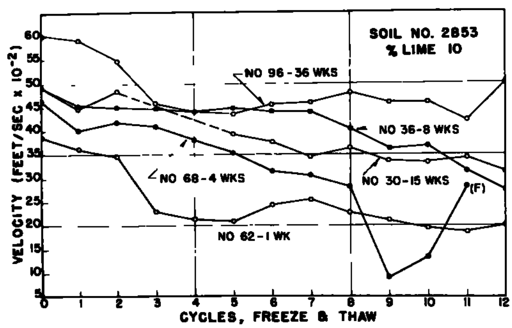

Figure 9. Influence of curing time on durability.

Specimens were molded in a split cylinder the size of the standard Proctor cylinder (1/30 cu ft). They were molded at optimum moisture content as determined by compaction tests. The quantities of lime used were 2, 5 and 10 percent by dry weight.

Curing and Freeze-Thaw Testing. After compaction each specimen was weighed and placed in a moist room to cure for periods of 1, 4, 8, 15, and 36 weeks. After the prescribed curing period, one of each pair of specimens was weighed, measured, and placed in a freezer for 24 hr. Air temperature in the freezer was maintained at 24 F. This temperature was chosen since soil temperatures in the Midwest seldom go below this level.

Upon the completion of the 24-hr freezing period, the specimens were removed from the freezer, reweighed, measured for volume change, and permitted to thaw. During the 24-hr thawing period the specimens rested on porous stone disks with free water available for absorption through the disks. At the end of this period the specimens were again weighed and measured, tested with the soniscope, and returned to the freezer. Twelve of the above described cycles constituted the durability test for each specimen.

Durability Tests. Pulse velocities were measured through all specimens at the end of the curing period and after each cycle of thawing. Each specimen was tested until it failed or until 12 cycles of freezing and thawing were completed. The only exception occurred when the soniscope was overhauled for four days. During this period some specimens underwent two cycles of freezing and thawing without being tested. This is indicated on the attached data curves by dashed lines. These curves have been selected to show the influence of certain variables upon the durability of lime-soil specimens as evidenced by change in velocity.

Figure 7 shows the influence of soil type upon durability. Each of the specimens contained 10 percent lime and was cured for 8 weeks. A marked difference in performance may be noted. The specimen made from Soil 2849, the Wisconsin drift soil, shows continuous progressive distress, the velocity at the end of 12 cycles being only about 56 percent of the original velocity. The specimen made from Soil 2853, Illinoian drift, showed little distress until after seven cycles were completed. Deterioration then progressed until after 12 cycles, the velocity being only about 58 percent of its value after curing. The specimen made from Soil 3068, river terrace gravel, showed no significant loss in velocity after 12 cycles of freezing and thawing. This specimen was actually put through 30 cycles without suffering severe distress.

Figure 8 shows the influence upon durability of the percentage of lime mixed with the soil. Specimen 34, containing no lime, failed while being handled at the end of two cycles of freezing and thawing after having lost approximately 36 percent of its original velocity. Specimen 35, made with 5 percent lime, showed a more or less gradual loss in velocity throughout the 12 cycles, its final velocity approximating 54 percent of the original value. The specimen with 10 percent lime, No. 36, showed no appreciable loss in velocity until after seven cycles. From this time on, the velocity fell steadily to a value at the end of 12 cycles equal to 58 percent of the original velocity. It may be observed that Specimens 35 and 36 had essentially the same velocity at the end of the curing period and at the end of 12 cycles of freezing and thawing. It may be important, however, that the time at which the loss in velocity begins to occur was considerably delayed by increasing the lime content of the specimen.

Figure 9 shows the effect of length of curing upon durability. Specimens 62, 68, 30, 36, and 96 were cured 1, 4, 8, 15 and 36 weeks, respectively. After 12 cycles of freezing and thawing their respective losses in velocity, based upon their velocities at the end of the curing periods, were 48, 39 (after 11 cycles), 37, 44 and 27 percent. In addition to the comparative loss in velocity during freezing and thawing, attention is called to the actual values of the measured velocities. The specimens cured for 4, 8 and 15 weeks showed a very similar percentage decrease. Generally speaking, however, at the end of any given cycle the specimens with the longer curing periods had the higher velocities. This indicates, in the light of past experiences in testing other materials, that the physical properties of these specimens (modulus of elasticity, strength, etc.) were higher than those of the specimens cured for the lesser time.

Conclusions

Relative to the use of the pulse velocity technique, Whitehurst and Yoder concluded that it was satisfactory for their purpose. Results were reproducible and there appeared to be little operator error. It was believed that changes in velocity are highly indicative of changes in the quality of specimens such as were tested in this study.

REFERENCES

1. Whitehurst, E. A., "Use of the Soniscope for Measuring Setting Time of Concrete." Proceedings, ASTM, Vol. 51, p. 1166 (1951).
2. Batchelder, G. M., and Lewis, D. W., "Comparison of Dynamic Methods of Testing Concretes Subjected to Freezing and Thawing." Proceedings, ASTM, Vol. 53, p. 1053 (1953).
3. Whitehurst, E. A., and Yoder, E. J., "Durability Tests on Lime Stabilized Soils." Proceedings, HRB, Vol. 31, p. 529 (1952).
4. Jones, R., "The Non-Destructive Testing of Concrete." Magazine of Concrete Research, London, No. 2 (June 1949).
5. Arndt, A. J., "Discussion of 'Dynamic Testing of Concrete with the Soniscope Apparatus' by W. J. Cheesman." Proceedings, HRB, Vol. 29, p. 176 (1949).
6. Long, B. G., and Kurtz, H. J., "Effect of Curing Methods upon the Durability of Concrete Measured by Changes in the Dynamic Modulus of Elasticity." Proceedings, ASTM, Vol. 43, p. 1051 (1943).
7. Long, B. G., Kurtz, H. J., and Sandenaw, T. A., "An Instrument and Technique for Field Determination of Modulus of Elasticity of Concrete (Pavements)," Proceedings, American Concrete Institute, Vol. 41, p.217 (1945).

8. West, H. H., "Determination of Young's Modulus of Elasticity for Concrete by a Velocity Method." U. S. Bureau of Reclamation, Materials Laboratories Report No. C-322 (September 19, 1946).
9. West, H. H., "Measurements of Vibration Wave Velocities Through Concrete Structures." U. S. Bureau of Reclamation, Materials Laboratories Report No. C-468 (November 10, 1949).
10. Leslie, J. R., and Cheesman, W. J., "An Ultrasonic Method of Studying Deterioration and Cracking in Concrete Structures." Proceedings, American Concrete Institute, Vol. 46, p. 17 (1950).

Evaluation of Pulse Velocity Tests

BAILEY TREMPER, Supervising Materials and Research Engineer, California Division of Highways, Sacramento

●THE CALIFORNIA Division of Highways acquired a soniscope of Canadian manufacture in 1952. It has been used intermittently since then in condition surveys of timber and concrete structures. A few examples of its use will be described.

The soniscope has been found to be useful in detecting hidden decay in wood bridge piles and timbers. Small volumes of decayed wood cause a substantial drop in pulse velocity. Since virtually the entire member can be scanned rapidly at close intervals, pulse velocity measurements permit a more thorough survey than is practical by conventional means of boring and sounding. The results, however, must be interpreted with caution. Sound Douglas fir or redwood when dry, has a pulse velocity of the order of 6,000 to 7,000 ft per second. When thoroughly saturated, the velocity may be as low as 5,500 ft per second. The velocity of decayed wood when dry, may be as low as 4,000 ft per second, but when saturated, may rise to 5,200 ft per second. Obviously, more significant results can be obtained during the dry season. Low velocities found in certain timber piles have been found to be due to hidden circumferential shakes. Small volumes of decayed wood that might be overlooked in a conventional survey by boring and sounding, can be detected by a systematic survey with the soniscope, but confirmation of the suspected condition should be made by boring.

The pulse velocity of concrete in sound condition may vary within the range of 12,000 to 15,000 ft per second. The interpretation of soniscope readings of old concrete is seriously handicapped unless a good value for the particular concrete in a sound condition can be established. One solution lies in assuming that the highest velocities found in protected portions of the structure represent sound concrete. In the absence of good information, velocities above 12,000 ft per second may or may not be indicative of deterioration.

If the velocity is lower than about 10,000 ft per second, it may be assumed that deterioration has occurred, but in such cases there is usually visible evidence of the condition. The value of the soniscope result, then, lies in the possibility of assigning a numerical rating to express the degree of deterioration. Unless the pulse velocity of the concrete when it was sound is known, the assumed rating may not be suitable for comparison with other concrete. Nevertheless, without knowledge of previous pulse velocity, information of value may be obtained if successive readings are taken over a period of years. Such data may indicate a trend in rate of deterioration from which estimates of useful life may be made.

Deterioration of concrete due to alkali-aggregate reaction has been studied with the soniscope on several bridges 25 to 30 yr old. The general experience has been that pulse velocities vary over considerable range within short distances, a result that undoubtedly is due to a random distribution of cracks of varying width and depth.

An example of pulse velocity measurements of a bridge affected by alkali-aggregate reaction is given in Table 1.

The velocities shown in Table 1 are averages of results across several paths with the transducers placed each time at marked points. Inability to secure consistent readings from year to year is believed to be due to variations in moisture conditions and consequent changes in the width of cracks or of exudations within the cracks.

TABLE 1

BRIDGE 44-06, CONSTRUCTED 1931
1000-ft Steel Spans and 654-ft Reinforced Concrete Approach Spans

Part of Structure	Average Pulse Velocities, (ft per second) Dec 1953	Nov 1954	Nov 1955	% Change, 1953 to 1955
Beams at E end				
Inner	13,700	14,600	14,100	+2.8
Outer	10,700	9,800	9,800	-8.4
Columns	9,600	8,600	8,100	-15.6
E. Pier for Steel Span				
Central Portion	8,800	7,800	8,400	-4.5
North End	6,300	6,000	6,600	+4.2

Figure 1. Crack in top face of bridge strut, December 1953.

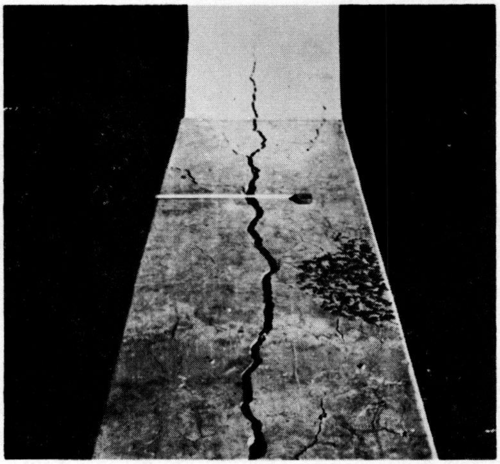

Figure 2. Same view as Figure 1, November 1955.

The inner beams are free from visible cracks and appear to represent concrete that has not been weakened by alkali-aggregate reaction because of protection from rainfall. They thus form a basis for estimating the percentage drop in pulse velocity of affected parts. Using the results obtained in 1955 (age 24 yr), reductions in pulse velocity are as follows:

Outside Beams	30 percent
Columns	43 percent
Pier, Central Portion	40 percent
Pier, End	53 percent

This bridge is still carrying main line traffic, and except for the deck, has not been repaired.

An illustration of periodic variations in pulse velocity due to alkali-aggregate reaction is afforded by tests of several large fragments from a bridge at Pismo Beach that was constructed in 1925 and was wrecked in 1955 to make room for freeway construction. The fragments in question were secured at locations where protection from rainfall was afforded by the deck. They were brought to the laboratory and after sawing the ends to produce plane faces for application of the soniscope transducers, were immersed in water for 10 days and subsequently have been stored in the fog room. A record of pulse velocity of one of the fragments which in general typifies the behavior of all, starting at the end of the 10-day soaking period, is as follows:

Months in Fog Room	Pulse Velocity (ft per second)	Months in Fog Room	Pulse Velocity (ft per second)
0	12,600	8	9,500
1	13,000	9	12,800
2	13,500	10	13,600
3	13,800	13	13,600
4	13,200	16	12,900
5	13,000	20	14,400
7	9,500	22	13,000

The results indicating alternate periods of weakening and recovery, are typical of five other specimens but maximum and minimum velocities are not found at the same ages. The results, therefore, indicate that the observed variations are not due to errors in

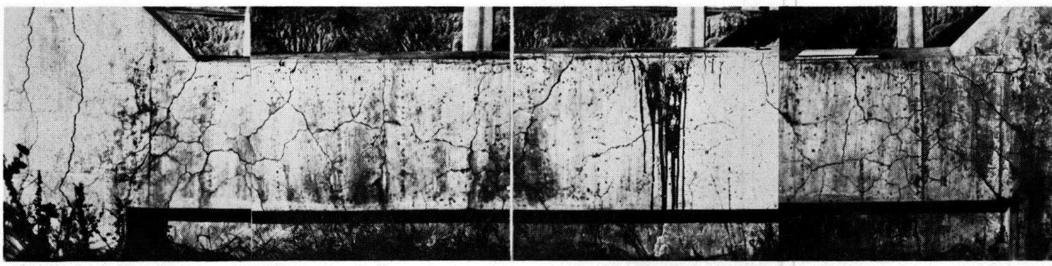

Figure 3. Side of strut shown in Figures 1 and 2.

soniscope measurements. Continuous exposure to saturated air has produced a gelatinous film on the surfaces and a number of pop-outs have developed.

The results illustrate the difficulty of forecasting the future course of deterioration of concrete in structures affected by alkali-aggregate reaction unless it can be done after many years of measurements.

A horizontal strut between columns of the Pismo Beach structure was observed to have a longitudinal crack which in 1953 had a surface width of $^3/_4$ in. The depth of the crack estimated from pulse velocity measurements at various distances was 6 in. In 1955, the surface width of the crack had increased to $1^1/_2$ in. and its depth was estimated to be 28 in. Top and side view of this strut are shown in Figures 1, 2, and 3.

The extreme width of cracks in this structure raised the question of the condition of the reinforcing steel, particularly since it is located about one-half mile from the ocean. Due to a misunderstanding with the contractor, an opportunity was not afforded to examine the reinforcement at critical locations as the structure was being wrecked.

The soniscope has been used in surveying the condition of the San Mateo-Hayward Bridge[1], a low level structure 7 mi long spanning the southern arm of San Francisco Bay. Chemical and physical tests of cores indicate that at the age of 25 years, the concrete has undergone a moderate amount of sulfate attack. The general average of pulse velocity in this concrete is about 13,000 ft per second. In a few locations, in uncracked concrete, pulse velocities lower than 11,000 ft per second have been measured. Only one series of pulse velocity measurements has been made to date, but it seems probable that future surveys will make it possible to follow the progress of sulfate attack and furnish a warning if a serious condition should develop.

A reinforced concrete bridge deck with frequent cracking visible on the surface was surveyed with the soniscope primarily because the lower side of the deck is difficult of access for visual inspection. Some difficulty was experienced in interpreting pulse velocities because of the presence of closely spaced reinforcing steel. However, when diagonal paths were selected, low pulse velocities were believed to be reliable indications that many of the cracks visible on the surface did in fact extend the full depth of the slab.

In cooperation with Southern California Edison Company and the Portland Cement Association, comparative tests for pulse velocity have been made with three soniscopes each operated by separate crews. Excellent agreement from a practical standpoint was found.

There is a need for a reliable calibration bar. It would serve a useful purpose in training soniscope operators. It would improve the accuracy of readings taken over short paths. It would provide a base for adjusting velocity measurements made several years apart, possibly with different instruments.

Periodic adjustments or the replacement of parts of the soniscope may be required. For this reason it is desirable that the operator be well trained in electronics of that he have ready access to the services of a competent technician.

---

[1] Tremper, Bailey, Beaton, John L., and Stratfull, R. F., "Corrosion of Reinforcing Steel and Repair of Concrete in a Marine Environment, Part II." HRB Bulletin 182.

Eight Years of Pulse Velocity Tests on Concrete Pavements in Kansas

RICHARD C. MEYER, Electronics Engineer, State Highway Commission of Kansas

For the past eight years the Kansas Highway Commission has been investigating the changes in pulse velocity which occur with changes in concrete quality. A soniscope, as developed by the Hydro Electric Power Commission of Ontario, Canada, and the Portland Cement Association, has been used for making these tests.

Pulse velocity tests have been made regularly on eight experimental pavements which have been constructed in Kansas. Each of these test roads are made up of a number of test sections which contain concrete of varying composition. One such test road near McPherson, Kansas, is made up of 60 test sections which contain five different brands of cement along with several pozzolanic additives. Test sections in the other experimental pavements contain concrete which in some cases is air-entrained. Other variables included in these test sections are coarse and fine ground cement, different types of aggregate, and different methods of curing. The regular tests on these several test pavements have been made in an effort to establish a non-destructive method for studying changes in concrete quality which may not be apparent upon visual inspection.

Along with the regular velocity tests made on concrete pavements, pulse velocity determinations were also made periodically on test beams containing concrete comparable to that found in the several pavement test sections. These test specimens were then loaded in flexure to failure so that the modulus of rupture could be calculated. These velocity tests were then compared with the flexural strengths to see if changes in velocity could be associated with changes in modulus of rupture.

After studying the results of the large number of tests, several observations can be made. For the tests made on Kansas highway pavements, visual evidence of deterioration is obvious before this condition is reflected in a significant change in pulse velocity. Seasonal changes in pulse velocity tend to obscure velocity trends which otherwise might be significant. Although a small change in pulse velocity is often associated with a large change in flexural strength, no good relationship between the two is apparent at this time.

●FOR MANY YEARS investigators have been searching for a non-destructive test to determine concrete quality. In recent years attempts have been made to use resonant frequency and pulse velocity techniques for such tests. The resonant frequency method, which is only applicable to small, regularly shaped sections, has been used successfully. The pulse velocity method, which was originally developed to test large masses of concrete for deteriorated areas or cracks, has recently been used as a tool to check the general quality of concrete. For these tests a high pulse velocity has been thought to be indicative of good concrete quality and low velocity to indicate inferior quality.

In 1949 the Kansas Highway Commission embarked upon an accelerated program of concrete pavement research. A number of test roads were planned with test sections constructed of concrete of varying composition. Along with the conventional methods of evaluating the results of these roads, it was decided to use the soniscope to make pulse velocity determinations of the concrete in the pavement slabs.

One of these test roads, a 5-mi project near McPherson, Kansas, consists of 60 sections which contain various pozzolanic additions and five different brands of cement. Each combination of the above test variables is found in a section containing air-entrained concrete and in another section without air entrainment. The purpose of this project is to study the reactive expansion of concrete containing various pozzolanic additives in an attempt to reduce this expansion. This expansion, which is accompanied by map cracking, is thought to be a chemical reaction between the cement and the aggregate. Certain additives have been found to decrease expansion and make the cement and aggregate more compatible.

The second test road built in 1949 is located south of Topeka, on Highway US-75. This 8-mi test road is made up of 36 test sections which differ in the type of cement used, maximum size of aggregate and in the method of curing. The three types of cement used varied in composition and fineness. The purpose of this test road is to study the strength gaining qualities and durability of concrete containing these cements in an effort to establish which type of cement is superior.

In 1950 six other test roads were built in various locations in Kansas. The concrete in these test roads included these same three types of cement and in some cases was air-entrained. These roads were constructed to study the relative qualities of these several cement types under varying climatic conditions when used with different aggregates with and without air entrainment.

In the summer of 1949 the Kansas Highway Commission secured the loan of a soniscope which was used for the early pulse velocity tests on the McPherson and Topeka test roads. This soniscope had once been the property of the Portland Cement Association. The machine, while operating within rather wide accuracy limits, was difficult to use as a portable machine in the field.

In 1950 a new soniscope was built from plans obtained from Cheesman and Leslie of the Hydro Electric Power Commission of Ontario, Canada. This instrument is much smaller that the first model and easier to transport. The new soniscope is more sensitive and the transit time of the transmitted pulse can be more accurately determined. This machine has operated satisfactorily and has been used for all tests made since 1950.

TEST PROCEDURE

Pulse velocity tests have been made on these test roads at regular intervals at locations marked permanently in the slab. There are between 5 and 10 marked locations in each test section depending upon section length. This method of marking allows pulse velocity tests to be made each time at the same location. This rules out apparent velocity changes which might result if subsequent tests were made at slightly different locations on the pavement slabs.

All tests made on pavement slabs have been made with both of the transducers resting on the surface of the slab and spaced 4 ft apart. The transducer spacing is necessarily decreased when pulse velocity determinations are made on test beams. In order to insure that the transducer spacing remains constant, both transducers are mounted on a frame which facilitates the placing of the transducers on the slab. The trasducers are placed on the slab as a single unit which is then self-supporting. This method of transducer placement eliminates errors due to differences in transducer pressure, which change the effective path length of the transmitted pulse.

For the early tests, castor oil was used to lubricate the transducers to provide a good energy transfer between the transducer diaphragms and the surface of the concrete. For the past two years a carboxy methyl cellulose solution has been used for this purpose. No difference in transit time was noted for the different lubricants so long as sufficient quantities of both were used.

The pulse velocities as measured with the Kansas Highway Commission's soniscope are reproducible within one percent for path lengths of 3 ft or more. Little difficulty has been experienced in obtaining the pulse velocities, but the significance of these velocities is in doubt.

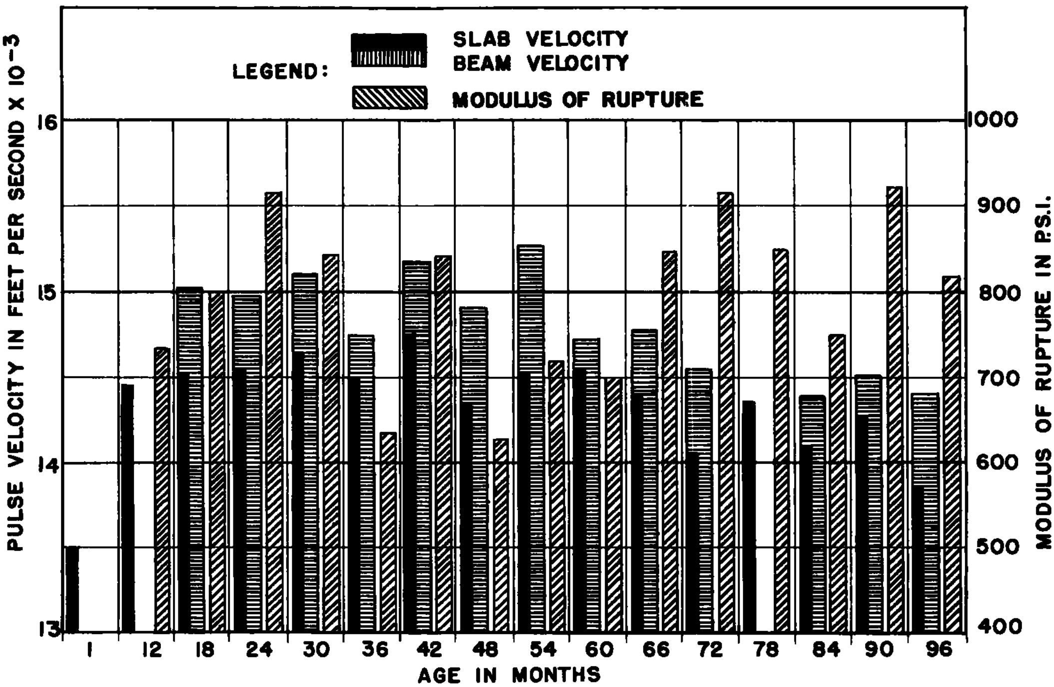

Figure 1. Correlation of pulse velocity and flexural strength on the McPherson Test Road.

RESULTS OF PULSE VELOCITY TESTS ON EXPERIMENTAL ROADS

Pulse velocity determinations have now been made regularly on these tests roads for a period of 8 yr. Each year some 1,400 separate pulse velocity determinations have been made on pavement slabs. Since 1951 about 250 determinations have been made on associated test beams each year prior to their being tested for modulus of rupture. For the past 2 yr all test beams have been soaked 24 hr prior to testing in an effort to obtain a standard moisture condition.

The average pulse velocities for all of the test sections and beams of the McPherson test road are plotted along with the modulus of rupture of the test beams in Figure 1. The tests plotted on the chart at ages 12, 24, 36, etc., were made in the fall. The pulse velocities have generally followed a seasonal pattern with the velocities being somewhat higher in the spring than in the fall. The pulse velocities for the test specimens averaged about 500 ft per sec higher than the velocities on the associated slab sections. The general velocity trend shows a slight decrease in both beam and slab pulse velocity.

Little correlation is visible between pulse velocities and the modulus of rupture. There have been large fluctuations in the modulus of rupture for the several test periods. The periodic or seasonal variation in both modulus of rupture and pulse velocity for the test beams has continued for the last four test periods shown in Figure 1 in spite of the 24-hr soaking interval. Large changes in modulus of rupture are accompanied, in most cases, by rather small changes in pulse velocity in the same direction. Small changes in modulus of rupture, however, may be associated with velocity changes in either direction.

Pulse velocities of three of the ten classes on concrete in the McPherson test road are shown in Table 1. The control sections for this project, designated as Class 1, are composed of concrete containing mixed aggregate with no pozzolanic material. This mixed aggregate is a river sand with a gradation factor of 3.58. Class 3FA concrete contains the same mixed aggregate with the addition of flyash as a pozzolan. Class 5 concrete contains this basic aggregate, 30 percent of which was replaced with crushed limestone.

TABLE 1

PULSE VELOCITIES BY CLASSES ON THE McPHERSON TEST ROAD[1]

	1 Mo	12 Mo	18 Mo	24 Mo	30 Mo	36 Mo	42 Mo	48 Mo	54 Mo	60 Mo	66 Mo	72 Mo	78 Mo.	84 Mo	90 Mo	96 Mo
Class 1																
Slab	13,500	14,660	14,590	14,640	14,560	14,490	14,610	14,330	14,530	14,410	14,210	13,960	14,150	13,880	14,010	13,670
Beams	--	--	15,140	15,150	15,140	14,540	14,680	14,300	14,580	13,810	14,030	13,760	--	13,480	13,720	13,320
Class 3 FA																
Slab	13,650	14,860	14,940	15,030	15,150	14,980	15,340	14,850	15,050	15,090	14,960	14,550	14,890	14,570	14,810	14,360
Beams	--	- --	15,380	15,350	15,520	15,290	15,740	15,400	15,900	15,280	15,340	15,280	--	14,910	15,020	15,080
Class 5																
Slab	14,070	14,970	15,030	15,030	15,190	15,100	15,340	14,850	15,030	14,990	14,850	14,580	14,840	14,580	14,680	14,320
Beams	--	--	15,420	15,450	15,510	15,220	15,610	15,540	15,790	15,300	15,160	15,110	--	14,970	14,910	14,850

[1] Pulse velocities in ft per sec

The pavement slabs in Class 1 show greater signs of deterioration than any of the other classes. Map cracking is extensive on these slabs and the test beams are also badly map cracked. This class has had a greater loss in pulse velocity than any of the other classes. Pulse velocities on some of the Class 1 test beams have decreased as much as 2,000 ft per sec. These beams, however, have deteriorated to such an extent that the received pulse on the soniscope in indefinite and the transit time is difficult to determine accurately. The pulse velocities for Class 3FA have averaged higher than any of the other classes. The flexural strength of the test beams in this class has also been high, but the condition of the slab is no better than some of the other classes which have lower velocities. The Class 5 concrete has the best service record in the field. This class has a high pulse velocity and very little map cracking on the pavement slab.

Pulse velocities for the Topeka test road along with the modulus of rupture of the test beams are plotted in Figure 2. Large fluctuations in pulse velocity and in modulus of rupture are not found for this test road. The seasonal pattern is not so apparent as on the McPherson test road. The pulse velocity of the slab has been in most cases somewhat higher than that of the beams.

No significant trends in velocity are apparent at this time for the Topeka test road. The pavement in this road is in generally good condition and little difference is visible between the several test sections. No close correlation is found between pulse velocity and modulus of rupture on the Topeka test road.

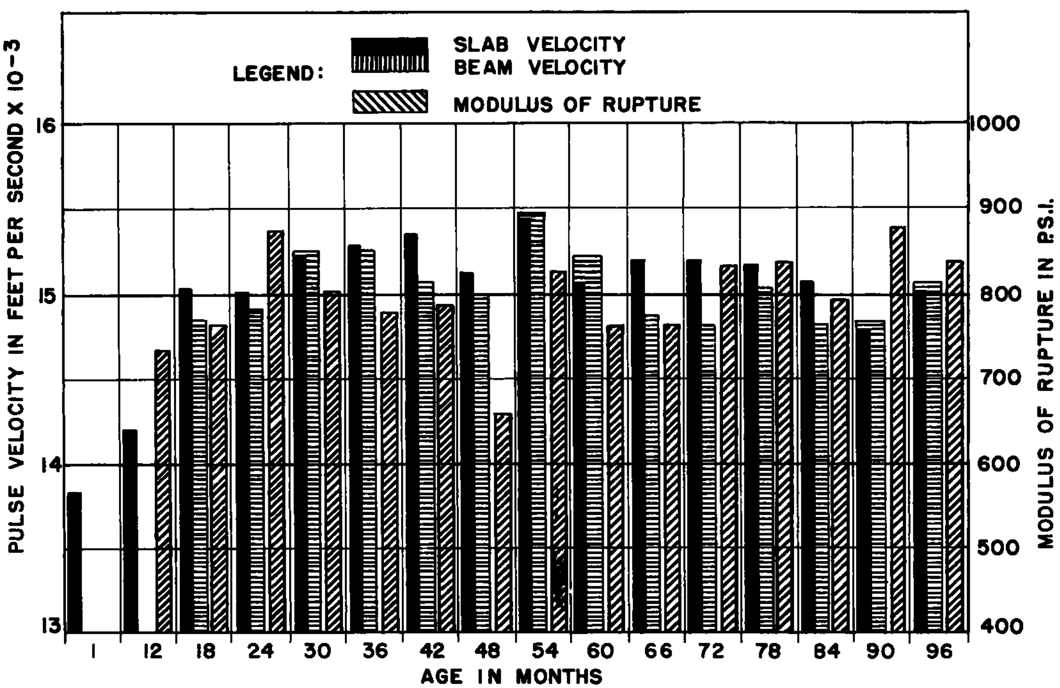

Figure 2. Correlation of pulse velocity and flexural strength on the Topeka Test Road.

The average pulse velocities for the six other test roads and the modulus of rupture of the test beams are plotted in Figure 3. The slab and beam velocities show decreasing trends, but no decrease in the modulus of rupture is in evidence. The pavement slabs are generally in good condition with few visible signs of deterioration at this time.

The test sections having air-entrained concrete have consistently had a pulse velocity 500 to 600 ft per sec lower than the same type of concrete without air entrainment.

OTHER PULSE VELOCITY INVESTIGATIONS

During the summer of 1951 a pulse velocity survey was made on a number of older concrete pavements. Between 20 and 40 separate velocity determinations were made on 48 projects which ranged in age from 1 to 29 yr. The average velocities for these projects fell between 13,800 and 15,900 ft per sec. No definite relationship between the age of the projects and the pulse velocity was apparent.

Map cracking was prevalent on a number of these pavements. In an effort to establish a relationship between pulse velocity and the degree of map cracking, test locations where map cracks were visible are classified as faint, medium, or severely map cracked. These averages are shown in Table 2 along with the number of test locations included in each category.

A decrease in sound velocity evidently accompanies map cracking, but the average difference was only about 500 ft per sec between severely map cracked areas and areas in the same projects where no map cracking was found. This apparent decrease in velocity may be due entirely to an increased path length because of the map cracks, and may not represent an actual change in velocity through the material. Changes in moisture content in the field were thought to be responsible for the seasonal changes in pulse velocity as found on the McPherson test project. In 1953 a group of thirty-six 3- by 4- by 16-in. test beams, which were cast at the time the test roads were built, were used for making moisture tests. These beams were soaked in water for six days and pulse velocity determinations were made. The beams were then dried in an oven at 125 F for 7 days. After the beams had cooled to room temperature, pulse velocity measurements were again made.

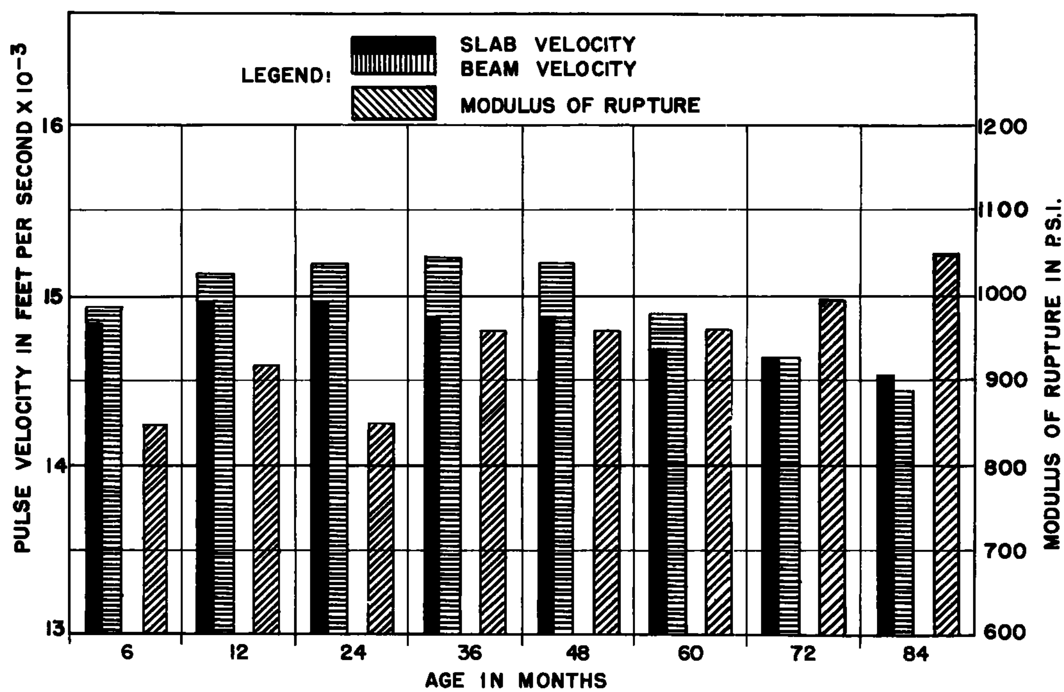

Figure 3. Correlation of pulse velocity and flexural strength on other Kansas Test Roads.

TABLE 2

Map-Cracking Category	Number of Determinations	Average Velocity ft per sec
None	155	14,445
Faint	109	14,300
Medium	64	14,265
Severe	53	13,975

The average velocity for the test beams in the saturated condition was 16,780 ft per sec. In the dry condition, the velocity was 15,760 ft per sec. Between the two tests the specimens had lost an average of 1.2 percent of their weight due to loss of moisture, and the pulse velocity decreased 6.1 percent. This change in pulse velocity due to a change in moisture content indicates that much of the seasonal variation found on the several test roads may be due to changes in concrete moisture.

In an attempt to establish in what manner the pulse velocity varies as an area of visible deterioration is approached, a number of special velocity investigations were made. Special emphasis was placed on areas and joints where considerable "D" cracking was evident. Successive readings were taken in the vicinity of such discontinuities so that velocity patterns could be established. The pulse velocity was expected to decrease substantially as the transducers were placed successively closer to a deteriorated area; this, however, was not the case. In a few instances there was a small decrease in velocity, 200 to 300 ft per sec, as a deteriorated spot was approached, but no pronounced decrease was noted until the transducers were actually resting on a cracked or disintegrated area of concrete. If this deterioration was of a nature that the concrete was no longer a continuous medium, a definite transit time could not be determined and the pulse velocity became meaningless.

CONCLUSIONS

1. For all tests made on concrete pavements in Kansas, visible signs of distress have been apparent before significant changes in pulse velocity have indicated this deterioration.
2. Changes in moisture content of concrete slabs apparently account for a seasonal variation in pulse velocity. These changes vary in magnitude with the season and tend to disguise pulse velocity trends which otherwise might be obvious.
3. Small decreases in velocity have been found on concrete pavements in deteriorated areas. In most cases, however, if the deterioration is pronounced the transit time cannot be accurately measured and no true velocity can be calculated. The apparent decrease in velocity in disintegrated areas seems to be due to a longer path length for the transmitted pulse rather than to a decrease in the modulus of elasticity.
4. Although changes in pulse velocity and changes in modulus of rupture correlate in a general way, no close relationship between the two seems to exist.

REFERENCES

1. Breuning, S.M., and Roggeveen, V.J., "Fundamentals of Field Soniscope Testing." HRB Proceedings, Vol. 34, p. 379 (1955).
2. Cheesman, W.J., "Dynamic Testing of Concrete with Soniscope Apparatus." HRB Proceedings, Vol. 29, p. 176 (1949).
3. Jones, R., and Catfield, E.N., "Testing Concrete by an Ultrasonic Pulse Technique." Road Research Technical Paper No. 34, London (1955).
4. Kozan, G.R., "Nondestructive Testing of Concrete Pavements." HRB Proceedings, Vol. 34 p. 368 (1955).
5. Leslie, J.R., and Cheesman, W.J., "An Ultrasonic Method of Studying Deterioration and Cracking in Concrete Structures." A.C.I. Journal, p. 17 (Sept, 1949).
6. Whitehurst, E.A., "Pulse-Velocity Techniques and Equipment for Testing Concrete." HRB Proceedings, Vol. 33, p. 226 (1954).

Effect of Certain Variables on Pulse Velocities Through Concrete

R. E. BULLOCK, Assistant Professor of Civil Engineering; and
E. A. WHITEHURST, Associate Director, Engineering Experiment Station,
The University of Tennessee

● IT HAS been recognized, almost since pulse velocity testing of concrete was first successfully accomplished, that there are many variables involved which will influence the velocity. Few reports, however, have been published of work undertaken to clearly establish the effect of even the more common variables. One notable exception exists in the work of Jones,[1] who reported as a result of his studies, that pulse velocities might be adequately employed as a measure of variation in concrete quality if the aggregate-cement ratio of the concretes did not vary.

With the continually increasing use of pulse velocity techniques for examining concrete in place, it has become clear that an investigator must have some knowledge of the effect of variables upon pulse velocity if he is to intelligently evaluate the pulse velocity differences which may be found within a structure. This study was undertaken to determine the effect of variations in type of aggregate, maximum size of aggregate, percentage of paste, water-cement ratio, age, and curing conditions upon pulse velocities. The work was accomplished in the laboratories of the Department of Civil Engineering at the University of Tennessee under the supervision of the Engineering Experiment Station.

MATERIALS

Two types of coarse and fine aggregate were employed throughout the study. One was manufactured from a dolomitic limestone obtained from the Mascot Quarries of the American Zinc Company. This aggregate has a saturated surface dry specific gravity of 2.81. The other was a Tennessee River sand and gravel supplied by the Knoxville SanGravl Materials Company and has a saturated surface dry specified gravity of 2.64.

All cement used in the study was a Type I portland cement supplied in a single order by the Volunteer Portland Cement Company.

PROCEDURES

Three specimens were made from each mix. They were cast into steel molds nominally 3 by 4 by 16 in. with the 3-in. dimension vertical. After one day in the molds the specimens were removed and stored in a moist room. They were periodically removed from the moist room for only a sufficient time to permit pulse velocity measurement by the use of a soniscope, and then immediately returned.

After 28 days of moist curing, one specimen from each mix was removed and stored in air in the laboratory for an additional 28 days. The others remained in the moist room. At an age of 56 days, all specimens were tested with the soniscope and then broken in flexure by third-point loading on a 12-in. span with the 4-in. dimension vertical. One end of each broken beam

TABLE 1

AGGREGATE DESIGNATIONS OF SPECIMENS

Central No.	Max. Size	Type
6	No. 4	Limestone
7	3/8 in	Limestone
8	1/2 in.	Limestone
9	3/4 in.	Limestone
10	1 in.	Limestone
11	No. 4	River Aggregate
12	3/8 in.	River Aggregate
13	1/2 in.	River Aggregate
14	3/4 in	River Aggregate

[1] Jones, R., "Testing of Concrete by Ultrasonic-Pulse Technique." HRB Proceedings, Vol. 32, p. 258 (1958).

was then tested in compression using 3- by 3-in. steel plates to apply the load at the end of the specimen, along the 4-in. axis. Care was takenthroughout the experiment to insure that moist specimens remained moist until tested.

The type and maximum size of aggregate and the water-cement ratio for each specimen is indicated by a specimen designation. A prefix letter, A, B, or C, was used to indicate a water-cement ratio of 5, 6, or 7 gallons per sack, respectively. The central number indicates the type of aggregate and maximum size thereof as shown in Table 1. All aggregates were well graded below the indicated maximum size. A final number identifies the individual specimen within a group. Thus, Specimen B-8-2 was the second specimen in a group having a water-cement ratio of 6 gallons per sack and limestone aggregate having a maximum size of ½ in.

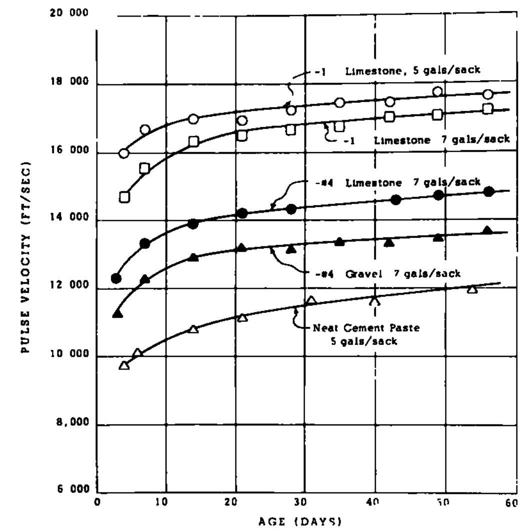

Figure 1. Variations in pulse velocity with age during continuous moist curing.

RESULTS

Figure 1 indicates the variation of pulse velocity with age for a number of specimens selected from those stored continuously in the moist room. In all cases the pulse velocity increases at a decreasing rate similar to a strength versus age curve.

Figure 1 also indicates variations between mixes. The lowest curve on the figure is for a neat cement paste having a water-cement ratio of 5 gallons per sack. Moving up the graph the next two curves represent concretes containing river and limestone aggregates, respectively, in which the maximum size aggregate passed the No. 4 sieve and the water-cement ratio was 7 gallons per sack. The top two curves represent concretes containing limestone aggregate all of which passes a 1-in. sieve, with the lower of the two curves having a water-cement ratio of 7 gallons per sack and the higher a water-cement ratio of 5 gallons per sack.

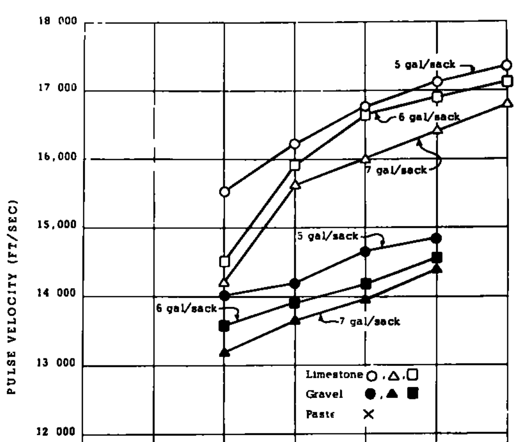

Figure 2. Variations in pulse velocity with maximum size of aggregate after 28 days curing.

Figure 2 shows the effect of aggregate, both type and maximum size, upon pulse velocities through concrete at an age of 28 days. Points at the lower left of the figure represent tests through specimens of neat cement paste. It should be observed that the specimens made from pastes having water-cement ratios of 6 and 7 gallons per sack had identical velocities. There was considerable cement particle settlement before initial set in the specimen having the highest water-cement ratio, the resulting upper surface was quite concave, and the specific gravities of the two specimens were determined to be equal to 1.89. It is believed that sufficient settlement occured in the specimen made with a 7 gallon per sack water-cement ratio to reduce its actual ratio to a value quite near to 6 gallons per sack.

When aggregate was added to the paste the velocity increased considerably, regardless of the type or size of the aggregate. In every case the velocity continued to rise as the maximum size of aggregate was increased, from the No. 4 size to ¾ in. in the case of the river aggregate or to 1 in. in the case of the limestone aggregate. It should also be observed that all mixes containing limestone aggregates had considerably higher velocities than did similar mixes containing river aggregate.

Since it is clearly evident that the addition of aggregate to cement paste increases the pulse velocity materially, it might be presumed that the pulse velocity is a function of the percentage of paste. Figure 3 shows a relationship between the percentage of paste and pulse velocity for mixes of each of the three water-cement ratios with the limestone aggregate concrete. In a general sense the velocity decreases as the percentage of paste increases. At the left edge of the three curves, however, are three points representing tests on specimens having essentially the same paste content but differing in maximum size of aggregate. In each case, velocity increased as the size of the aggregate increased although the percentage of paste remained practically constant. It is thus indicated that the velocity is a function of both the percentage of paste and the maximum size of aggregate.

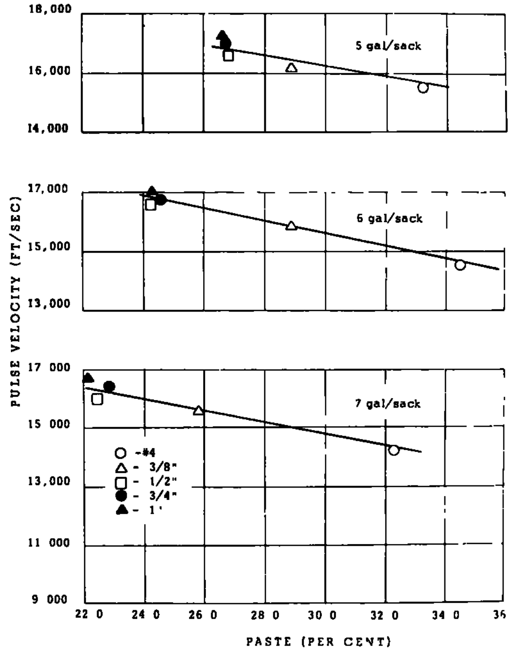

Figure 3. Variations in pulse velocity with paste content for limestone aggregate concrete.

TABLE 2

EFFECT OF DRYING UPON PULSE VELOCITY

Mix No	Type Curing[1]	Velocity at Indicated Age (days) 28	35	42	56
A-7	1	16,100	16,300	16,400	16,700
A-7	2	16,200	16,100	16,300	16,300
A-8	1	16,700	17,000	17,100	17,300
A-8	2	16,700	16,700	16,800	16,900
A-10	1	17,300	17,500	17,500	17,700
A-10	2	17,500	17,500	17,500	17,500
A-13	1	14,600	14,800	14,800	14,900
A-13	2	14,700	14,300	14,400	14,400
B-7	1	15,900	16,000	16,200	16,300
B-7	2	15,900	15,900	16,000	16,100
B-8	1	16,700	16,600	16,800	16,900
B-8	2	16,700	16,500	16,500	16,600
B-10	1	17,100	17,300	17,400	17,600
B-10	2	17,100	16,900	16,900	17,200
B-13	1	14,100	14,400	14,400	14,500
B-13	2	14,100	14,000	14,000	14,000
C-7	1	15,600	15,800	15,900	16,000
C-7	2	15,600	15,400	15,500	15,600
C-8	1	16,000	16,000	16,300	16,500
C-8	2	16,000	15,900	16,000	16,100
C-10	1	16,700	16,800	17,100	17,200
C-10	2	16,700	16,500	16,600	16,600
C-13	1	14,000	14,100	14,300	14,300
C-13	2	14,000	13,600	13,700	13,700

[1] Types of curing: 1. Continuously moist for 56 days.
2 Moist for 28 days, followed by exposure to laboratory air for 28 days

The specimens which were removed from the moist room at the end of 28 days and stored in air in the laboratory for the succeeding 28 days were studied carefully in an effort to determine the effect of drying, or the dicontinuance of moist curing, upon pulse velocities. The noted effect was small. Typical results are shown in Table 2 which shows velocities through companion specimens at the end of 28 days of moist curing and at the end of 7, 14, and 28 additional days of either moist curing or drying in the laboratory.

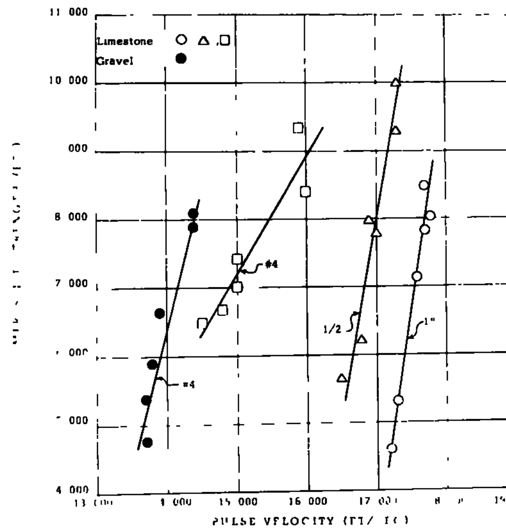

Figure 4. Relationship of compressive strength to pulse velocity after 56 days moist curing.

All but one specimen exhibited a slight decrease in velocity or no change during the first week of drying. All of the limestone specimens then exhibited an increase in velocity or no change during additional air storage. At the end of 28 days air storage, the limestone specimens made from 5 gallons per sack mixes had an average increase over the pulse velocity at the end of moist curing of 140 ft per sec, those from 6 gallon per sack mixes had an increase of 40 ft per sec, and those from 7 gallons per sack mixes averaged no change. Companion limestone specimens continuously moist cured showed an average increase of very nearly 500 ft per sec over the same period regardless of their water-cement ratio. On the other hand, the specimens made from river aggregate averaged a decrease in velocity at the end of 28 days air storage. The average decrease from the pulse velocity at the end of moist curing was 150 ft per sec for specimens made from both 5 and 6 gallons per sack mixes, and the average decrease was 250 ft per sec for those specimens made from 7 gallons per sack mixes. Companion river aggregate specimens which were continuously moist cured, showed an average increase of 330 ft per sec over the same period. The river aggregate specimens also lost a slightly greater percentage of weight in drying than did the limestone aggregate specimens.

A comparison of the compressive strengths of the ends of the continuously moist cured specimens tested as modified 3-, by 3-, by 4-in. prisms with pulse velocities measured through the specimens immediately prior to test is shown in Figure 4. There appears to be a reasonably good straight line relationship between compressive strength and pulse velocity for any particular aggregate type and gradation. In general, however, the slopes of the lines are very steep, indicating a large change in strength for a comparably small change in velocity. Since the inherent accuracy of the soniscope is such that the measurements of velocity on small specimens may not be expected to be more accurate than 100 ft per sec, it is suggested that considerable errors in strength prediction might occur. No apparent relationship was found between pulse velocities and flexural strengths of the specimens tested.

SUMMARY

The results of the tests described above indicate the following:

1. Pulse velocities through concrete continue to increase during moist curing of the concrete to ages of 56 days. This increase is essentially terminated when moist curing is terminated and in the case of some specimens a small decrease in velocity is noted when the specimens are removed from the moist room and stored in air in the laboratory.

2. Pulse velocities through neat cement paste are appreciably lower than those through concrete containing the paste.

3. For the same water-cement ratio and maximum size of aggregate, the pulse velocity will vary markedly with aggregate type.
4. For the same water-cement ratio and type of aggregate, the pulse velocity increases as the maximum size of aggregate increases and as the percentage of paste decreases.
5. For the same maximum size and type of aggregate, the pulse velocity decreases as the water-cement ratio increases.
6. A relationship between compressive strength and pulse velocity can be determined but it is different for each aggregate and aggregate gradation.

These results indicate that strength and pulse velocity are not affected in the same way by mix variables and suggest that the investigator of concrete quality in field structures must have rather accurate knowledge of any variations in age, materials, or mix proportions if he is to adequately interpret velocity variations.

Use of the Soniscope by Concrete Division, U. S. Army Engineer Waterways Experiment Station

BRYANT MATHER, Chief, Special Investigations Branch;
E. E. McCOY, Chief, Thermal Research and Field Durability Section;
E. C. ROSHORE, Materials Engineer (Concrete Research); and
J. H. SANDERSON, Physicist; Concrete Division USAEWES, Jackson, Mississippi

● THE CONCRETE Division, U. S. Army Engineer Waterways Experiment Station, was first introduced to soniscope measurements of velocity in concrete in June 1948, when it observed tests conducted at the Tuscaloosa Lock and Dam by representatives of the Portland Cement Association. The first soniscope was obtained in December 1951, another in December 1954.

Since 1951 soniscopes have been employed on a variety of field and laboratory projects, some of which are selected for comment here because of the bearing that they have on this subject. In 1957 the method was standardized for use in the Corps of Engineers by the publication of "Method of Test for Pulse Velocity of Propagation of Elastic Waves in Concrete" (CRD-C 51-57) (1).

REPRODUCIBILITY

One question that has interested many users of soniscopes is whether different soniscopes and different operators will give similar results on the same concrete. A series of comparative tests were arranged in 1952 between representatives of the Hydro Electric Power Commission of Ontario, the Portland Cement Association and the Corp of Engineers, the results of which have been previously published (2). It was indicated that checks within 2 percent could be obtained from readings through uncracked concrete of moderate path length but that when the path length was 1 ft or less or the concrete was cracked, differences between operators and instruments were greater. Since 1955 the obtaining of comparisons between the two soniscopes has been considered. The relatively frequent absence of one or the other, either on field jobs or for repair, has prevented doing so to date. It is believed, however, that they can be adjusted to check within ±1 percent. Better requirements on tolerances in electrical and electronic components and adherence thereto would probably improve the situation generally.

RELATION OF VELOCITY TO OTHER PARAMETERS

Another question that has interested many users has been that of relating velocity determinations to other parameters of the concrete. The application of velocity data has been generally limited to comparison of velocities rather than conversion of velocities to other parameters for comparison. In connection with reporting changes in specimens at field exposure stations where changes have been customarily reported in terms of relative dynamic Young's modulus of elasticity (E)—that is, change in the square of the resonant frequency; changes based on soniscope measurements have been expressed as change in the square of the velocity since E varies as the square of the velocity. Batchelder and Lewis (3) also used variation in velocity squared when relating changes indicated by soniscope tests to changes indicated by resonant frequency tests of specimens subjected to freezing and thawing, as pointed out by Woods and McLaughlin in their paper in this symposium. In a few cases it has been asked that dynamic Young's modulus be calculated from velocity data. In one set of 42 test specimens velocities from 12,000 to 21,000 fps were found, giving calculated values for E from 4 to 14 x 10^6 psi, while corresponding values of E from flexural frequency ranged from 2.3 to 6.1 x 10^6 psi. The six specimens having values of E calculated from velocity over 9 million all had E values of 6.0 to 6.1 calculated from flexural frequency. The accuracy of the velocity values greater than about 15,000 fps is doubtful.

The relation of velocity to strength of concrete has been much discussed—perhaps best by Whitehurst (4). One lot of 6 x 12 concrete test cylinders consisting of six sets of three each that gave average velocities between 14,000 and 16,000 fps has been tested. The cylinders were then broken in compression giving average compressive strengths from 2,700 to 4,900 psi. The average strengths and average velocities fall very close to the correlation line for these seven sets of data. This is probably an exception to the general rule.

In the course of tests involving the Schmidt rebound hammer, soniscope tests were made on four concrete panels that were fabricated for rebound hammer tests. No relation was found between rebound number and velocity. However, it was noted that a consistent difference was found between velocities through the same specimen over different path length—the velocity decreasing with increase in path length.

EFFECT OF SPECIMEN SIZE AND PATH LENGTH ON VELOCITY

The question of actual differences in velocity with size of specimen has been long considered. Long et al. in January 1945 (5), stated the assumption that, in small specimens, longitudinal strain is accompanied by lateral expansion or contraction that retards the wave, while in large masses, lateral displacements are suppressed and the wave travels at greater velocity. Leslie and Cheesman in 1950 (6), and later Whitehurst (7), in 1954, imply that this difference was not significant, since they indicated that if E were to be computed from velocity, the equation recommended by Long et al. for mass concrete should be used for all concrete regardless of size of the member.

Data have been obtained both from tests of relatively small prisms, 6 by 12 by 12 in., and relatively large blocks, 5 by 10 by 15 ft and 5 by 10 by 20 ft, in which velocity was found to decrease with path length—or perhaps, as Long suggested, velocity increases with increase in volume of concrete normal to the path. In the case of the small specimens (6 by 12 by 12 in.) velocities were measured over a 6-in. path ending in the centers of 12- by 12-in. faces; over a 12-in. path ending in the centers of a 6- by 12-in. face, and diagonally over a 10-in. path between points on the opposite 12 by 12 faces. On the average, velocities were found to decrease with increasing path length from 17.3 thousand fps over 6-in. length to 16.7 over the 10-in. length to 16.2 over the 12-in. path. In the larger blocks that had velocities of 14.8 to 16.0 over a 10-ft path, the velocities over a 15-ft path were 14.0 to 15.3, or 95 to 97 percent of those over the 10-ft path. These are averages of two paths in each direction in each of seven blocks with tests at four ages. Twenty-five 5- by 10- by 20-ft blocks were tested along four 20-ft paths, and six 10-ft paths at each of four ages. Again the longer path gave lower velocities. At two days age the average velocity at 10 ft was 13.7 as compared with 13.0 at 20 ft and at 365 days age the 10-ft average was 15.9 as compared with 15.0 for 20 ft.

Data comparing velocity along different path lengths through the same specimen do not permit a decision regarding the question as to whether the consistently lower velocities over the longer path are due directly to greater path length or due to lower concrete mass per unit length of path. Further tests are planned to see if this question can be answered.

EFFECT OF MOISTURE CONTENT ON VELOCITY

Data on the effect of moisture content on velocity would be desirable. Others, e.g., Sturrup, have reported that the velocity is found to increase when specimens are saturated. As an exploratory step in this direction a molded prism, 6 by 6 by 45 in., about 90 days old, that had been stored in the laboratory was obtained. It had a velocity in this condition of 15,000 fps. After soaking in water for two weeks, the velocity increased to 15,800. After drying for a week, it had dropped to 15.5 and at a month to 15.4. Then readings ceased. This experience may be similar to that reported by Sturrup on the dried slab tested in his laboratory. Then the specimen was soaked for

72 hr and the velocity was 15.4 again. It was then decided to cut the specimen into two 22-in. lengths and store one immersed, the other at 50 percent RH. The results of tests on these have shown a disappointing scatter. The two halves showed a difference in velocity initially—15.6 and 16.0; they both appeared to increase in velocity for the first few months, to about 15.9 and 16.3, respectively; then both showed an apparent tendency to decline. The one stored at 50 percent RH dropped after two years to about 14.5 and the one that is stored immersed to about 15.6. Insofar as these data may be regarded as demonstrating anything, they seem to tend to confirm the argument that velocity should be greater through a soaked (wet) concrete than through dry concrete merely because velocity through water is some four times greater than velocity through air. Data on the rate and smoothness of the increase of velocity with increasing moisture content and decrease of velocity with decrease in moisture content is still desired.

EFFECT OF AGGREGATE PARTICLE SIZE ON VELOCITY

Jones (8) and others have discussed the effects of differences in velocity of the aggregate used in the concrete on the velocity measured through the concrete. The work of Whitehurst and Bullock (included in this symposium) is a most valuable contribution to this question. The authors of this paper, being concerned rather more than many soniscope users with concrete made with large aggregate, have wondered whether the grading of the aggregate had an effect. For one study limestone coarse and fine aggregate having a velocity of about 19,000 fps was used. From mixture proportions the percentage of paste and aggregate that should have been intersected by a random straight line through the concrete was calculated. A typical example was 17 percent paste, 83 percent aggregate. Since velocity in the concrete was 15,400 fps, it would follow that the velocity in the paste would theoretically be 8,000 fps. In further studies of this relation, a 6- by 6- by 30-in. paste specimen at an 0.4 w/c was made. It had velocities of 9.9, 11.7, 12.3, and 12.1 thousand fps at 2, 14, 182, and 400 days age. A similar prism of 0.4 w/c paste and limestone sand so proportioned as to have 45 percent by volume sand had velocities of 12.3, 14.3, 15.0 and 13.8 thousand fps at comparable ages. From these data, calculating the difference in observed and theoretical velocities, it is found that on the average an excess of 11.5 microseconds or 6.3 percent of the travel time, is actually required over what the theoretical calculations indicate. It is suggested that this is due to the need for the wave to pass through paste-aggregate interfaces, to go a longer distance to go around low velocity spots (air?), or be retarded by lateral movement. Similar calculations on a concrete specimen, indicate an increase in actual over theoretical travel time of only about one percent—this tends to confirm the assumption that the actual time is greater than the theoretical due to interface effects, since the effect is due less to coarse than to fine aggregate, coarse aggregate particles contribute fewer interfaces per unit path length.

EFFECT OF CONDITION OF CONCRETE

Now the factor--or rather collection of factors—that was of most concern in the use of the soniscope will be discussed. The first field job, in January 1952, was to attempt to outline the distribution of longitudinal vertical cracking in a floodwall that had been cracked by reverse loading as flood waters that had gotten behind it loaded it after the flood stages in the river fell. The detection of the extent of severe cracking was successful. It was indicated by later removal of concrete during repair work, that hairline cracking extended somewhat beyond the areas outlined by velocity measurements.

In another field project an outline of the position of inferior concrete placed in a bridge pier was required. The bad concrete was later shown (9, Fig. 1) to have been due to an overdose of air-entraining admixture sufficient to bring the air content up to about 25 percent and the 28-day compressive strengths down to about 900 psi. The soniscope clearly outlined the position in the structure in which this inferior concrete was located.

A somewhat similar project involved the concrete represented by the cylinders referred to previously.

The use of the soniscope has been fairly satisfactory for detecting major differences.

in condition of concrete in a given structure at a given time when, in the absence of abnormal factors, the condition would have been expected to be similar.

REFERENCES

1. Waterways Experiment Station, "Handbook for Concrete and Cement." Distribution No. 30 (March 1957).
2. Mather, Bryant, "Comparative Tests of Soniscope." HRB Proceedings, Vol. 33, p. 217 (1954).
3. Batchelder, F. M., and Lewis, D. W., "Comparison of Dynamic Methods of Testing Concrete Subjected to Freezing and Thawing." ASTM Proceedings, Vol. 53, p. 1053 (1953).
4. Whitehurst, E. A., "Dynamic Testing of Concrete Evaluated." Civil Engineering, New York, Vol. 29, p. 57 (1957).
5. Long, B. G., Kurtz, H. J., and Sandenaw, T. A., "An Instrument and Technique for Field Determination of Modulus of Elasticity of Concrete (Pavements)." Proceedings Amer. Concrete Inst., Vol. 41, p. 217 (1945).
6. Leslie, J. R. and Cheesman, W. J., "An Ultrasonic Method of Studying Deterioration and Cracking in Concrete Structures." Proceedings, Amer. Concrete Inst., Vol. 46, p. 17 (1950).
7. Whitehurst, E. A., "Pulse-Velocity Techniques and Equipment for Testing Concrete." HRB Proceedings, Vol. 33, p. 226 (1954).
8. Jones, R., "Testing of Concrete by Ultrasonic Pulse Techniques." HRB Proceedings, Vol. 32, p. 258 (1952).
9. Mather, K., "Petrographic Examination—Hardened Concrete." ASTM Sp. Tech. Publ. No. 169 (1955).

Appraising the Quality and Performance of Concrete by Pulse Velocity Measurements

R. W. SPENCER, Manager of Engineering Department; and
B. R. LAVERTY, Senior Civil Engineer;
Southern California Edison Company, Los Angeles

● THE SOUTHERN California Edison Company has utilized the technique of soniscope testing at numerous concrete structures to evaluate the condition and performance of existing concretes and to determine the strength properties and quality of new concretes.

The soniscope program includes the taking of periodic measurements at concrete dams, the experimental testing of concrete samples for proposed new structures, and tests of new concrete in miscellaneous structures.

The Edison Company is pleased to share its findings with members of the Highway Research Board and hopes that the results of its soniscope investigations, which have been conducted on structures other than roads and bridges, will be of value in supplementing the collection of data and ideas presented before this symposium.

PURPOSE AND HISTORY

In 1953, the Company initiated its program of annual soniscope testing of concrete in dams at the Big Creek-San Joaquin Hydroelectric Development in central California. This testing was in part an outgrowth of studies begun in 1942 by the Portland Cement Association in cooperation with the Edison Company and others to observe the long-time performance of concrete using 27 different cement types from various parts of the United States.

The first soniscope tests were made at the Florence Lake Dam, a multiple arch structure located in the Sierra Nevada Mountains at an elevation of over 7,000 ft. At this elevation the severity of exposure to freeze-thaw cycles is such that concrete is subject to deterioration if permitted to be in intermittent contact with water during the winter season. Deterioration that developed in the concrete on the upstream face of the dam was arrested by the application of an asbestile coating, and it was the practice for a number of years to take cores from the dam periodically for testing. In this manner it has been possible to maintain an up-to-date evaluation of the dam's performance. The time and expense of the coring were considered excessive, and following the establishment of P. C. A. soniscope test measurement points at the dam, it was believed that continued soniscoping by the Company would be effective in maintaining an up-to-date evaluation of the performance of the concrete with minimum coring. Since the use of the soniscope was begun at Florence Lake Dam, no cores have been taken for testing; and in the future only rarely will cores be taken to confirm the data gathered by soniscoping. In conjunction with the P. C. A. studies pulse velocity measurements are still made on groups of test bars and on walkway test slabs made from concretes utilizing various types of cement.

The initial program has now been expanded to include the periodic testing at all the dams at the Big Creek Development. The soniscope has been used to determine representative pulse velocities in these structures and to establish trends, if any, in these pulse velocities over a period of several years' duration. Consequently, the Company has gathered considerable field data and now welcomes the opportunity to join other soniscope users in an effort to analyze more closely the significance of its findings.

The first phase of this soniscope program has been the investigation of the condition of representative concrete in each structure. The second phase has been that of determining long-time trends in pulse velocities, which are considered probably the most important data provided to date by the soniscope. The third phase of investigation is the determination of the more specific relationships of measured pulse velocities to various concrete properties, when certain data such as design mixes, the use of admixtures, types of aggregate and types of cement are known. This latter phase is certainly still in its initial stages, and only the most preliminary information obtained regarding these more complex relationships will be indicated.

In addition to testing various massive concrete structures, the instrument has been used for the qualitative analysis of concretes in building structures and in large diameter concrete pipes; and to a limited extent it has been used in experimental tests of other materials, including wood and steel.

APPRAISING THE PRESENT CONDITION OF EXISTING STRUCTURES

Among the concrete structures that have been tested are those older structures wherein deterioration or concrete of questionable quality could have existed to an undetermined degree. The soniscope technique has been found useful to determine the extent of deterioration, if any, and to verify the adequacy of otherwise questionable concrete.

Pulse Velocity Measurements at the Big Creek-San Joaquin Hydroelectric Development

At the Big Creek Development the soniscope program has been of tangible value; for the tests have shown that the concretes in the eleven major dams are satisfactory, with pulse velocity measurements in the concretes varying from 11, 600 to over 15, 000 ft/sec. Of particular interest are the relatively high pulse velocities at some of the older dams that were constructed between 1913 and 1927. A number of the structures, having comparatively low concrete design strengths, have pulse velocities that compare remarkably well with new structural concretes at other more recently constructed structures. An example of this is at Shaver Dam, a gravity dam built in 1927, where mass concrete with a mix of 1:3. 2:7. 5 (by vol) exhibited average pulse velocities from 14, 550 to 15, 100 ft/sec. On the other hand, the Florence Lake Dam arch dam buttresses, having a richer mix of 1:2. 2:4. 7 (by vol), showed lower pulse velocities averaging 12, 750 ft/sec. Nevertheless, as shown in Figure 2, pulse velocity measurements at all locations have been found to be adequate; and this has materially reduced the need for other physical tests to confirm the existence of satisfactory concrete. The soniscope crew is shown working at Bear Dam, one of the small arch dams in Figure 5.

The concretes in the several dams have been designed to provide various strengths. For this reason it is helpful to classify the structures in groups based on the concrete design strength requirements--massive concrete in the gravity dams, intermediate concrete in the arch dams, and structural concrete in the appurtenant structures—when analyzing the results of the soniscope tests that have been conducted.

Massive concrete structures tested include three gravity dams: Shaver Dam, Dam 7 and Dam 3. Soniscope measurements at Shaver Dam show excellent pulse velocities for concrete regardless of its type as discussed above, and the Dam 7 pulse velocities in mass concrete are adequate, averaging about 13, 000 ft/sec. The measurements made at Dam 3 are low (11, 790 ft/sec and below) because of deterioration resulting from the dam's age, the severity of the local exposure conditions, and the nature of the pit-run mixes incorporated in the concrete. Dams 1 and 2 at Huntington Lake, companions to Dam 3, were steel-plate faced in 1955 to arrest further deterioration of the concrete on their upstream faces.

The soniscope pulse velocities for the structures having intermediate strength concrete cover a wide range of variation. Excellent performance is shown by Dam 4, an arch dam, where pulse velocities averaging 14, 790 ft/sec exceed those found in some structural concretes. The average pulse velocity values at Mono Dam, Bear Dam and at the Dam 1 overflow spillway (13, 790; 14, 130; and 14, 410 ft/sec, respectively) are considered satisfactory and are believed typical for 2, 000 to 3, 000 psi concrete in this region. Somewhat below the anticipated pulse velocities for intermediate concrete are the measurements made in Dam 5 and 6 and the Florence Lake Dam buttresses, which were in order: 12, 560; 12, 670; and 12, 750 ft/sec. However, the uniformity of

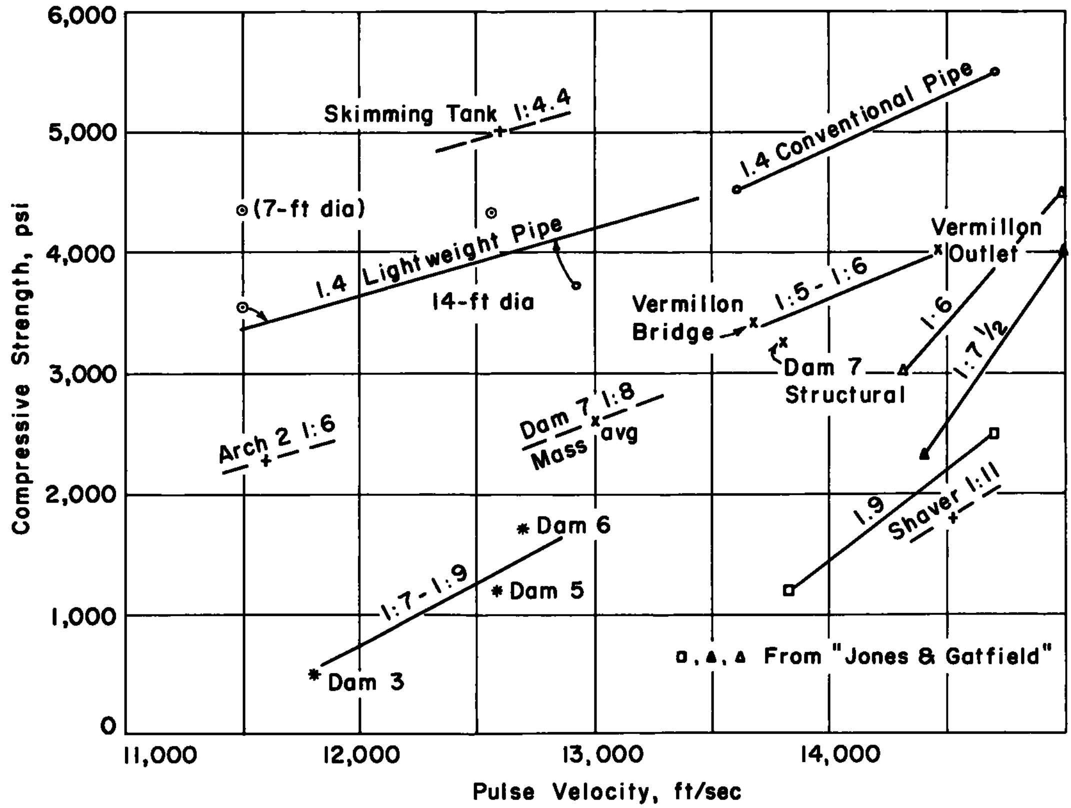

Figure 1. Relation between pulse velocity and compressive strength for various concrete mixes.

the yearly measurements has minimized the need for questioning of the above concretes' satisfactory performance.

The structural concretes in the outlet works and in the service spillway bridge at Vermilion Dam, in the training walls at Dam 7, and in the walkways at Florence Lake Dam were found to have satisfactory pulse velocities as indicated in Figure 2. However, they are in some instances lower than the pulse velocities that have been recorded by others for structural concrete. Pulse velocities exceeding 15,000 ft/sec have been infrequently found, as a rule.

Local aggregates were used in the concrete mixes for all the Big Creek dams. These aggregates may be classified as hornblende, biotite granites. They are characterized by their density, durability and lack of reactivity and they have usually been produced by quarrying or by processing of tunnel muck.

Figure 2 shows representative pulse velocities observed over periods of four to six years at each of the above-mentioned Big Creek dams.

Correlation of Laboratory Tests with Pulse Velocity Measurements

While no simple relationship has been established between the ultrasonic pulse velocity, modulus of elasticity, and ultimate compressive strength of a concrete specimen, the continuing accumulation of data does give insight into general relationships. The following test data are cited from Portland Cement Association investigations at Florence Lake Dam where soniscope measurements were conducted at 20 points on a section 1.65 ft in thickness on Arch No. 2 at an area where 4-in. diameter concrete cores were removed for testing to determine both Young's modulus of elasticity and the ultimate compressive strength of the concrete:

Core No.	Compressive Strength (psi)	Young's Modulus of Elasticity (psi)	Soniscope Pulse Velocity (ft/sec)
2-1 (1943)	2480		
2-1 (1945)	2540	1,770,000	
2-1 (1947)	2248	1,980,000	
2-1 (1949)	2230 (approx.)	1,270,000	
2-1 (1951)	2040	-	
Average:	2308	1,670,000	11,600 (avg. of 20 tests)

In this instance the existence of the comparatively low average modulus of elasticity determined by laboratory compression tests of cores was substantiated by the corresponding low average sonic pulse velocity. The average compressive strength of the cores taken from this structure, while not exceptionally high, did illustrate that a concrete may show only moderate elastic properties from both physical and sonic tests yet have satisfactory strength.

Further data to assist in the correlation of pulse velocity measurements with other physical tests are given in Table 1 which contains pulse velocities, concrete compressive strengths, and other physical characteristics of the Big Creek Development structures where soniscope tests have been conducted. Included also are other data which are believed to effect the pulse velocity measurements of a concrete.

Reference is made to Figure 1 which shows observed relationships of pulse velocity to compressive strength for concretes of varying mix proportions. If compressive strength be considered a criteria for measuring quality, the plot becomes useful for gauging the quality of an aged concrete by means of pulse velocity tests when the approximate mix proportions are known. Applications of these relationships must be

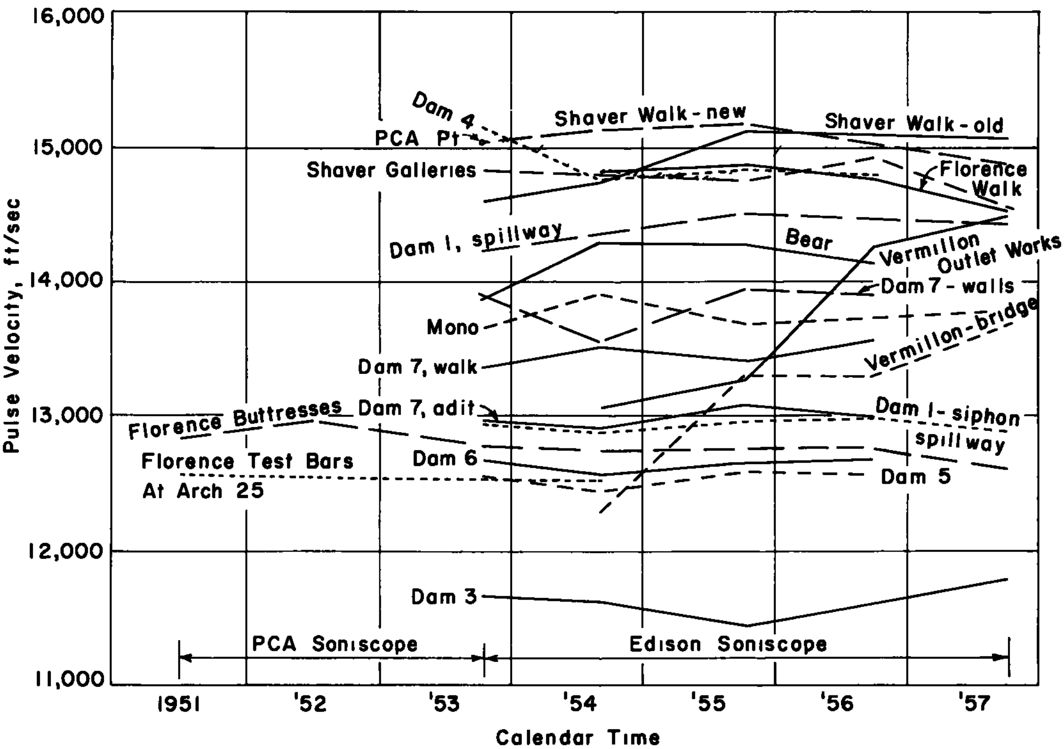

Figure 2. Comparison of pulse velocity vs time; soniscope testing of concrete—Big Creek Project Dams.

TABLE 1

PULSE VELOCITIES AND PHYSICAL CHARACTERISTICS AT BIG CREEK DAMS

Structure	Typical Mix Proportions	Admixture	Recent Pulse Velocity ft/sec	Tested Compressive Strength psi
Dam 7				
Mass Concrete	1:1¾:6¼ by wt[2]	Darex[1]	13,500	2600 - 28 day
Mass Concrete	1:1.84:7 60 by wt[3]	Pozzolan	12,500	
Structural Concrete	1:1¾:3½ by wt	Darex[1]	13,830	3300 - 28 day
Dam 6				
Crest	1:2¼:4½ by vol	-	12,670	1680 - 28 day
Shaver Dam				
Mass Concrete	1:3.2:7.5 by vol	-	14,550	1800 - 28 day
Florence Lake Dam				
Buttresses	1:2.2:4.7 by vol	-	12,750	
Arch 21	1:1.9:4.1 by vol	-	13,440	2860 - 1951 cores
Arch 2	1:1.9:4.1 by vol	-	11,600	2308 - 1943-51 cores
Vermilion Dam				
Outlet Works	1:2:3 by wt	Darex[1]	14,480	4040 - 28 day
Spillway Bridge	1:2.7:3.7 by wt	Darex[1]	13,690	3390 - 28 day
Mono Dam	-	-	13,790	
Bear Dam	-	-	14,130	
Dam 1				
Overflow Spillway	1:6 by vol	-	14,410	est. 2500 - 28 day
Dam 2				
Mass Concrete	1:8 by vol	-	-	700 - 28 day
Dam 3	1:9 and 1:7½ by vol	-	11,790	515 - 28 day
Dam 4	1:7 by vol	-	14,790	1230 - 28 day
Dam 5	1:9 by vol	-	12,560	1225 - 28 day

Structure	Dam Type	Height ft	Crest Length ft	Date Built	Elev. at Crest	Aggregate Source[4]
Dam 7	Gravity	250	891	1950	1413	
Mass Concrete						Local Quarry
Mass Concrete						Local Quarry
Structural Concrete						Local Quarry
Dam 6	Arch	155	495	1923	2250	
Crest						
Shaver Dam	Gravity	198	2169	1927	5371	
Mass Concrete						Local Quarry
Florence Lake Dam	Multiple Arch	154	3156	1926	7329	
Buttresses						Tunnel Muck
Arch 21						Tunnel Muck
Arch 2						Tunnel Muck
Vermilion Dam	Earth fill	165	4248	1954	7650	
Outlet Works						Alluvial Deposits
Spillway Bridge						Alluvial Deposits
Mono Dam	Arch	64	184	1927	7360	Tunnel Muck
Bear Dam	Arch	55	276	1927	7356	Tunnel Muck
Dam 1	Gravity	170	1335	1917	6954	Alluvial Deposits
Dam 2	Gravity	120	1862	1917	6954	Alluvial Deposits
Dam 3	Gravity	152	666	1917	6954	Alluvial Deposits
Dam 4	Arch	81	287	1913	4814	Tunnel Muck
Dam 5	Arch	60	224	1921	2950	Tunnel Muck

[1] Mixes containing Darex are designed for 5 percent entrained air content.
[2] Mix used for mass concrete within 8 ft of face of dam.
[3] Mix used for mass concrete over 8 ft from face of dam
[4] All aggregates are hornblende, biotite granites.

applied cautiously for the compressive strength data tabulated above were in numerous instances determined from test cylinders taken from concrete batches not placed in the immediate vicinity of the pulse velocity measurement points. Nevertheless, this manner of presenting the data is useful, and it is intended to gather further field and laboratory test data to clarify the relationships indicated above.

It is seen in Figure 1 that for a given pulse velocity, richer mixes will have a higher compressive strength than lean mixes, and that for a given mix and pulse velocity, the compressive strength of the concrete will vary with the compressive strength of the coarse aggregate.

Once sufficient testing has been done to establish the above relationships for a particular range of aggregates and mixes, it will be possible more closely to evaluate the probable compressive strength of concrete in an existing structure by use of soniscope measurements. Through this type of appraisal the Company hopes in the future to develop a useful tool to assist in accurately judging the competence of its structures.

Pulse Velocity Tests in Miscellaneous Structures

An example of the soniscope's usefulness on a "one test series" basis to appraise the condition of concrete was illustrated by tests recently conducted at a Los Angeles

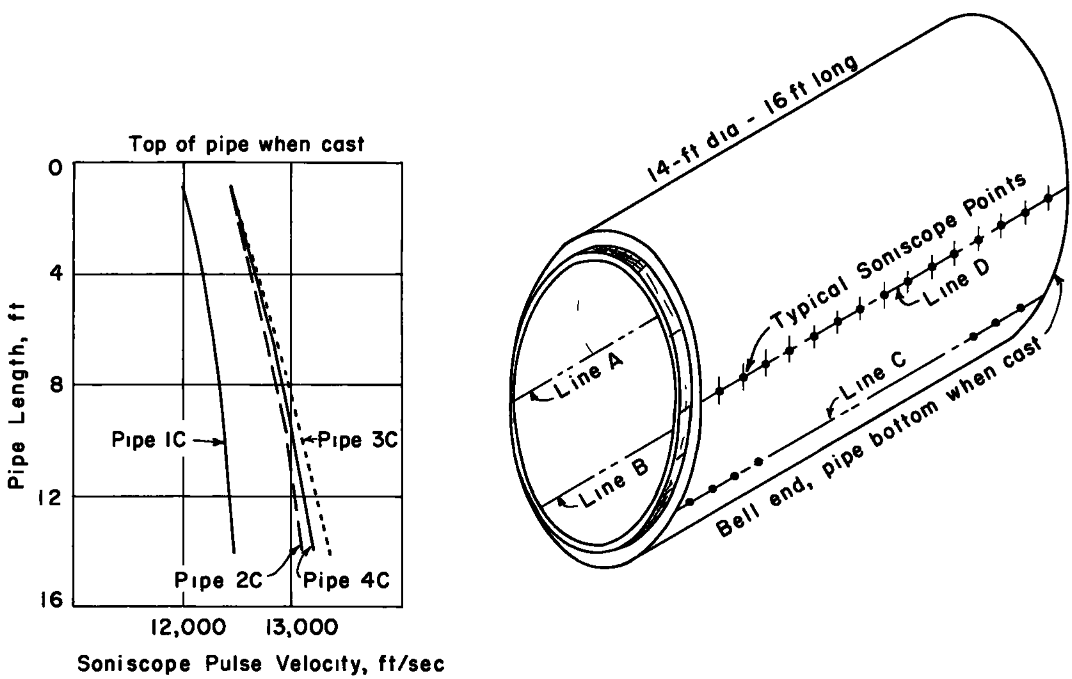

Figure 3. Variation of soniscope pulse velocity with length, lightweight concrete pipe.

area oil refinery. Here the soniscope was used to verify the acceptability of newly placed concrete in the walls of a large oil skimming tank where surface irregularities had caused the owners to fear the existence of internal discontinuities such as honeycomb voids and voids at lift joints. A series of 89 soniscope measurements in 8- and 10-in. thick walls revealed that the concrete was consistently homogeneous and entirely satisfactory, thus discounting the need for any doubt on the part of the contractor or the owner as to the concrete's quality. The average measured pulse velocity for the one-month old concrete tested was 12,650 ft/sec. The concrete mix was 1:1.9:2.5 by wt, developing a 28-day compressive strength of 5,000 psi. San Gabriel aggregates, produced from nearby alluvial deposits of granitic and gneissic rock, were used in the concrete. The owner was accordingly satisfied by the qualitative report of the concrete's condition, based on the pulse velocity tests.

Another instance of the soniscope's use for in-place testing of concrete was at a local aircraft plant where visual observation of a building's structural performance indicated the existence of unusual material. These tests were made to assist in the analysis by the designers of excessive, progressive deflections that were occurring in a second-floor, flat slab floor system. The visibly questionable performance of the concrete evidenced by 2- to 3-in. midspan deflections in 30-ft spans caused concern over the acceptability of the concrete placed in the structure. Pulse velocity measurements indicated concrete having a modulus of elasticity less than that generally adopted in design and of less than normal quality. It was suspected that deflections due to sustained plastic flow would be similar to those which occurred in the highly flexible structure.

The following data summarize both the findings of the pulse velocity measurements made through the second story floor slab and the physical charcteristics of concrete beams and cores taken for testing from nearby floor areas of excess deflection:

Concrete Compressive Strength:	4,500 psi, average
Concrete Mix Proportions:	1:5.5
Young's Modulus of Elasticity: (from stress-strain measurements).	2,700,000 psi, weighted average
	1,700,000 psi, minimum
Modulus of Rupture:	720 psi, average
Unit Weight:	142.3 pcf
Soniscope Pulse Velocity:	11,600 ft/sec

It was concluded, following laboratory tests of samples of the concrete cut from the structure and after the evaluation of extensive consulting advice, that the excessive deformation was the evidence of initially underestimated deflection characteristics in the design combined with the use of a low-alkali Type II cement with unusually high shrinkage characteristics which would likely be accompanied by excessive plastic flow or creep. Since there has been no evidence of overstress in the structure, no major remedial measures have been necessary, and the building has been fully occupied.

In this case the value of the pulse velocity tests was in indicating the early necessity for more comprehensive coring and strength testing and in providing data in support of the final conclusions drawn from the results of the subsequent laboratory tests.

DETERMINING TRENDS IN EXISTING STRUCTURES

A trend toward deterioration is a matter following next in importance the existing condition of the concrete in any structure. Knowledge of such a trend, once established, permits the scheduling of maintenance and repairs to control the rate of deterioration and also facilitates an estimate of the probable future service life of the structure.

To date no definite deterioration, not previously corrected, has been noted in any of the Big Creek dams. These dams have an average age of 29 years and one is 44 years old. There has been a slight reduction in pulse velocities in the last year or so in some of the older structures, but the changes are of the same order of magnitude as those caused by changes in moisture content and are still too small to indicate a definite trend. Data presented in England in 1955 by Jones and Gatfield (Department of Scientific and Industrial Research Road Research Laboratory; Road Research Technical Paper No. 34) in the paper "Testing Concrete by an Ultrasonic Pulse Technique" give the effect of drying on the wave velocity in concrete beams of various mix proportions. It is shown that complete saturation of a specimen can increase in longitudinal pulse velocity by as much as 1 percent for a rich mix and 4 percent for a lean mix. From the foregoing it is indicated that pulse velocities for a structure may vary under certain field conditions by as much as 500 ft/sec due to changes in concrete moisture content. To minimize soniscope variation not directly attributable to normal instrument variation, it is the Company's practice to schedule the Big Creek soniscope program at the same time each year to approach as nearly as possible similar conditions of concrete moisture content and stress induced by temperature and water loading.

The influence of moisture content variation on pulse velocity interpretation at these dams has yet to be analyzed. Annual variations in concrete moisture content and in climatic conditions probably have a measurable effect, for the dams are located over a wide range of climatic zones. Opposite extremes in exposure conditions are represented by Dam 7 in the warm, dry San Joaquin Valley foothills in contrast with Florence Lake Dam in an area of locally high precipitation at elevation of over 7,000 ft in the Sierras.

the compressive strength of the concrete will vary with the compressive strength of the coarse aggregate.

Once sufficient testing has been done to establish the above relationships for a particular range of aggregates and mixes, it will be possible more closely to evaluate the probable compressive strength of concrete in an existing structure by use of soniscope measurements. Through this type of appraisal the Company hopes in the future to develop a useful tool to assist in accurately judging the competence of its structures.

Pulse Velocity Tests in Miscellaneous Structures

An example of the soniscope's usefulness on a "one test series" basis to appraise the condition of concrete was illustrated by tests recently conducted at a Los Angeles

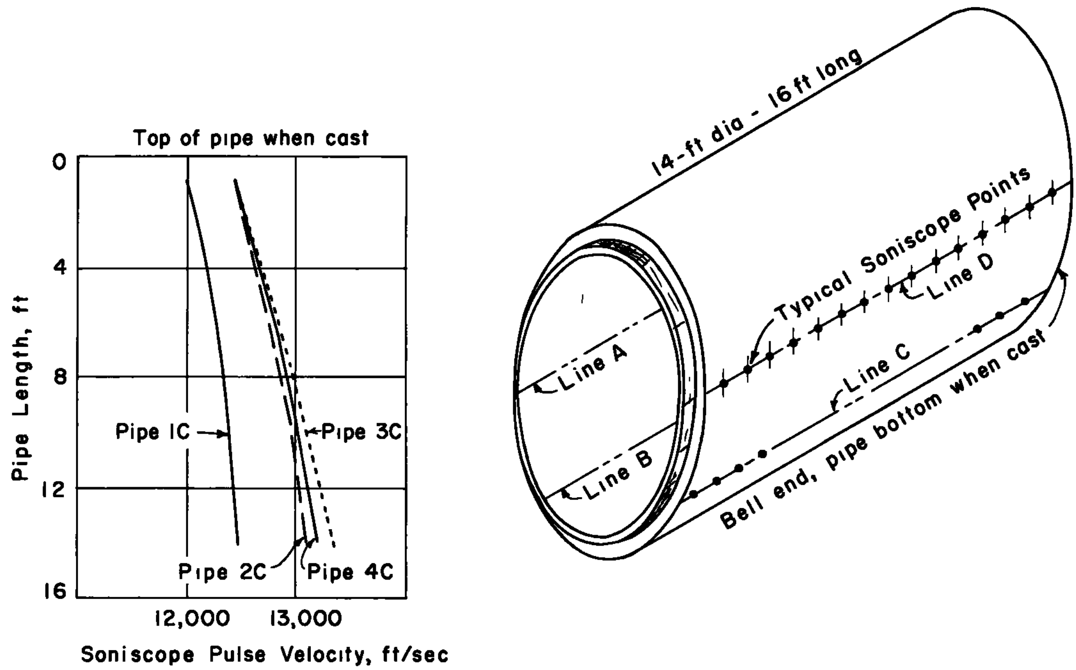

Figure 3. Variation of soniscope pulse velocity with length, lightweight concrete pipe.

area oil refinery. Here the soniscope was used to verify the acceptability of newly placed concrete in the walls of a large oil skimming tank where surface irregularities had caused the owners to fear the existence of internal discontinuities such as honeycomb voids and voids at lift joints. A series of 89 soniscope measurements in 8- and 10-in. thick walls revealed that the concrete was consistently homogeneous and entirely satisfactory, thus discounting the need for any doubt on the part of the contractor or the owner as to the concrete's quality. The average measured pulse velocity for the one-month old concrete tested was 12, 650 ft/sec. The concrete mix was 1:1. 9:2. 5 by wt, developing a 28-day compressive strength of 5, 000 psi. San Gabriel aggregates, produced from nearby alluvial deposits of granitic and gneissic rock, were used in the concrete. The owner was accordingly satisfied by the qualitative report of the concrete's condition, based on the pulse velocity tests.

Another instance of the soniscope's use for in-place testing of concrete was at a local aircraft plant where visual observation of a building's structural performance indicated the existence of unusual material. These tests were made to assist in the analysis by the designers of excessive, progressive deflections that were occurring in a second-floor, flat slab floor system. The visibly questionable performance of the

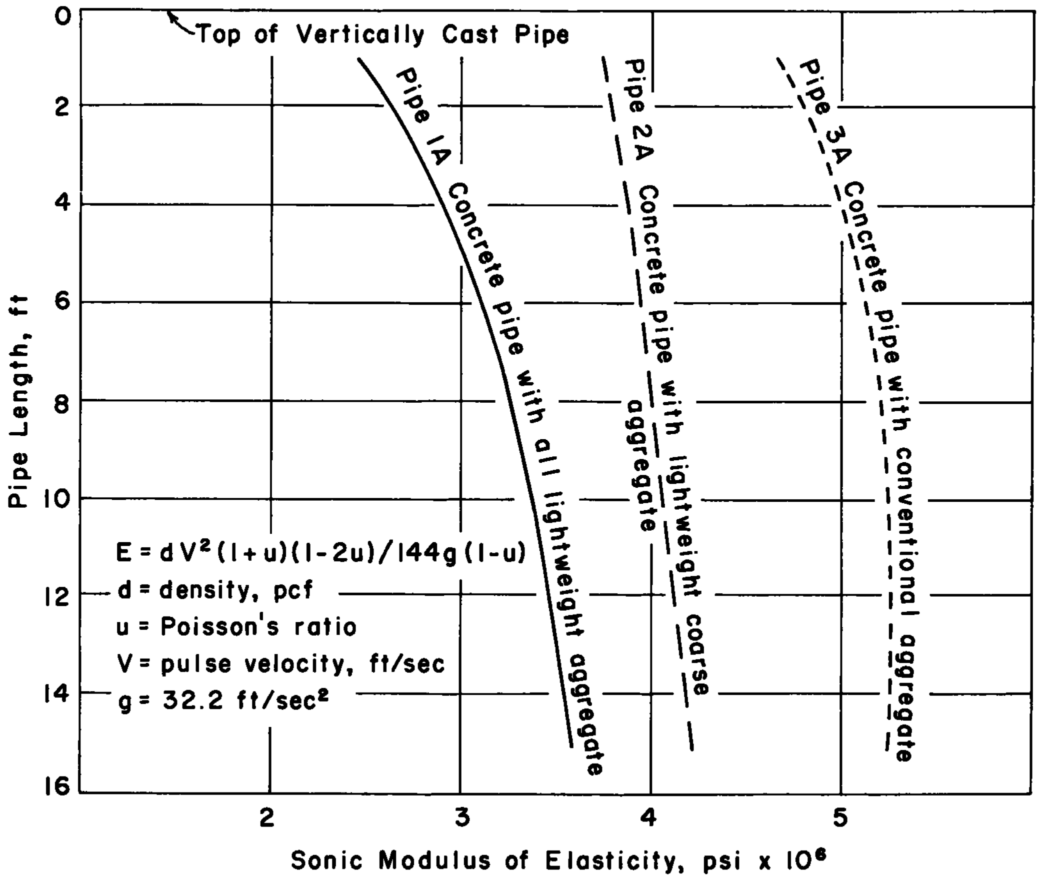

Figure 4. Variation of sonic modulus of elasticity with pipe length.

To illustrate the results of the Company's Big Creek soniscope tests, reference is made to Figure 2 which shows the average pulse velocities measured from 1951 to 1957 at many of the structures tested. No significant trends indicating decreased concrete quality are shown. On the contrary the pulse velocities at the Vermilion Dam outlet structure and service spillway bridge have increased substantially with age. This concrete was placed in 1953 and first soniscoped in 1954. To date the average pulse velocity at the outlet structure has increased by about 1,400 ft/sec, indicating a substantial rise in concrete strength with age. The comparatively cold climate at this location as well as the use of low-alkali, Type II cement in the concrete probably contributes to the slow attainment of maximum pulse velocities.

To date some experimental tests by other soniscope users comparing pulse velocity build-up with age have indicated that an increase in pulse velocity will parallel the usual compressive strength gains and will reach a near-maximum velocity within a few months after placement of the concrete. Findings at Vermilion Dam suggest that structural concretes without admixtures, except for air entrainment, will under certain conditions continue to show pulse velocity increases after the period generally accepted for nearly complete strength build-up.

Figure 2 shows that where no trends toward either increasing or decreasing concrete quality are indicated, yearly variations in pulse velocities at a given structure generally do not exceed about 2 percent; and in the past five years the greatest pulse velocity variation has not exceeded 3½ percent for any structure except at Vermilion Dam. These variations are cited to indicate the range of random deviations that have been measured over an extended test period.

It is believed that one of the very useful applications of the soniscope is in the periodic retesting of structures over a period of years, for the pulse velocity trends in a structure are useful indicators of its present performance as well as of its future physical condition. This is accordingly among the most economical test methods now available for appraising the condition and performance of massive concrete structures.

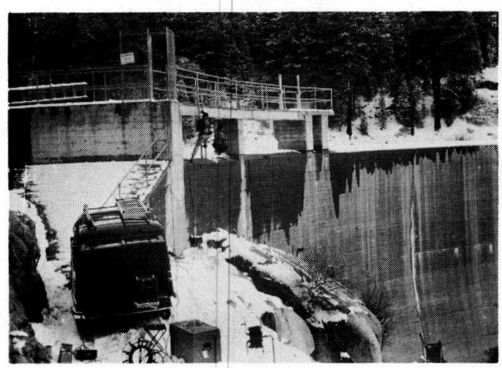

Figure 5A. Soniscope testing at Bear Dam; Big Creek-San Joaquin Hydroelectric Project.

EXPERIMENTAL TESTING

Soniscope testing has been of value as a qualitative test to contribute to the knowledge of a material proposed for a new or otherwise unusual application. When used with other standard tests, the pulse velocity test data will tend to either verify or cause question of such data. This was the case with tests conducted on samples of lightweight concrete to be used in large diameter, lightweight concrete pipe proposed for installation in the condenser cooling water system of the Edison Company Huntington Beach Steam Station. Engineering studies indicated that a reduction in cost of several hundred-thousand dollars could be effected in an offshore, pipe-placing trestle if 14-ft inside diameter conduit made with lightweight aggregate concrete and having only two-thirds the weight of normal concrete were utilized. Soniscope tests were performed to supplement other physical tests, and the combined results of all the tests indicated that conduit made with this type aggregate would be acceptable. It was found that the elastic properties of the lightweight pipe were satisfactory for the use intended and that lightweight concrete could be placed and vibrated in vertical steel forms and be free from damaging segregation or rock pockets. Sections of the pipe are shown in Figure 5, before installation.

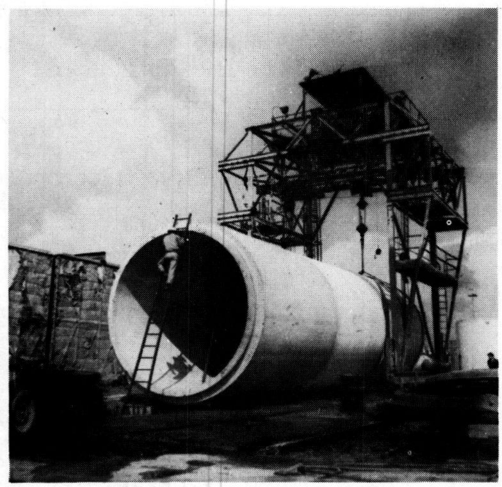

Figure 5B. Fourteen foot diameter lightweight concrete pipe; Huntinington Beach Steam Station.

Reference is made to Figure 3 which illustrates the variation of pulse velocity with pipe length for vertically cast, lightweight concrete pipe and to Figure 4 which presents the variation of the sonic modulus of elasticity with pipe length as determined by pulse velocity measurements using the general relationship:

$$E = dv^2 \frac{(1+u)(1-2u)}{144g(1-u)}$$

in which:

E = sonic modulus of elasticity, psi
d = concrete density, pcf
v = pulse velocity, ft/sec
u = Poisson's ratio
g = 32.2 ft/sec^2

TABLE 2

EXPERIMENTAL TESTS ON CONCRETE PIPE[1]

Pipe No.	Sacks Cement cy	Type of Pipe	Date Made	Date Soniscoped	Avg Pulse Velocity ft/sec	Avg Sonic Modulus psi ($x10^6$)	Test Cylinder Density pcf	Test Cylinder Comp Strength psi
1 A	8.7	All Rocklite aggregate	8/18/56	9/18/56	12,800	3.09	106.0	4185
2 A	9.3	Rocklite coarse with natural concrete sand	8/29/56	9/18/56	13,400	3.91	121.0	4835
3 A	7.0	Conventional	9/13/56	9/18/56	13,600	5.08	147.0	4500
1 B	8.0	Conventional Centrifugally spun	Not known	9/18/56	14,700	6.03	150.0	5500
1 C	8.5	All Rocklite aggregate	9/13/56	2/26/57	12,260	2.55	101.7	3620
2 C	8.5	All Rocklite aggregate	9/15/56	2/26/57	12,740	2.83	100.9	3750
3 C	8.5	All Rocklite aggregate	9/18/56	2/26/57	12,850	2.99	101.2	3710
4 C	8.5	All Rocklite aggregate	9/19/56	2/26/57	12,890	2.86	99.5	2970

[1] All pipes were cured in 60 hr steam with the exception of 1 B which was cured in air

The variation in pulse velocity with height as cast is attributed to the tendency of lightweight aggregate to float to the top of the fluid concrete leaving the more dense paste at the bottom. Similar pulse velocity increase with depth occurs in normal concrete where the dense coarse aggregates settle downward leaving excess moisture and air voids near the surface of the fluid concrete.

The design mix for the lightweight concrete was 1:1¾:2¼ by volume, and the expanded clay shale aggregate used in the mix was manufactured by the Rocklite Company. Tests were made on pipe sections composed of lightweight coarse aggregate and natural sand as well as on conventional concrete pipes both vertically cast and centrifugally spun. Summarized results of these tests are contained in Table 2.

The average sonic modulus of elasticity calculated from pulse velocity measurements for the all-lightweight aggregate pipe 1A, shown on Figure 4, was 3,100,000 psi, with a corresponding average compressive strength determined by physical tests to be 4,400 psi. In comparison, soniscope measurements of concrete pipe 2A made using lightweight coarse aggregate and natural concrete sand indicated an average sonic modulus of 3,900,000 psi. Concrete pipe 3A made using all natural San Gabriel aggregates exhibited an average sonic modulus of 5,100,000 psi.

Although the moduli of elasticity of the lightweight pipe are relatively low when compared to those of conventional concrete pipe, the compressive strengths of both are of the same magnitude. It was believed that with aging the sonic modulus of elasticity of the lightweight pipe would approach 3,000,000 psi and be acceptable.

Figure 1 shows the correlation of pipe pulse velocity with test cylinder compressive strength for lightweight concrete tested at the Huntington Beach Steam Station.

One of the subsidiary findings was that for the monolithically cast pipe, of the diameter and length used, high-frequency vibration during placement must be carefully controlled to assure the production of homogeneous concrete. The forms for pipe number 1C were vibrated during casting by 8 high-frequency pneumatic form vibrators, whereas the successive pipes, 2C, 3C and 4C were more effectively vibrated by 10 vibrators. This explains the lower pulse velocities measured in pipe 1C. Although the density of the test cylinder taken from pipe 1C approximated the density of the test cylinders from the other pipes, there was no doubt that the concrete in the cast pipe section was of lower density than the concretes in pipes 2C, 3C and 4C.

The example cited above also indicated the usefulness of the soniscope in providing quality control using an expeditious non-destruction test method.

Experimental tests have been conducted on materials other than lightweight concrete pipe including wood and steel. Substantial data have been collected in an attempt to determine the relationship of pulse velocity to the actual elastic modulus of wooden power pole cross arms, but to date no usable correlation has been developed.

INTERPRETATION OF PULSE VELOCITY TEST DATA

The measured pulse velocity through a concrete specimen is a property whose proper interpretation must recognize that the transmitted series of compression waves will tend to find the fastest and best path between transducers. Accordingly, a high pulse velocity over a given measurement path is not proof that zones of lower pulse velocity material do not exist adjacent to or in the line of a straight line path, for the compression waves will tend to follow the line of shortest transmission time—deflecting where necessary to bypass lower velocity zones or partial cracking. Therefore, discretion should be exercised when comparing the results of physical tests on test cylinders, beams, or cores with pulse velocity measurements, because the usual physical tests of compressive or bending strength of a test specimen will often be influenced by the average or weakest portion of the test specimen, whereas the pulse velocity test will be somewhat differently affected by variations in composition of the material tested.

The interpretation of pulse velocity measurements should, therefore, be tempered by awareness of all circumstances and conditions surrounding the material tested as well as by the test procedure. This is not unique to soniscope testing, for many test results are subject to wide variations if testing techniques are permitted to vary. Since there are often variables which affect the pulse velocity of a given concrete, the pulse velocity measurement at a given time by itself cannot be an explicit indicator of compressive strength or durability or modulus of elasticity; yet pulse velocities can nonetheless be a very useful property to use, together with all other known data, in evaluating the condition and capabilities of a given concrete.

Effect of Variations in Mix Design or Curing Conditions on a Pulse Velocity-Strength Relationship

E. A. WHITEHURST, Associate Director, Engineering Experiment Station, and Director, Tennessee Highway Research Program, University of Tennessee

The paper summarizes a series of tests on 6- by 6- by 30-in. beams. Pulse velocities were first measured through the lengths of the beams. The beams were then twice broken in flexure by mid-point loading on an 18-in. span and the two ends of the beams were broken in compression as modified 6-in. cubes. One aggregate was used throughout the series. Specimens were made from four cements and three water-cement ratios. Tests were made at ages of 3, 7, and 28 days. Some specimens were continually moist cured for 7 days and then stored in air in the laboratory until the time of test. These were tested in a dry condition. A third group, identified as air-soaked, were moist cured for 7 days, then stored in air in the laboratory until 48 hr prior to test and immersed for the final 48-hr period. These were tested in a wet condition.

The data show that for any one cement, mix, and curing condition a fair relationship between pulse velocity and either flexural or compressive strength may be established. In some cases such a relationship may be extended to include more than one cement, several mixes, and all three curing conditions. In other cases the relationship is distinctly limited to one cement, mix, and curing condition.

It is concluded that in a general sense a relationship between pulse velocity and strength exists and may be determined for any given set of conditions, but that any effort to apply such a relationship to concrete of unknown origin for which the relationship has not been specifically determined is likely to lead to large errors in strength estimation.

●SINCE THE MEASUREMENT of pulse velocities through concrete was first reported by Long and Kurtz (5), equipment and techniques for making such measurements have developed rapidly and extensively. This development probably received it greatest impetus from the work of Leslie and Cheesman (4) which terminated in 1947 in the successful construction of an instrument now generally known as the soniscope.

Details of the continued development of the soniscope and of other similar instruments, and of the uses to which these instruments have been put, have been widely reported in the technical literature. Such uses have included the testing of soils (7), timber (3), and bituminous materials (6), as well as a continually widening use in the testing of concrete. In the latter field much attention has been given to increasing the range of the instrument to permit the testing of larger monolithic sections. The largest section known to have been successfully tested is located at Boone Dam near Kingsport, Tennessee, where, during the summer of 1955, a crew of the Portland Cement Association using a soniscope built by that organization and a crew of the Engineering Experiment Station of the University of Tennessee using a McPhar soniscope both succeeded in testing a section 75 ft thick.

During the past few years as instruments have become more generally available and as pulse velocity testing of concrete has become more common, there has been an

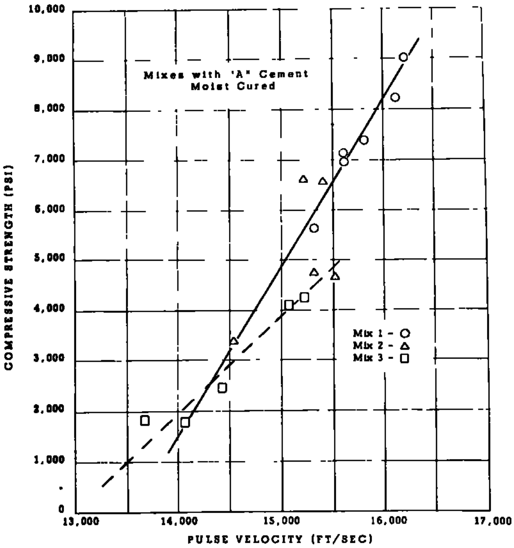

Figure 1. Compressive strength vs pulse velocity.

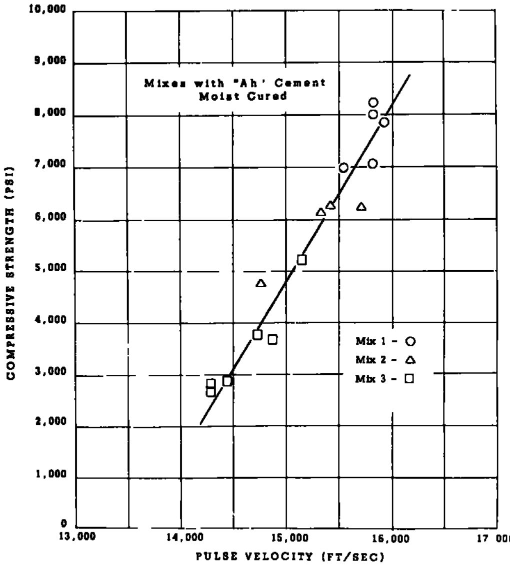

Figure 2. Compressive strength vs pulse velocity.

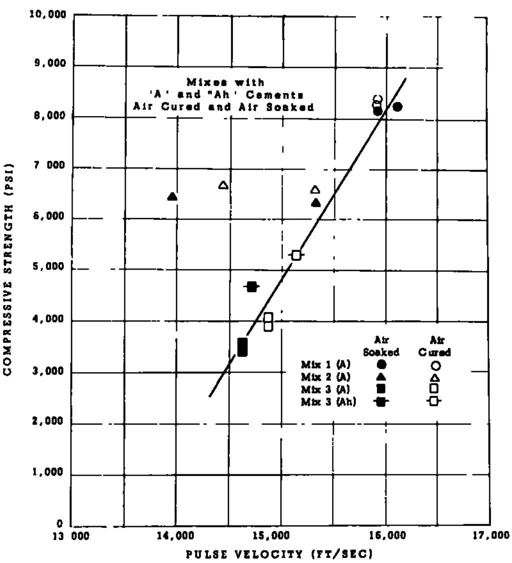

Figure 3. Compressive strength vs pulse velocity.

increasing tendency for investigators to propose that pulse velocity tests be used for estimating the strength of concrete. Such proposals may be found in the literature of the Highway Research Board (2) and of the American Society of Civil Engineers (1). These proposals have great appeal, inasmuch as pulse velocity tests may be quickly and economically conducted, either in the laboratory or in the field, upon concretes of practically any shape and of considerable section. Many investigators, however, including the author, have argued that little evidence has been presented to show the existence of or to define a general relationship between pulse velocity and either compressive or flexural strength which would hold for all concretes; and that to estimate the strength of concrete from pulse velocity tests unless a thorough study of the pulse velocity-strength relationship for that concrete had been conducted is a dangerous procedure.

In an effort to further clarify the pulse velocity-strength relationship for concrete, a review was conducted of several test series performed in the past which might permit an evaluation of such relationships. One series was found which does provide a direct comparison between pulse velocities and both flexural and compressive strengths. The results of these tests are reported below, not with the purpose of recommending that pulse velocity tests be employed to evaluate strength, but rather to indicate some of the hazards associated with such evaluation.

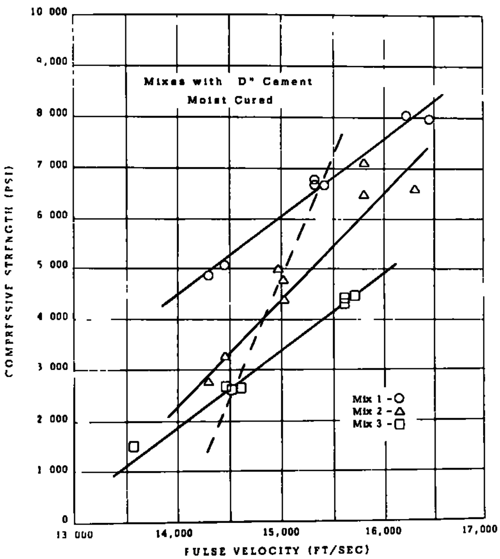

Figure 4. Compressive strength vs pulse velocity.

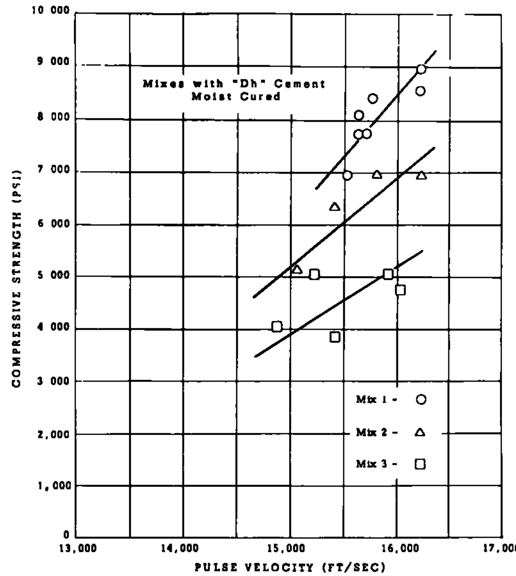

Figure 5. Compressive strength vs pulse velocity.

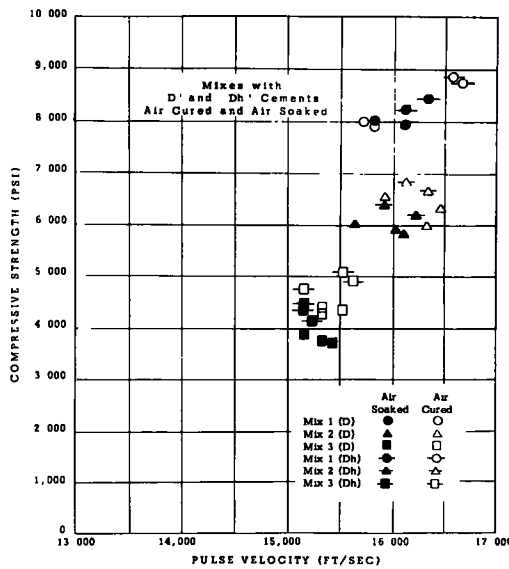

Figure 6. Compressive strength vs pulse velocity.

MATERIALS AND PROCEDURES

Four portland cements were used in the concretes made for this study. Two, identified as cements A and D, were Type I cements. The other two, identified as cements Ah and Dh, were ground from the same clinkers, respectively, but were ground to the fineness of Type III cements. One aggregate, a sand and gravel from the south-central United States, was used in all mixes. Three different water-cement ratios, 4½ gallons per sack, 6 gallons per sack, and 8 gallons per sack were employed. Mixes with these water-cement ratios are identified as Mixes 1, 2, and 3, respectively.

Three types of curing were employed in the study. Some specimens were continually moist cured until immediately before testing. Others, identified as air cured, were stored in a standard moist room for seven days and then in air in the laboratory until the time of test. These were tested in a dry condition. The third group was moist cured for seven days, stored in air in the laboratory until 48 hr prior to test, and immersed in water for the final 48-hr period. These were tested in wet condition and are referred to as air-soaked.

All specimens were 6- by 6- by 30-in. prisms. The pulse velocity was measured through the 30-in. length of each specimen immediately before strength tests. The specimen was then twice broken in flexure by center point loading on an 18-in. span.

The two beam ends were finally broken in compression as modified 6-in. cubes. All strengths reported below, both compressive and flexural, are the average of the two tests made on each specimen.

COMPARISON OF PULSE VELOCITIES WITH COMPRESSIVE STRENGTHS

The relationship between measured pulse velocities and compressive strengths for the three mixes containing the A cement is shown in Figure 1. All of these specimens were moist cured. A single relationship may be expressed by the solid line. In this case the standard error of estimate for all mixes is 840 psi. This line fits the data for Mix 1 very well. The values for Mix 2 are quite scattered. The dashed line of somewhat flatter slope is a better fit for Mix 3. The solid line realtionship gives a standard error of estimate of 230 psi for Mix 1 only, while the dashed line gives a standard error of estimate of 250 psi for Mix 3.

A similar comparison of velocity with compressive strength for the moist cured specimens of the three mixes containing the Ah cement is given in Figure 2. The line passed through the points is identical to the solid line on Figure 1. The fit is somewhat better in this case, the standard error of estimate for all mixes being 490 psi. Only slight improvement in this error could be obtained by treating the mixes separately.

Figure 3 shows the results of tests on specimens from the three mixes containing the A cement and one mix containing the Ah cement which were air cured or air soaked. The line drawn through the data is again the same as that on Figures

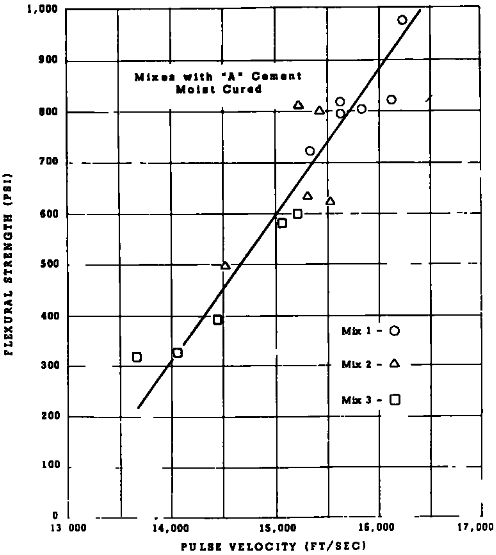

Figure 7. Flexural strength vs pulse velocity.

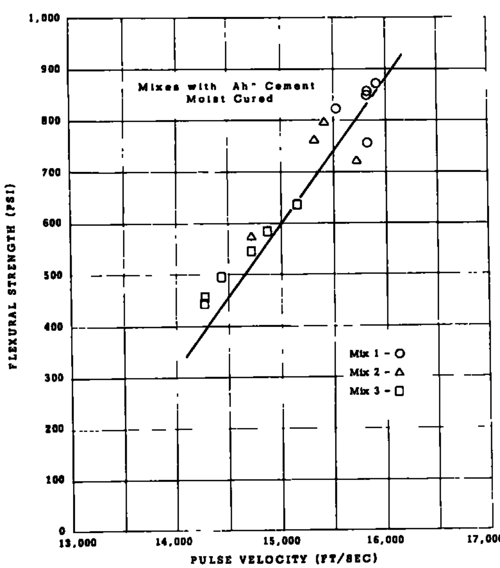

Figure 8. Flexural strength vs pulse velocity.

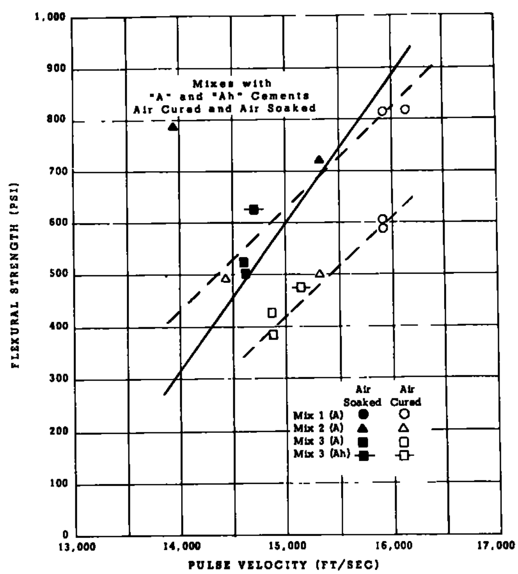

Figure 9. Flexural strength vs pulse velocity.

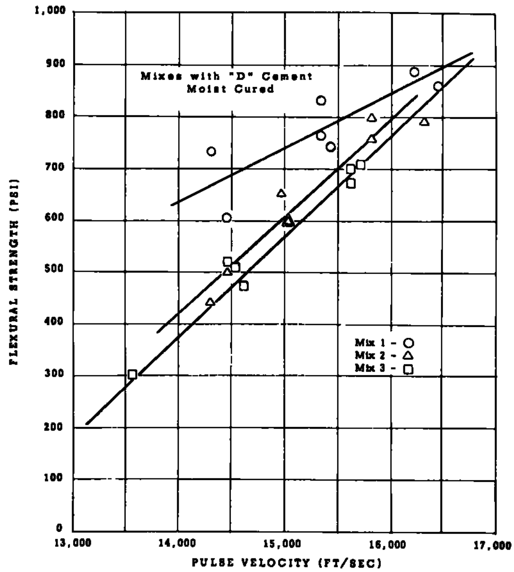

Figure 10. Flexural strength vs pulse velocity.

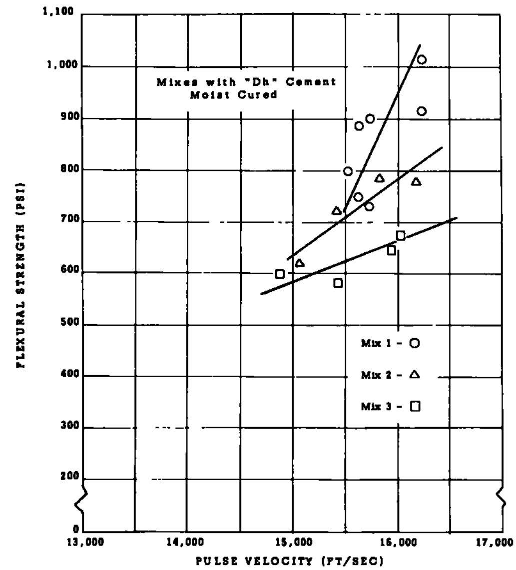

Figure 11. Flexural strength vs pulse velocity.

1 and 2. With the exception of two points, one representing an air cured specimen and the other an air-soaked specimen of the same mix and made the same day, the line fits the data reasonably well.

It may thus be observed that for the three mixes, using both the A and Ah cements and for all three curing conditions, a single pulse velocity-compressive strength relationship may be established which is fairly satisfactory. In some cases, however, notably better results may be obtained by treating individual mixes separately.

The results of similar tests on the three mixes containing the D and Dh cements are shown in Figures 4, 5, and 6. An entirely different performance is immediately evident. In the case of the three mixes using the D cement shown in Figure 4, a separate relationship between velocity and compressive strength exists for each mix. These are shown by the three solid lines on the figure and have standard errors of estimate of 175 psi, 515 psi, and 130 psi, respectively, for Mixes 1, 2, and 3.

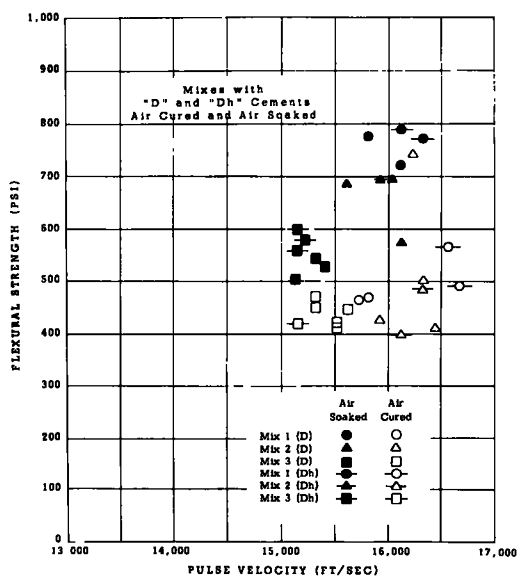

Figure 12. Flexural strength vs pulse velocity.

A second relationship might also be established from this figure. The dashed line shows a velocity-strength relationship for all specimens of a common age, 7 days, the variable being the water-cement ratios. The standard error of estimate is 360 psi. It is clear that there is no satisfactory single relationship accounting for the variables of both age and water-cement ratio.

When the Dh cement was used in the same three mixes (Fig. 5), again three different relationships were found. These are not the same as those found for the D cement mixes, and are apparently not as reliable, having standard errors of estimate of 385 psi, 335 psi, and 525 psi, respectively. Comparison with Figure 4 shows that for any water-cement ratio a given velocity defines a concrete having higher strength with the Dh cement than with the D cement.

The results of tests made on air cured and air-soaked specimens of the three mixes containing D and Dh cements are shown in Figure 6. Inasmuch as all specimens tested in these conditions were tested at an age of 28 days, data are insufficient to permit the establishment of a velocity-strength relationship for each mix. There is no single line which appears to fit all of the data reasonably well. It may be observed that in almost every case the specimens which were air cured had both higher compressive strengths and higher velocities than did those which were air-soaked.

COMPARISON OF PULSE VELOCITIES WITH FLEXURAL STRENGTHS

A comparison of flexural strengths with pulse velocities through specimens from the three mixes containing the A cement is shown in Figure 7. Again a straight line fits the data for the three mixes reasonably well, the standard error of estimate being 70 psi. The same straight line is shown on Figure 8 where flexural strengths are plotted versus pulse velocities for the three mixes containing the Ah cement. The line fits these data somewhat better than it does those from the three mixes containing the A cement, with a standard error of estimate of 55 psi.

The results of tests on the air-soaked and air cured specimens containing the A and Ah cements are shown in Figure 9. All three mixes containing the A cement were tested and one containing the Ah. The same line shown in Figure 7 and 8 has been constructed on this figure. In this case, however, it does not fit the data very well. With the exception of two points, representing the same specimens which showed unusual compressive strength-velocity relationships, the two dashed lines on the graph would fit the data quite well, the upper one representing the locus of points for air-soaked specimens and the lower one the locus for air cured specimen. It should be observed that this relationship is materially different from that found when compressive strengths of the same specimens were measured. In that case data from specimens cured by any of the three methods were about equally well satisfied by the same line.

Results of flexural strength tests on the three mixes containing the D and Dh cements are shown in Figures 10, 11, and 12. It again appears necessary to establish a different relationship for each mix. For the three containing the D cement the relationships shown in Figure 10 have standard errors of estimate of 50, 35, and 25 psi, respectively. In Figure 11, showing the results of tests on the same mixes containing the Dh cement, the standard errors of estimate are 75, 30 and 45 psi.

Figure 12 shows the results of tests performed on the three mixes containing the D and Dh cements when the specimens were air cured and air-soaked. It may be observed that in this case specimens tested under the two curing conditions have generally similar velocities but the air-soaked specimens have much higher strengths than do the companion air cured specimens. This is a most interesting performance when it is recalled that the compressive strength tests on the same specimens showed the strengths of the air cured specimens to generally exceed those of the air-soaked.

SUMMARY

The data outlined above represent tests on 113 specimens. They are sufficient to lead to certain observations concerning the use of pulse velocities for predicting either flexural or compressive strength of concrete, as follows:

1. For any specific concrete there may be a demonstrable relationship between pulse velocity and either compressive or flexural strength.
2. In some cases such a relationship may persist throughout considerable variation in mix proportions, age, and curing conditions. In other cases the relationship may be valid for only one variable.
3. Variations in curing conditions affect the relationship between pulse velocity and flexural strength to a considrably greater degree than the relationship between pulse velocity and compressive strength.

No rationalization may be used to show that pulse velocity is, or should be, more directly related to strength than is either the modulus of elasticity or the density of the material tested. It is generally agreed that neither of these properties bears a uniformly applicable relationship to strength in the case of concrete. The figures presented in the paper suggest that the relationships shown may not, with propriety, be extended beyond the limits of the plotted points, since relatively high velocities would invariably be associated with concrete of zero strength.

It is concluded that pulse velocities may sometimes be used to estimate flexural or compressive strength of concrete provided considerable care has been exercised to establish a pulse velocity-strength relationship valid for the concrete to be tested. No attempt should be made to estimate the strength of a concrete for which such a relationship has not been determined.

REFERENCES

1. Armstrong, C. C., Ulp, R. B., and Larson, K. C., Jr., "Sonic Method Proves Valuable for Testing Concrete Specimens." Civil Engineering (Nov. 1956).
2. Kozan, G. R., "Nondestructive Testing of Concrete Pavements." HRB Proceedings, Vol. 34 (1955).
3. Leslie, J. R., "Pulse Techniques Applied to Dynamic Testing." Special Technical Publication No. 101, ASTM (1951).
4. Leslie, J. R., and Cheesman, W. J., "An Ultrasonic Method of Studying Deterioration and Cracking in Concrete Structures." Proceedings, ACI, Vol. 46 (1949).
5. Long, B. G., and Kurtz, H. J., "Effect of Curing Methods Upon the Durability of Concrete as Measured by Changes in the Dynamic Modulus of Elasticity." Proceedings, ASTM, Vol. 43 (1943).
6. Whitehurst, E. A., "The Soniscope—A Device for Field Testing of Concrete." Proceedings of the 37th Annual Road School, Purdue University, Series No. 77 (1951).

Evaluation of Pulse Velocity Tests Made with Portland Cement Association Soniscopes

CALVIN C. OLESON, Principal Research Engineer, PCA Research and Development Laboratories, Skokie, Illinois

●SHORTLY before 1947 engineers of the Hydro-Electric Power Commission of Ontario, Canada began work on a method for measuring velocity of mechanical pulses through concrete. In 1947 the Portland Cement Association was invited to participate in this investigation. Using the Canadian designs, an apparatus later known as the "Leslie Soniscope" was constructed and used in tests on concrete structures (1). Since the tests were initiated much has been learned about the usefulness and limitations of pulse velocity tests of concrete. It is the purpose of this symposium to bring together the knowledge accumulated in America (2) during the past 10 yr so that some conclusions may be drawn regarding applicability of pulse velocity testing to current engineering problems.

DEVELOPMENT OF INSTRUMENTATION

Eleven models of the soniscope have been constructed in the PCA laboratories. The first 5 models followed closely the designs developed by the Hydro-Electric Power Commission (3). The last 6 models have followed slightly different patterns mainly for the purpose of achieving lighter weight and smaller size, improving the ease of operation and eliminating a number of operational problems that were present in the earlier soniscopes. The preamplifier has been discarded, placing all the receiver amplifier inside the soniscope. A single-beam cathode-ray tube has replaced the split-beam tube. Transducers have been improved. The trend toward smaller size and greater simplicity is illustrated by a comparison of Soniscopes No. 5 through No. 9 shown in Figure 1.

Study of the data obtained with the various PCA soniscopes appears to indicate that the accuracy of the measurements is about the same for all models. However, it has been observed that tests could be made with the later models that were impossible when attempted with the earlier equipment, due to the higher noise level in the early soniscopes.

USE OF THE SONISCOPE

The PCA soniscopes have been used principally for the testing of concrete, although other materials have been tested with some degree of success. A recent investigation being made with this equipment is the study of the knitting of human bone structures.

The quantity measured by a soniscope is the least time required for the transmission of a pulse of mechanical energy between two transducers. While the net time might be useful by itself under certain conditions, it is generally used with appropriate corrections as a factor to determine pulse velocity, or the velocity at which a pulse of energy travels through a given material, expressed in feet per second. The straight line distance between the centers of application of the two transducers is taken as the path length.

The most informative and reliable method of test appears to be that in which the two transducers face each other on a direct path through the concrete, provided the path length may be determined with a reasonable degree of accuracy.

Occasionally, the only practicable method of making a test is to place both transducers against the same face of the concrete, as for example a highway slab (5), or a wall having one side inaccessible. Investigations have shown that where the concrete is free of cracks or other forms of deterioration, pulse velocities obtained with both transducers against the same face are reasonably comparable with pulse velocity measured directly through the same concrete. In any case, however, the soniscope will measure only the shortest time interval required for the transmission of the signal, and for this reason tests made with both transducers on top of a slab that is deteriorated on the surface but not in the interior may be misleading. The pulse, leaving the transmitter in all directions, probably passes through the deteriorated surface layer to the undamaged interior where it travels rapidly to the receiver. Here it again passes through a thin layer of deteriorated surface, the net path being that which permits the quickest transmission of the signal. The pulse that travels at a slower rate through the deteriorated surface all the way is obscured by the pulse that travels a longer but fast path, most of which may be through sound concrete.

The relationship between pulse velocity and other properties with which engineers

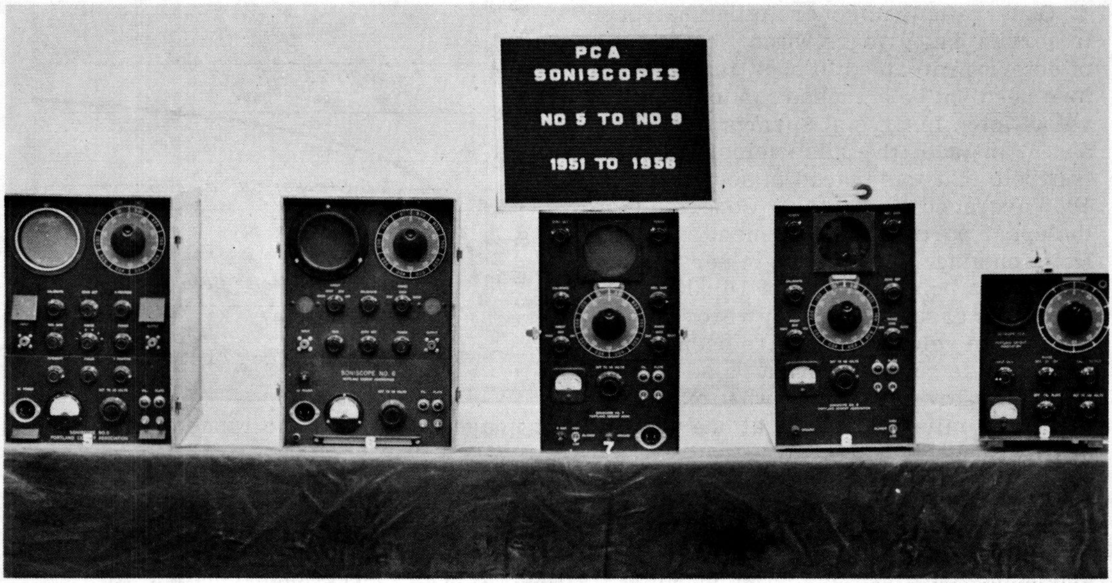

Figure 1. PCA soniscopes.

are more familiar, such as Young's modulus or compressive strength, has been the subject of considerable study by other investigators (4, 7, 8). No attempt is made in this paper to discuss the validity or desirability of these conversions since pulse velocity, as such, has been the principal field of this investigation.

FACTORS AFFECTING THE VALUE OF PULSE VELOCITY

Among the factors which are believed to have a bearing on the rate at which a mechanical pulse moves through concrete are:

1. Time of moist curing;
2. The fine and coarse aggregate;
3. Relative mixing water content;
4. Cement content;
5. Entrained air;
6. Absorbed moisture in the hardened concrete; and
7. The degree and extent of deterioration.

Effect of Curing

Tests made in the PCA laboratories and elsewhere show that the gain in pulse velocity through concrete from the freshly mixed state to any later time follows a curve which resembles a strength-time curve. The rate of gain is relatively rapid for a week, after which the curve tends to level off to a much more gradual rate of increase. It seems reasonable to assume that pulse velocity should continue to increase as long as hydration continues, or until deterioration has begun. Figure 2 shows a typical pulse velocity vs time curve for 1 yr for concrete having a cement content of 5½ sk. per cu yd. and subjected to continuous moist curing. For comparison, a typical compressive-strength curve for 6-sk. concrete is shown.

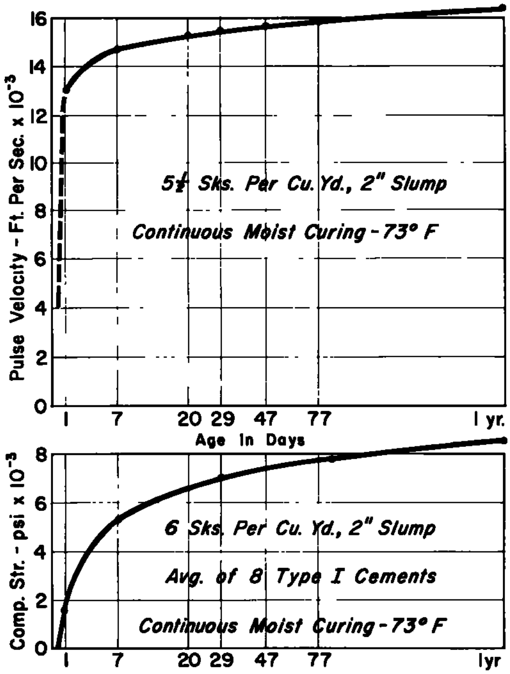

Figure 2. Effect of curing.

Observations of concrete that has been in service many years without evidence of deterioration tend to show that age alone need not be a reason for low pulse velocities. In Crystal Springs Dam, near San Francisco, the pulse velocities through concrete that was placed in service in 1885 averaged 13,800 fps. Concrete from the upper portion of a pavement slab in Bellefontaine, Ohio placed in service in 1892 had a pulse velocity of 16,600 fps. In neither case is there any record of what pulse velocity may have been at some earlier date but the present pulse velocities are representative of what may be found in similar concretes at one year or less in age, and are in the range of good-quality concrete.

Effect of Aggregate Characteristics

At an outdoor test plot located in Georgia, three coarse aggregates were used for concretes that were otherwise essentially alike. Annual inspections, coupled with annual soniscope tests since 1948, indicate that there is no evidence of deterioration that should influence the relative values of the pulse velocities in the concrete. Average values are about 13,000 fps for granite, 14,500 fps for gravel and 16,000 fps for limestone coarse aggregates. However, the range of pulse velocities for different specimens containing each of the aggregates is so broad that it would be virtually impossible to identify by means of pulse velocity alone, the kind of coarse aggregate in any given concrete.

At another outdoor test plot located in Illinois, there is an opportunity to observe the effect of good-quality sand compared with sand having a poor service record. The coarse aggregate in both cases is gravel from a source having a good service record. Here the concretes containing the good-quality sand are consistently higher in pulse velocity than the comparable concretes containing the poor-quality sand. On the other hand, tests made at different times during a single year have disclosed seasonal differences for the same specimens that are greater than have been found between the good and the poor aggregates.

It is apparent that the aggregate does exert a significant influence on pulse velocity in concrete. It is equally apparent that other factors such as moisture content or deterioration may completely obscure the effect of the aggregate.

Effect of Relative Water Content

An increase in the mixing water used with a given set of ingredients will increase the water-cement ratio, increase the slump in the fresh mix, and decrease the strength of the hardened concrete. It is generally conceded that pulse velocity will likewise de-

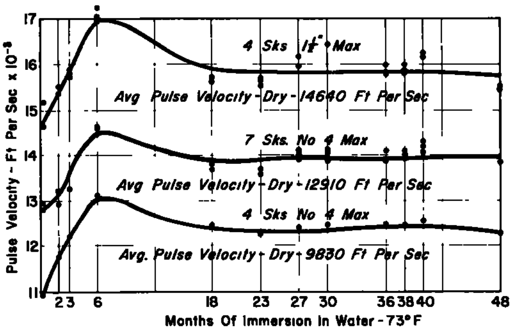

Figure 3. Effect of absorbed moisture.

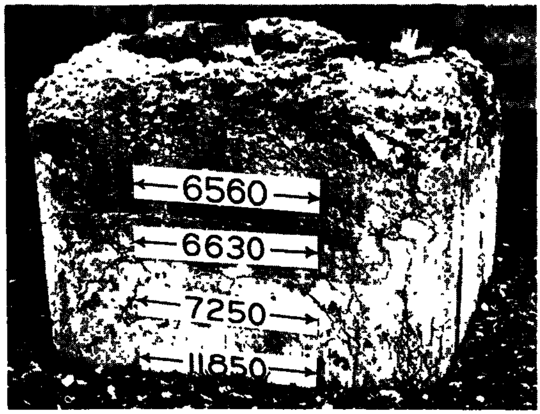

Figure 4. Pulse velocity in terms of deterioration.

crease in value and laboratory tests appear to confirm such a conclusion. However, the soniscope tests on hundreds of outdoor-exposure specimens located in Illinois and Georgia reveal that after 15 yr there is no significant or consistent difference in pulse velocity between concretes that are similar in all respects except slump of the fresh mix due to added mixing water. At these test plots dry-batch proportions were established for 3-in. slump concrete based on 4½ and 6 sk. of cement per cu yd. Parallel rows of like specimens were then cast, using the same dry-batch proportions but adding water to produce an 8-in. slump. It would be impossible to take any of the 1957 test data and say with assurance that the concrete was originally of either 3- or 8-in. slump. Based on these findings and in spite of laboratory tests to the contrary, it would appear that soniscope tests are not a reliable means of evaluating the probable relative amount of mixing water used in concrete placed in the field.

Effect of Cement Content

Again referring to data obtained from observations made on many hundreds of outdoor-exposure specimens, it is quite clear that the effect of cement content (within normal ranges) is of minor importance so far as pulse velocity is concerned and it must be concluded that the soniscope test is of little value in attempting to determine the amount of cement per cu yd that was used in the fresh concrete. For example, comparing two rows of specimens of 3-in. slump concrete located in Georgia, the average pulse velocity for the 6-sk. mix is 13,100 fps, while for a nearby 4½-sk. mix it is 13,500 fps. Another row of 4½-sk., 3-in. slump concrete in the same type specimens cast a few days later using the same materials in the same proportions as before, has an average pulse velocity of 12,800 fps.

At an exposure plot located in California, hundreds of beams cast with cement contents of 4, 5½, and 7 sk. per cu yd show a somewhat better relationship between the various mixes but here too there are reversals which emphasize the danger of attempting to use pulse velocity as a means of identifying the cement content of the hardened concrete.

It would appear that other factors counterbalance, and, in some cases, overshadow the influence of cement content within the limits covered by the test data.

Effect of Entrained Air

Laboratory tests show that as the amount of entrained air in concrete is increased, the pulse velocity is diminished. It may be possible under carefully controlled conditions to prepare a curve which gives the relationship between amount of entrained air and pulse velocity. The test of such a curve would be its applicability to concrete in the field. Observations made at the outdoor test plots in Illinois and Georgia, where there are 6 air-entraining cements in each row, show that the pulse velocities for the air-entrained concretes are in many cases equal to the velocities measured in their non-air-entrained counterparts, and, in some cases, the air-entrained concretes are the higher of the two.

In the case of entrained air, as has already been noted for other factors that have an influence on pulse velocity in sound concrete, it appears to be very doubtful that a soniscope test would be a satisfactory means of determining the presence or absence of the air.

Effect of Absorbed Moisture

Successive soniscope tests made on the same field specimens over a period of years have shown some irregularities in pulse velocities that have been difficult to explain. Other specimens that have not been exposed to weather have shown remarkably uniform test results. Study of factors which might have resulted in the irregularities have pointed to variations in moisture content as being the probable cause. In order to find out how much variation in pulse velocity might be expected from variations in moisture content, laboratory tests are being made and additional field observations at different times of the year have been undertaken.

Figure 3 shows graphs of pulse velocity tests made on 8 beams which were dried in the laboratory air for an extended period before soniscope tests were started. When the beams were placed in water in February 1953, the pulse velocities immediately started increasing. The graphs show a high point at 6 months. No tests were made between 6 and 18 months, at which time the velocities had apparently dropped to about the 3-month level. Unexplained fluctuations have taken place between 18 months and 48 months. However, aside from the 6-month tests, the variations are equivalent to about one microsecond in net time, a limit of accuracy that experience has shown to be reasonable.

Field tests at outdoor test plots show that extended periods of heavy rain result in a partial saturation of the concrete with an increase in pulse velocity, and that for extended dry periods the pulse velocity drops.

Effect of Deterioration

The soniscope appears to hold a great deal of promise in the study of deterioration of concrete. The effect of deterioration of poor-quality concrete, expressed in terms of pulse velocity, is shown by Figure 4. The trouble in this example is due to many natural cycles of freeze-thaw while saturated; the concrete being of 8-in. slump, low-cement content, and containing a poor-quality sand.

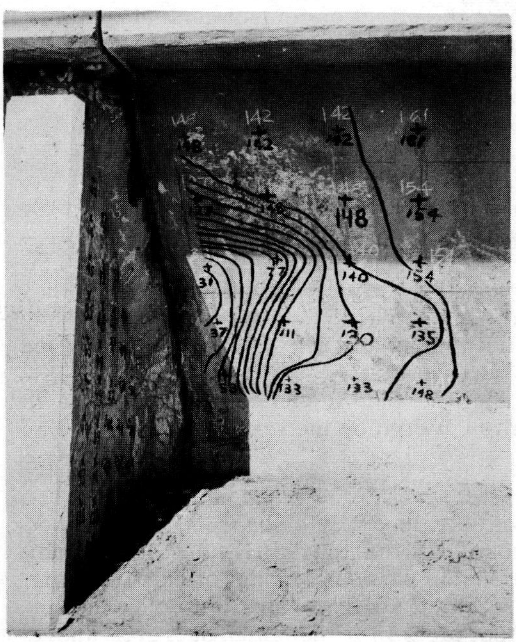

Figure 5. Relative deterioration measured by pulse velocity.

Figure 5 shows tests that were made on the walls of a large concrete reservoir that had been in service about 40 yr. Grid patterns were laid out in the areas to be investigated. Pulse velocities at each point, ranging from 16,100 fps to 3,100 fps, were marked on the concrete. Velocity contours were drawn as shown, helping to define the areas and degree of deterioration. This method of investigating structural concrete deterioration has been used by the Ontario Hydro-Electric Power Commission, and possibly by other organizations.

In another field study, the soniscope has been of service in evaluating the relative performance of concrete silo staves in an experimental silo investigation.

Deteriorating concrete does not always exhibit the visual evidence shown in Figure 4. An installation of test piles exposed to fresh water in a severe climate began to show marked decreases in pulse velocity long before there were visual signs of distress. Effects of mix proportions and water-cement ratio were brought out clearly by the soniscope tests. Now that surface deterioration has developed on the piles, the early soniscope evidence is borne out at least qualitatively. These results offer the hope that soniscope tests over a period of time (as yet undetermined) may provide a basis for predicting the useful life of structures.

CONCLUSIONS

1. The soniscope is capable of measuring the transit time of a mechanical pulse through concrete with a precision of approximately one microsecond.
2. Pulse velocity, the rate of travel of a mechanical pulse, is a measure of a property of concrete which may often be associated with other properties with which engineers are familiar.
3. Laboratory tests show that for a given concrete subjected to continuous moist curing the curve of pulse velocity vs. age is similar in shape to the curve of gain in strength.
4. Pulse velocity for a given concrete is a function of many factors; such as the kind of curing, aggregate, relative mixing water content, cement content, and others.
5. Variations in pulse velocity in hardened concrete are caused by changes in amount of absorbed moisture.
6. In every case observed, deterioration in concrete is accompanied by a drop in pulse velocity. This relationship provides the most useful field for the soniscope. It offers a possibility for predicting performance of concrete structures.

REFERENCES

1. Whitehurst, E. A., "Soniscope Tests on Concrete Structures." Proceedings, ACI, Vol. 47, p. 433 (1951).
2. "International Symposium of Non-Destructive Testing of Materials and Structures." RILEM, Vols. I and II (1954).
3. Leslie, J. R., and Cheesman, W. J., "An Ultrasonic Method of Studying Deterioration and Cracking in Concrete Structures." Proceedings, ACI, Vol. 46, p. 17 (1950).
4. Philleo, R. E., "Comparison of Results of Three Methods for Determining Young's Modulus of Elasticity." Proceedings, ACI, Vol. 51, p. 461 (1955).
5. Meyer, R. C., "Dynamic Testing of Concrete Pavements with the Soniscope." Proceedings, HRB, Vol. 31, p. 234 (1952).
6. "Comparative Tests of Soniscopes for Ultrasonic Testing of Concrete." Miscellaneous Paper 6-48, U. S. Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi (Sept. 1953).
7. Jones, R., "The Non-Destructive Testing of Concrete." Magazine of Concrete Research, Vol. 1, No. 2, pp. 67-76 (June 1949).
8. Jones, R., and Gatfield, E. N., "A Method of Measuring Ultrasonic Pulse Velocities." Magazine of Concrete Research, Vol. 1, No. 2, pp. 77-78 (June 1949).

General Discussion

K. S. BAWA, Soils and Foundation Engineer, Gannett Fleming Corddry and Carpenter, Inc., Consulting Engineers, Harrisburg, Pennsylvania

● THIS SYMPOSIUM is a welcome opportunity for pooling knowledge and exchanging views on the subject of evaluation of pulse velocity data; and the organizers of this difficult task deserve special thanks.

The pulse velocity data and discussions presented in this symposium relate primarily to concrete. Actually, pulse velocity technique has been used with a considerable success for the testing of other highway materials such as soils (1, 2) and bituminous mixtures (3). The use of this technique for soil or bituminous mixtures has so far been confined to mostly laboratory samples and so far no data from field observations have been reported for structures (in situ) constructed with these materials. The laboratory data (pulse velocity vs compressive strength, etc.) have a scattering generally similar to that shown by concrete. It is found that pulse velocity data for soils generally follow, with a few exceptions, the pattern obtained in the laboratory testing of concrete under the same conditions. The pulse velocity technique for concrete is based primarily on a correlation of the pulse velocity and some other well known property, such as compressive strength or modulus of elasticity, which is taken to indicate the quality of concrete. Often the quality of concrete is directly interpreted from the relative changes in the pulse velocity observed under a given set of conditions. Due to the existing empirical nature of this technique, a number of limitations are inherent in this test method. Hence, while evaluating the pulse velocity test data, the various limitations should be kept in mind and, as far as possible, such data should be supplemented by all other available test information.

The interpretation of pulse velocity data for concrete, about which there is no other information, is a hazardous task fraught with difficulties and any conclusions derived from trends of pulse velocity alone should be treated with caution. Although it is now considered almost a general rule that changes in quality of concrete are reflected by corresponding changes in pulse velocity, several exceptions are known to exist and two such are reported in this symposium. In their paper, Woods and McLaughlin (1) report that the deterioration of concrete specimens subjected to alternate freezing and thawing cycles in the laboratory was hardly reflected by any consistent changes in pulse velocity. Similarly Meyer (4) shows that after 8 yr of regular observations of pulse velocity for several experimental concrete pavement sections in Kansas, no significant changes in velocity were noticed. In fact, he reports that visual evidence of deterioration was obvious before the condition was reflected by pulse velocity data. It seems that if some of the data reported by Spencer and Laverty (5) are corrected for seasonal variations, as suggested by Meyer, it is quite possible that they may come to a negative conclusion similar to those indicated above. No satisfactory explanation has been attempted for the lack of correlation in these and many other instances.

Such exceptions or negative conclusions point to the inadequacy of the empirical concept alone in interpreting the pulse velocity test data and emphasize the need for a basic theory, as was also pointed out by Pickett during the course of this symposium, which should take into consideration the fundamental principles involved in determining velocity of transient waves. In developing such a theory, consideration should be given to the nature of the stress-strain phenomenon caused by the propagation of transient low energy waves through a material ordinarily regarded as elastic. It is quite possible that the difference between static and dynamic moduli of elasticity might appear as a natural corollary from such a theory.

REFERENCES

1. Woods, K. B., and McLaughlin, J. F., "Application of Pulse Velocity Tests to Laboratory Studies of Materials." This Symposium.

2. Bernhard, R. K., and Finelli, J., "Pilot Studies on Soil Dynamics." Symposium on Dynamic Testing of Soils, ASTM Sp. Tech. Pub. No. 36 (1953).
3. Goetz, W. H., "Sonic Testing of Bituminous Mixtures." Proc., AAPT (Tech. Sess.) Vol. 24, p. 331 (1955).
4. Meyer, R. C., "Eight Years of Pulse Velocity Tests on Concrete Pavements in Kansas." This Symposium.
5. Spencer, R. W., and Laverty, B. R., "Appraising the Quality and Performance of Concrete by Pulse Velocity Measurements." This Symposium.

Symposium Summary

E. A. WHITEHURST, Director, Tennessee Highway Research Program, University of Tennessee, Knoxville;
C. C. OLESON, Principal Research Engineer, Portland Cement Association, Chicago;
R. C. VALORE, Jr., Director of Research, Texas Industries, Inc., Dallas

THE SUMMER of 1957 represented the tenth anniversary of the first rather extensive use of the soniscope in testing concrete. It seems most appropriate, therefore, that this symposium has been held to review such use, to summarize the experiences of those who have used the instrument, to define the present state of knowledge with respect to interpretation of test results, to delineate areas of investigation in which sufficient information is not available for adequate analysis of tests results, and to point out potentially promising fields for further research.

It should be immediately appreciated that this symposium has dealt only with the measurement of pulse velocities through the use of the soniscope. It is acknowledged that other devices are being used for measuring pulse velocities through concrete and that the users of these devices and the users of soniscopes have not always agreed upon the interpretation of test results. It is believed, however, that the papers presented during the symposium represent an excellent cross-section of those who have made use of the soniscope. Indeed, practically every organization which has had extensive experience in such use was represented on the program.

In summarizing the opinions expressed in the formally presented papers and in the discussions following their presentation, it is quite clear that most investigators believe that there are two rather distinctly different categories of use of the soniscope. The first might be termed routine use. Such use is characterized by general agreement concerning procedures to be followed and by comparative ease in interpretation of results. The second category is research use, the characteristics of which are lack of agreement in regard to appropriate techniques, lack of information sufficient to permit adequate interpretation of test results, and the need for further investigative work.

ROUTINE USES

Several routine uses have been repeatedly detailed in the papers presented during the symposium. Foremost among these, and apparently agreed to be of greatest value at the present time, is the evaluation of uniformity in structure. Such evaluations have been made by a number of organizations. The testing normally involves the performance of many tests, frequently quite close to one another and usually in some form of grid pattern. Differences in measured velocities are taken to be indicative of variations in quality unless the observed velocity differences may be accounted for through some known physical variation in the structure. Investigations of this nature are particularly valuable where there is some visual indication of distress in the structure but where such indications and other test methods do not provide adequate information concerning the extent of the distress.

Another routine use of the soniscope lies in the determination of a trend in the performance of concrete over a period of time. Such tests may be made either on laboratory specimens or on structures. They involve the repeated performance of velocity tests on the same specimens or at the same locations on the same structures over a period of time, in some cases many years. Systematic trends in velocity variations during a number of such tests are believed to be indicative of similar systematic trends in the condition of the concrete.

A third use of the soniscope is the determination of a general level of concrete quality. It is agreed that high velocities are associated with concrete of good quality and low velocities with that of poor quality. It is realized that no very sharp delineation may be demonstrated between high and low velocities as used in this sense, and that many concretes will fall into a velocity zone which does not, per se, permit adequate evaluation of concrete quality. It seems to be agreed, however, that either very good or very poor concretes may be readily identified through pulse velocity tests.

Crack detection might also be considered in some cases a routine use of velocity techniques. Certainly such techniques may prove useful in demonstrating the absense of major cracks in monolithic concrete. The full usefulness of this method in establishing the exact location and extent of cracks has probably not yet been realized.

RESEARCH USES

Some applications of soniscope testing have been described which it is generally agreed are not yet routine in nature, although in time they may become so. One of these, as suggested above, is the determination of the exact location and extent of cracks in concrete. Rather considerable work has been done in this area, particularly by the Ontario Hydro Electric Power Commission. Detailed information concerning such matters as the minimum width of crack which may be detected or the effect of water within the crack is not yet available. This does not eliminate the usefulness of the instrument in studies of this nature but suggests that extreme care be employed in interpreting test results.

Several authors commented upon the usefulness of soniscope tests in evaluating the setting or hardening of concrete. It has been clearly demonstrated that major variations in the velocity occur during the first hours or days after concrete is placed. Again the exact interpretation of such variations is not yet clear. This, however, does not obviate the usefulness of the technique in observing early changes in the nature of concrete.

Finally, rather considerable discussion was given to the evaluation of various other properties of concrete, notably strength, on the basis of pulse velocity tests. It was generally agreed that such evaluation is very difficult. In some cases useful and helpful information may be developed, but interpretation of the velocity tests must be undertaken with great caution. Such usage was certainly agreed to be other than routine.

AREAS OF AGREEMENT

In reviewing the several papers presented during the symposium, it is clear that in a number of instances there is almost complete unanimity of opinion among the authors. These areas are as follows:

1. There appears to be no urgency for further major developmental work on the soniscope itself. Few questions were raised concerning instrumentation or the ability of the instrument to perform in the desired manner.
2. It was universally agreed that the soniscope does not replace other testing techniques but rather supplements them. No author suggested that the testing of concrete be limited in any way because of the availability of pulse velocity testing techniques.
3. There was almost complete agreement that little was to be gained by computing anything except pulse velocity from soniscope tests. If anything further must be computed, it was agreed that this should be the dynamic modulus of elasticity.
4. There was uniform awareness among the authors of the grave difficulties associated with predicting either flexural or compressive strength on the basis of pulse velocity tests. Warnings were repeatedly given against such interpretation of velocity data.
5. It was generally agreed that pavement slabs represent the most challenging structural form for evaluation through pulse velocity tests. Comments ranged from complete lack of faith in their usefulness for testing slabs to mild statements of optimism concerning such tests.

During the course of the symposium, it was suggested that soniscope tests might prove useful and would doubtless be attempted in certain applications not previously widely made. With respect to concrete, the principal suggested use was in the quality control of products. It was specifically suggested that a plant producing precast concrete products in large numbers, over a period of time, and from presumably uniform materials and mixes, might well employ frequent pulse velocity tests of its products to evaluate the uniformity thereof. It was clearly pointed out that such testing would not replace more routine physical testing to establish the level of quality of the product, but would merely assist in uncovering any deviations from this level.

Although the symposium dealt with the testing of concrete, several comments were made concerning the testing of other materials. It is apparent that the next few years will see rapid advances in the use of the soniscope in the testing of timber, soil, and bitumen-aggregate mixtures. Limited investigations are reported to have already been made in each of these fields.

RECOMMENDATIONS FOR FUTURE DEVELOPMENTS

The very real accomplishments in the field of pulse velocity testing of concrete during the past ten years notwithstanding, the symposium has brought to light certain areas in which additional work is clearly indicated. Some of these involve basic studies of the manner in which certain variables affect pulse velocity. Some data were presented which indicate that pulse velocities through concrete are not truly independent of size and shape of specimen, but may vary with path length or with volume of concrete normal to the path. Data were also presented to show that the pulse velocity was dependent upon the maximum size of aggregate used in the concrete and the percentage of paste incorporated therein. Questions were raised concerning the effect of moisture content of the concrete upon its pulse velocity. In all of these areas extensive basic research appears to be indicated.

Some discussion was given to the development of a suitable "test bar" or "standard" which could be tested repeatedly for the purpose of providing assurance that the instrument was operating in the proper manner. Several such standards have been developed by various organizations. There does not appear to be agreement upon which are best or whether any are truly satisfactory. This, too, is an area requiring further investigation.

Attention was called from a practical point of view to the very real need for an operating manual or some other form of publication which would clearly describe appropriate techniques in operating the soniscope, collecting information with it, and interpreting the results thereof. This information is probably available at the present time but is spread through the publications of several societies and has been published over a ten-year period. A material service to those interested in employing soniscope tests would be made by the preparation and publication of such a manual.

Finally, considerable discussion was given to the necessity for better programing in the testing of a structure. It was pointed out that tests made in a haphazard fashion are likely to give results which are of relatively little value. For the results of such tests to be of greatest value, transducer positions and test paths must be carefully selected. Attention was repeatedly directed to the work of Breuning and Roggeveen, which has been the most outstanding to date in this field.

SUMMARY

The papers presented during this symposium and discussions thereof show clearly the vast development in this field during the past ten years. The instrumentation has been completely developed during approximately this time and is satisfactory. The technique has progressed from one assigned solely to the research laboratory to one having numerous practical applications. Useful interpretation of test results may now be made in many instances although a complete understanding of all of the factors influencing such results has not yet been reached. The term "pulse velocity" has now become a proper fragment of the concrete engineers' vocabulary.

HRB:OR-206

THE NATIONAL ACADEMY OF SCIENCES—NATIONAL RESEARCH COUNCIL is a private, nonprofit organization of scientists, dedicated to the furtherance of science and to its use for the general welfare. The ACADEMY itself was established in 1863 under a congressional charter signed by President Lincoln. Empowered to provide for all activities appropriate to academies of science, it was also required by its charter to act as an adviser to the federal government in scientific matters. This provision accounts for the close ties that have always existed between the ACADEMY and the government, although the ACADEMY is not a governmental agency.

The NATIONAL RESEARCH COUNCIL was established by the ACADEMY in 1916, at the request of President Wilson, to enable scientists generally to associate their efforts with those of the limited membership of the ACADEMY in service to the nation, to society, and to science at home and abroad. Members of the NATIONAL RESEARCH COUNCIL receive their appointments from the president of the ACADEMY. They include representatives nominated by the major scientific and technical societies, representatives of the federal government, and a number of members at large. In addition, several thousand scientists and engineers take part in the activities of the research council through membership on its various boards and committees.

Receiving funds from both public and private sources, by contribution, grant, or contract, the ACADEMY and its RESEARCH COUNCIL thus work to stimulate research and its applications, to survey the broad possibilities of science, to promote effective utilization of the scientific and technical resources of the country, to serve the government, and to further the general interests of science.

The HIGHWAY RESEARCH BOARD was organized November 11, 1920, as an agency of the Division of Engineering and Industrial Research, one of the eight functional divisions of the NATIONAL RESEARCH COUNCIL. The BOARD is a cooperative organization of the highway technologists of America operating under the auspices of the ACADEMY–COUNCIL and with the support of the several highway departments, the Bureau of Public Roads, and many other organizations interested in the development of highway transportation. The purposes of the BOARD are to encourage research and to provide a national clearinghouse and correlation service for research activities and information on highway administration and technology.