by R. Jones and E. N. Gatfield, pp 77–78.
15. Jones, R., "The Non-Destructive Testing of Concrete." Reinforced Concrete Review, Tech. Paper No. 16, pp 315–328, Jan. 1951.
16. Jones, R., "Measurement of the Thickness of Concrete Pavement by Dynamic Methods: A Survey of the Difficulties", Magazine of Concrete Research, vol 1, No. 1, Jan. 1949, pp 31–34.
17. Chefdeville, J. and Dawance, G., "L'Auscultation Dynamique du Beton." *Ann.* de l'Inst. Tech du Batiment et des Trav. Pub., No. 16 (July-Aug 1950), 27 pp.
18. Dawance, G., "The Use of Acoustic Methods for Testing Reinforced Concrete Structures." 4th International Congress on Bridge and Structural Engineering, 1953, pp 505–510.
19. Kesler, C. E. and Higuchi, Yoshiro, "Determination of Compressive Strength of Concrete by Using its Sonic Properties." ASTM *Proceedings*, vol. 53, 1953 (Preprint No. 80).

Ultrasonic Testing of Other Materials

20. Hughes, D. S., Pondrom, W. L., and Mims, R. L., "Transmission of Elastic Pulses in Metal Rods." *Physical Review*, vol. 75, No. 10 (1949), pp 1552–1556.
21. Huntington, H. B., "Ultrasonic Measurements on Single Crystals." *Physical Review*, vol. 72, No. 4 (1947), pp 321–331.
22. Price, W. J., "Ultrasonic Measurements on Rochelle Salt Crystals." *Physical Review*, vol. 75, No. 6 (1949), pp 946–952.

Descriptions of Structures Tested

23. Mather, Bryant, "Cracking of Concrete in the Tuscaloosa Lock", *Proceedings*, Highway Research Board, vol 31, 1952, p. 218.
24. "Investigation of the Suitability of Prepakt Concrete for Mass and Reinforced Concrete Structures." Technical Memorandum No. 6–330, Waterways Experiment Station, 1951.

Pulse-Velocity Techniques and Equipment for Testing Concrete

E. A. Whitehurst, *Director,*
Tennessee Highway Research Program
University of Tennessee

● SINCE about 1938, when Powers (*27*) published what is generally considered to be the first complete report of a dynamic testing technique for concrete, few years have passed which have not brought forth new and significant developments in this field. With the passage of time, however, as the various resonant-frequency techniques became highly developed and standardized, the desirability of the development of similar methods suitable for testing concrete in situ became ever more pressing. It was appreciated, of course, that the techniques developed for laboratory specimens could not readily be extended to use in field testing, because of the difficulty and, possibly, the danger of vibrating a structural member at resonance and because of the complexity of the computations which would be required to convert such resonant frequency to some significant quality of the concrete.

The early investigators appreciated that there was available another avenue of investigation which might result in the development of equipment and techniques satisfactory for field testing. Powers, in his paper previously referred to, stated: "Incidentally, it should be possible to determine E from the velocity of sound in the concrete as well as by the dynamic method discussed in this paper, that of using flexural vibrations. Once the method was developed, it might be more generally applied than the one described in this paper."

Within a few years, several investigators had reported measuring velocities through concrete, and in 1943 Long and Kurtz (*19*) reported the development of an apparatus suitable for making such tests in the field. Their technique, and that of other investigators to that time, consisted of inducing a continuous vibration of known frequency in the concrete and determining its wave length. In the report mentioned above, Long and Kurtz described their apparatus as a converted auditorium loud speaker driven by a variable-frequency oscillator. The device was capable of delivering 50 watts at audio frequencies. A rod connected to the speaker cone was rigidly attached to the concrete under test. A vibration pickup and cathode-ray oscilloscope were used to analyze the wave forms in the concrete. A portion of the output of the oscillator was fed to one pair of plates of the oscilloscope, while the signal detected by the vibration pickup was amplified and fed to the other plates. The resulting Lissajous figures revealed the phase relationship of the two signals. In testing, the pickup was placed on the concrete at any radial line from the speaker and the oscillator tuned until a straight line occurred in either the first and third or second and fourth quadrants of the oscilloscope face. The pickup was then moved away from the speaker along the chosen line until the straight line on the oscilloscope face had reversed its position and now appeared in the opposite two quadrants. The distance through which the pickup had been moved, representing half a wave length of the known frequency in the concrete, was carefully measured, and from this distance and the frequency the velocity was computed.

In the discussion of the report of the above work (*19*) the writers state as follows: "These tests were supplemented by a few experiments with a Shepard siesmograph, in which the longitudinal velocity of the pulsation created by a single impact was measured between arbitrarily placed geophones. Although only a limited number of experiments have been conducted at this time it appears that this latter method holds great promise provided that the apparatus can be adapted to the measurement of much shorter intervals of time than is practicable with the present equipment".

Insofar as is known, this is the first published reference to the measurement of the velocity of a pulse traveling through concrete. It is interesting to note that the writers commented that values of modulus of elasticity calculated from the velocity of such a pulse appeared to agree reasonably well with values obtained for small specimens of similar concrete tested at resonant frequency, whereas, values of modulus computed from velocities measured from continuous forced vibrations in concrete were invariably lower than those determined from the flexural resonant frequency.

Since 1943, when this work of Long and Kurtz was first published, numerous organizations have studied the problem of measuring the velocity of pulses through concrete. During the past two years a number of reports have reached the Committee on Dynamic Testing of Concrete, Highway Research Board, of devices developed in several parts of the world, many of which appear to be quite similar. At the same time, requests for information concerning instrumentation for this purpose have also been received in increasing numbers. As a result, this paper has been compiled with the thought that a summary of the various devices which have been developed may serve not only to coördinate the studies now being conducted in this field, but also as a guide to others interested in conducting such investigations.

EQUIPMENT AND TECHNIQUES

A survey of existing literature and correspondence with those active in the field indicates that pulse-velocity measuring devices developed to date fall into three classes. The first of these includes those in which the pulse is generated by a single physical impact upon the concrete, usually a hammer blow, and the transit time between two more or less arbitrarily placed pickups is measured by some electronic device. These units do not include any provision for visual observation of the test signals. In the second category are a number of devices which are entirely electronic, the pulse being generated by the firing of a thyratron and traveling directly from one pickup into the concrete and, hence, to the second pickup. In these units the repetition rate of pulse application is high, and the transmitted and received signals are displayed upon a cathode-ray oscilloscope with provisions for direct measurement of the transit time. Such devices are frequently referred to as "ultrasonic," although in some cases the actual pulse-modulation frequency may be in the upper half of the sonic range. The third group falls somewhere between these two extremes, with the pulse applied through a physical blow, usually that of a motor-driven hammer repeated at the relatively low rate of a few times per second, and the signal picked up very much as is that generated by the first group of instruments. With these devices, however, the transmitted and received signals are portrayed on an oscilloscope with provisions available for measurement of the transit time of the pulse. The various types will now be considered in some detail.

Single-Blow Devices

The first known published report of a satisfactory device for measuring pulse velocities through concrete was made by Long, Kurtz, and Sandenaw (*20*) in 1945. The device, an electronic interval timer, consists of two similar vibration pickups and amplifiers, two similar thyratron tube circuits, and a triode ballistic galvanometer circuit. A block diagram is shown in Figure 1.

To operate the device, the two pickups are laid on the surface of a concrete slab at some known distance apart and a hammer blow is applied to the concrete in a horizontal direction and in line with the two pickups. The impulse, upon reaching the first pickup, triggers the first thyratron, permitting a flow of current through the galvanometer. When

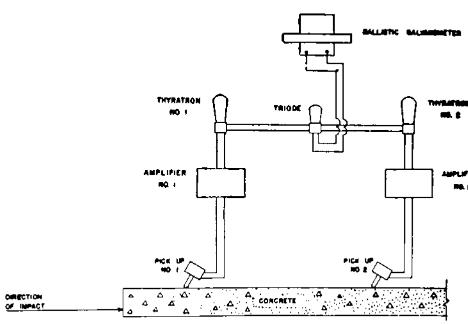

Figure 1. Electronic interval timer (American Concrete Institute).

the impulse reaches the second pickup and triggers the second thyratron, current through the galvanometer was cut off. The deflection of the galvanometer is directly proportional to the time required for the impulse to pass between the two pickups.

Because of differences in the time constants of the two pickup circuits, it is necessary that a calibration time, or "zero correction," be applied. This is accomplished by making a number of tests with the pickups spaced at different intervals, D, apart. If these D values are plotted as abscissa, and the values of galvanometer readings for each plotted as ordinates, the straight line drawn through the plots will intercept the ordinate axis at some value other than zero. This value is the correction time which was attributable to differences in the pickup-circuit characteristics and must be deducted from all measured transit times.

This apparatus was used by its developers in testing airport-runway concrete with some success. They reported, however, that the ballistic galvanometer circuit was quite critical and not altogether suitable for field usage. Morton (*25*), in a discussion to the above-mentioned paper, suggested certain circuit changes which he had investigated, resulting in a more-satisfactory field apparatus. These included the replacement of the ballistic galvanometer circuit by a capacitor which was charged during the interval between pulses. The charge was measured by a vacuum-tube voltmeter circuit, with the final reading given directly on a microammeter. This reading was apparently referred to suitable calibration charts, thus giving the direct transit time of the pulse in passing between pickups and eliminating the need for applying the zero correction. Morton also made comments concerning the response characteristics of various types of crystal pickups and suggested the use of a phonograph-pickup crystal to replace the vibration pickups originally employed.

The American Instrument Company is presently building an instrument under the name of the Electronic Interval Timer which is based upon that developed by Long, Kurtz and Sandenaw, and which, apparently, is nearly identical to the modified device described by Morton. This instrument is shown in Figure 2. It is reported that such

Figure 2. Electronic interval timer (American Instrument Company).

instruments are presently in field use by the Corps of Engineers. Results of recent tests are not presently available.

Other similar equipment has been developed, both in this country and abroad. The Bureau of Reclamation has been interested in this problem for a number of years and has built and used a device which is called a "microtimer." Much of this work was done and reported by West (*28*, *29*). This device also employs two phonograph pickups placed upon the surface of the concrete and makes use of a hammer blow in line with the pickups to initiate the desired pulse. Time is determined by the charge developed across a condenser, this charge commencing when the pulse reaches the first pickup and ending when it reaches the second. The instrument is calibrated in the laboratory by feeding into the condenser-charging circuit electronic pulses separated by known time intervals and recording the reading resulting upon a microammeter. In the field, when an unknown time interval is measured, the microammeter reading need only be referred to a proper calibration curve. No zero correction need be applied. This instrument has been used primarily for measuring velocities along or near the surface of concrete slabs, as has been the electronic interval timer, but West has, on at least one occasion (*29*), modified it to permit the measurement of pulse velocity through a massive concrete structure. In this case, the phonograph pickups were cemented to the upstream and downstream faces of an arch dam and a very heavy hammer blow struck near the first pickup. The tests were reasonably successful, but were quite time-consuming. This work was reported during the period 1946 to 1949. The microtimer is shown in Figure 3.

More recently another similar development has been reported from Denmark. In 1950, Andersen, Nerenst, and Plum (*1*), and in 1952, Andersen and Nerenst (*2*), reported the development and use of a device called a "condenser chronograph." It appears to be almost identical to the microtimer, differing only in minor details with respect to the timing circuit. In this case, the timing capacitor is charged to a known voltage prior to test. When the impulse reaches and triggers the first pickup, the condenser commences to discharge through a known-resistance circuit. When the impulse operates the second pickup, the discharge is stopped. The ratio of the final voltage to the original voltage is a direct measure of the time interval consumed by the impulse in passing between the two pickups. With the condenser chronograph, it is also necessary that a zero correction be taken into account. The writers appear to make a practice of making at least five tests with the spacing of the pickups increased by regular intervals. The distances and measured times are plotted as was the case for the electronic interval timer and the ordinate intercept is used as the zero correction.

The instrument described above is now available commercially through M. T. Weibel, Copenhagen, Denmark, who reports already having delivered them in several countries. They are identified as a Condenser-Chronograph, Joergensen-Weibel System, Type W-15. The device is shown in Figure 4.

Filter (*8*) recently reported the development at the National Physical Laboratory, South African Council for Scientific and Industrial Research, Pretoria, South Africa, of a device which appears to be similar in practically all details to the electronic interval timer. It is claimed that this device can be calibrated without the use of known interval pulses. No test data are presently available.

Ultrasonic Devices

Two instruments which might be considered to be fully electronic, developed for measuring pulse velocities through concrete, are known to exist. They were apparently developed

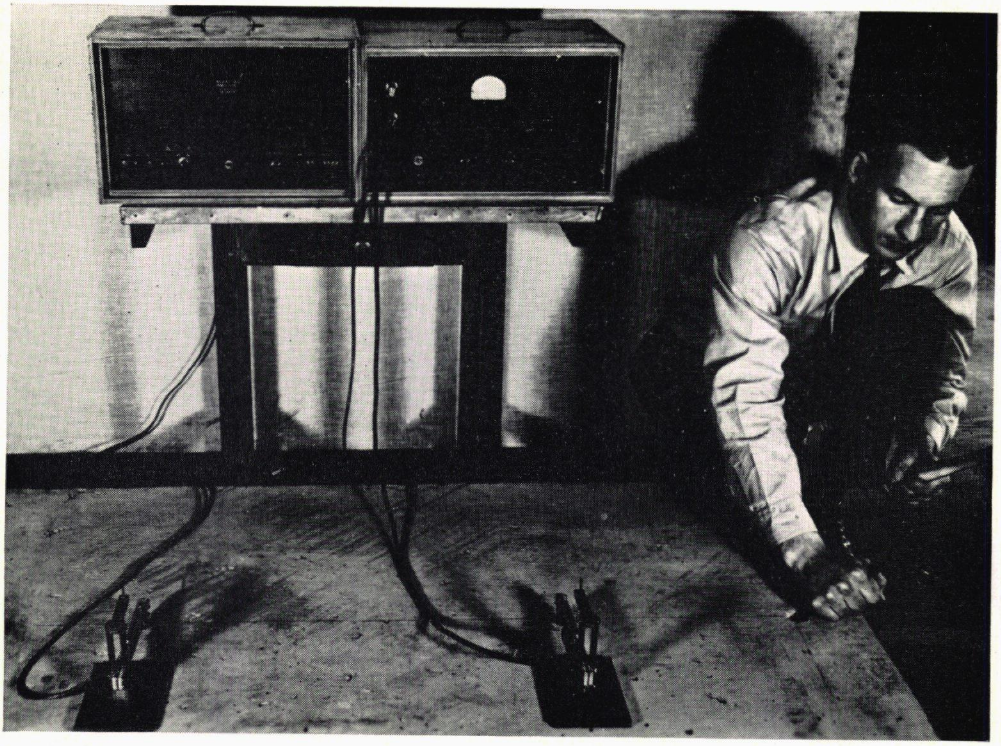

Figure 3. Microtimer in operation (Bureau of Reclamation).

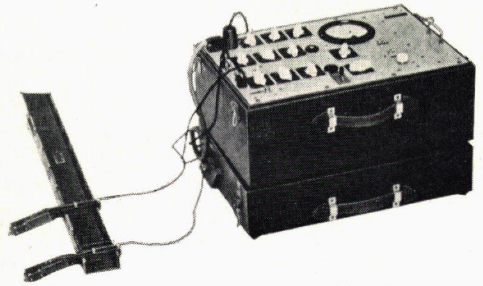

Figure 4. Condenser chronograph (M. P. Weibel).

independently and during approximately the same period. Although they differ in appearance, in minor details and, particularly, in the usage to which they have been put, they appear to be fundamentally quite similar.

The first is a device developed by the Ontario Hydro-Electric Power Commission, Toronto, in investigations starting in late 1945. The instrument, known as a "soniscope," was originally developed as a crack-detecting device for use on monolithic structures. It has, however, proved quite satisfactory for general use in determining the dynamic properties of concrete in place. The original development of the soniscope has been reported by Leslie and Cheesman (*17*), and its subsequent use in Canada by Leslie (*18*), Cheesman (*4*), and Parker (*26*). Its use since 1947 in the United States has been reported by Whitehurst (*30, 31, 32, 33*), Meyer (*22*), and Batchelder and Lewis (*3*).

The original soniscopes were bulky devices, consisting of three major units connected by a number of short cables and having a total weight in the order of 200 lb. More-recent models, however, consist of only one unit, approximately 14 inches wide, 18 inches high and 22 inches deep, and weighing about 60 lb. Two small transducers, each of which may be held in one hand, are also required. A recent model is shown in Figure 5.

A much-simplified block diagram of the soniscope is shown in Figure 6. A multivibrator provides synchronization for the remainder of the circuits. Its free-running frequency is approximately 100 cycles per second, and it is held constant by a small control signal from the crystal calibration oscillator. The cathode-ray oscilloscope employed in this unit is a Cossar double-beam tube, operating on the split-beam principle and requiring only one sweep circuit. A number of sweep speeds are available to facilitate accurate time measurement over paths of widely varying length. A strobe generator and precision delay provide

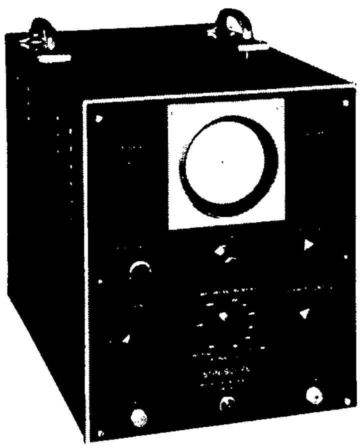

Figure 5. Soniscope (McPhar Engineering Company, Toronto).

a very sharp, accurate delay signal which is placed on one trace of the oscilloscope. The position of this strobe is controlled by a helipot calibrated in 1,000 units throughout its motion. The operation of the delay is essentially linear and will agree with the reading of the helipot dial within ± 1 percent throughout its range. The transmitter output is a gas-filled thyratron, type 3C45, operating with a plate voltage as high as 3,000. This may be reduced by an attenuator to provide a controlled output pulse. The pulse is carried by coaxial cable to a transmitting transducer consisting of a block of sixteen 1-by-$1\frac{1}{2}$-by-$\frac{1}{4}$-inch, 45-deg., X-cut, rochelle-salt crystals mounted in a cylindrical metal housing filled with castor oil. The end of the housing is closed by a rubber diaphragm, and sufficient oil is forced into the housing to distend this diaphragm beyond its retaining flange. The diaphragm is placed firmly in contact with the concrete to be tested, a thin film of oil being applied to the concrete. The electronic pulse striking the crystals causes them to oscillate for a few cycles at their resonant frequency. This oscillation is transferred, as mechanical energy, through the castor oil and the rubber diaphragm into the concrete. At some other location in the concrete, normally the far side of the specimen or member, the vibration is detected by a similar receiving transducer containing only

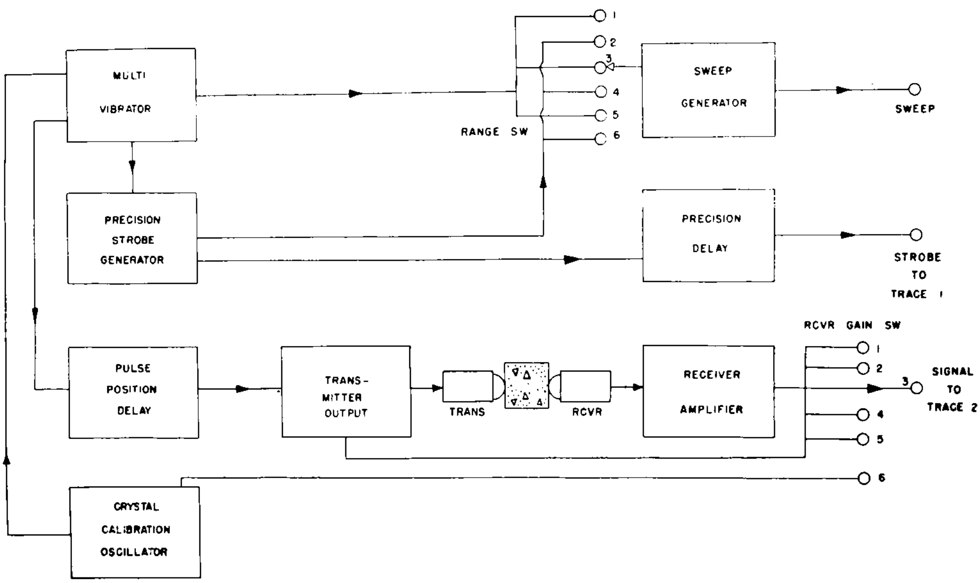

Figure 6. Block diagram of soniscope.

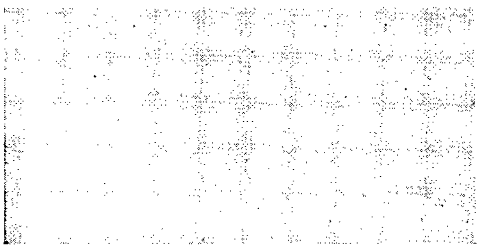

Figure 7. Appearances of traces of soniscope during testing (Waterways Experiment Station).

four rochelle-salt crystals. The received signal is returned to the soniscope by coaxial cable, where it is amplified and shown on one trace of the oscilloscope.

The appearance of the face of the oscilloscope during test is shown in Figure 7. In operation, the strobe control dial is moved to its zero position, at which time the strobe will appear near the left edge of its trace and should be in line with the transmitted signal. If it is not, a small pulse position delay may be employed to bring the transmitted signal and strobe into alignment. The helipot dial is then turned, moving the strobe toward the right until it coincides with the commencing edge of the received signal. The helipot dial will then indicate the time taken for the signal to pass from transmitter to receiver.

This measured time will also include a small time interval associated with the transducers and with the soniscope circuits. This calibration time, or zero correction, may be determined by placing the transmitting and receiving transducers in direct contact with each other and making a measurement like that described above. For various soniscopes and combinations of transducers, this delay may vary from only a few microseconds to as long as 40 microseconds. It will remain essentially constant, however, for any one instrument and one pair of transducers. This delay time must be subtracted from all measured times during testing. With the net test time determined, and the path length measured, the velocity of pulse propagation may be calculated directly.

It is, of course, essential that the calibration of the strobe delay be accurate and that it not change with time. Provision is made, therefore, through the use of a 100-kilocycle crystal-calibration oscillator for periodic checking and, if necessary, adjustment of this precision delay. When calibration is desired, the calibration signal, in the form of a sine wave or a modification thereof, may be shown directly on one trace of the oscilloscope and the timing strobe on the other. The strobe may then be moved past the timing wave, the cycles of the timing wave counted, and the actual time measured compared with the helipot dial reading. This system of time measurement has been found superior to that originally used in the soniscope, where the timing wave itself was shown on the upper trace and the number of cycles of this wave appearing between transmitted and received signals were counted to determine the transit time.

This instrument and several others built from similar plans, but varying in minor details, has been used extensively in Canada and the United States since about 1947. It has been used to test dams, navigation locks, highways, bridges and buildings, as well as laboratory specimens. It has also been used on materials other than concrete, including wood poles and stabilized soil mixtures. With respect to concrete, it has been used over path lengths as short as 2 inches and greater than 50 feet. It should be observed that the accuracy of time measurements is dependent upon the rapidity of rise of the received signal, which controls the accuracy with which the operator may detect the beginning edge of the received disturbance. Thus, the probable error is more or less constant with respect to time, that is, ±½ to 1 microsecond. Under these conditions the accuracy of a velocity measured through a very short path of concrete is much less than that measured through a longer path, since the probable error in measured time represents a much larger proportion of the total transit time involved.

The rise time of the received signal is, among other things, a function of the oscillation frequency of the transmitted signal. It is evident, therefore, that by increasing the resonant frequency of the transmitting transducer, a steeper rise time might be obtained. It has been found, however, that concrete tends to act as a high-frequency attenuator, i.e., low frequencies may be transmitted further at a given power level through concrete that can high frequencies. This is particularly true if the concrete has undergone

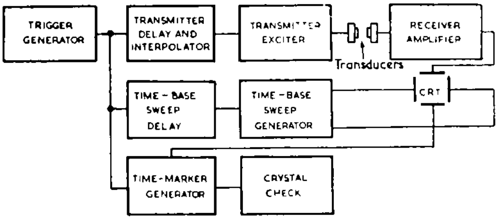

Figure 8. Block diagram of ultrasonic concrete tester (*Electronic Engineering*).

deterioration. The resonant frequency of the transducers originally developed and normally used with the soniscope is approximately 20 kilocycles. Recently, however, quartz-crystal transducers have been built which have a much higher natural resonance, in the order of 200 kilocycles. The distance through which transmission from this transducer may be accomplished is quite limited, but the accuracy of time measurement for small specimens is somewhat improved. The instrument requires about 250 watts power supply at 115 volts, 60 cycles, and will operate satisfactorily from a small gasoline-engine generator.

The second instrument referred to as a fully electronic device for measuring pulse velocities through concrete was developed at the Road Research Laboratory, Harmondsworth, Middlesex, England. It is called an "ultrasonic concrete tester." The design of the apparatus has been fully reported by Gatfield (*9*) and its use in England described at length by Jones (*10, 11, 12, 13, 14, 15, 16*). The block diagram, Figure 8, shows that the operation of the device is in many respects similar to that of the soniscope. The repetition frequency of the device is about 50 pulses per second. In the original development, and for most testing to date, the transducers were made from quartz crystals resonating at 250 kilocycles per second. More recently, transducers resonating at about 60 kilocycles have been developed in an effort to lengthen the maximum range of the instrument. At present, that range is reported as 7 feet. The instrument is 27 by 33 by 13½ inches, and when mounted on the special trolley provided is 53 by 36½ by 26 inches. It requires 210 watts power supply at 200 to 250 volts A.C., 50 cycles. It is reported that time may be measured to an accuracy of ± 0.2 microseconds. The device is shown in Figure 9.

In operation the transmitted and received signals are shown on the face of a cathode-ray oscillograph. Superimposed on the same trace are sharp pulses appearing at 10-microsecond intervals. The accuracy of these timing pulses may be checked against a 100-kilocycle crystal-controlled oscillator. A zero determination must be made, as with the soniscope, by placing the transmitting and receiving transducers in direct contact with each other. The time of transmission is determined by counting the number of calibration markers occurring between the two signals. An interpolating control is available, operating a small delay circuit, which facilitates accurate interpolation of the last time period when the received signal does not occur exactly at a calibration mark (which is normally the case). Provision is made for the use of an expanded and delayed sweep circuit to facilitate the counting of the timing marks. In this way the marks can be spread well apart and then caused to move across the face of the tube at any desired rate, permitting the operator to make a careful count.

Published reports indicate that this equipment has been used primarily in the labora-

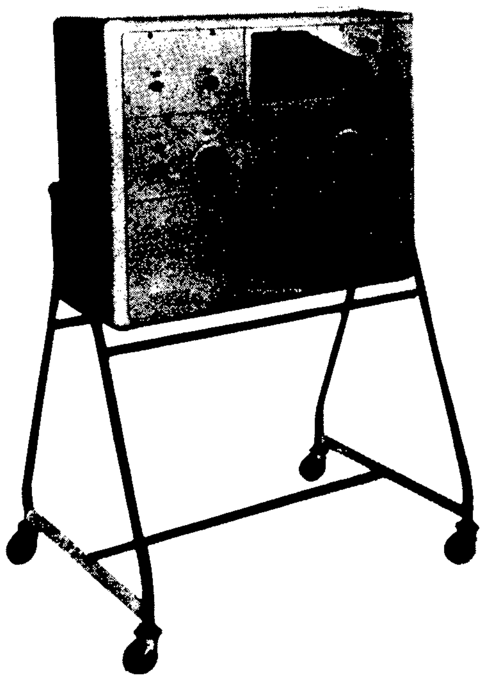

Figure 9. Ultrasonic concrete tester (Mullard Overseas, Ltd.)

tory for precise studies of the variation in quality of concrete specimens. It has, however, been used in the field on walls and other structures to determine the uniformity of quality of the structural members. It has also been used in the laboratory to study the formation of cracks in a specimen as it undergoes tension or compression testing.

The soniscope is now commercially available through the McPhar Engineering Company of Canada, Ltd., in Toronto. The ultrasonic concrete tester appears to be available through Mullard, Ltd., Century House, Shaftesbury Avenue, London.

Various other instruments have been built in this country for performing this function by electronic means. Most of these, to the author's knowledge, have been based upon the design of the soniscope, and several have been built directly from plans thereof. One instrument which appears to fall into this category is known as a "stimascope" and was used by the Sandia Corporation at their Sandia Laboratory. The primary difference between it and late model soniscopes appears to be that a single-trace tube rather than a double-trace one was employed and time was measured by the position of a blanking pulse on the tube trace rather than by the position of a vertical strobe. The device is not commercially available. It is probable that other similar instruments have been built by interested organizations for their own use.

Several inquiries have been received concerning the possibility of adapting various commercially available oscilloscopes for use in measuring pulse velocities through concrete. Insofar as is known, no such adaptation has yet been attempted. There are, however, several commercial instruments available which would appear to be suitable for such

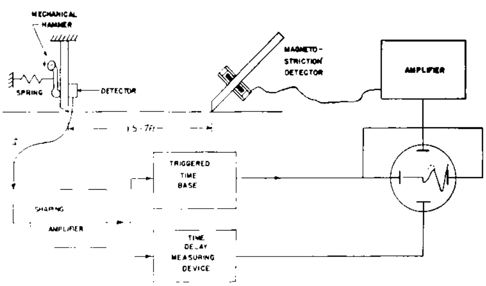

Figure 10. Block diagram of a repetitive-blow device (after Chefdeville and Dawance).

use. One of these, for instance, is the DuMont Type 256D Cathode-Ray Oscillograph. This instrument has sweep speeds varying from 4,500 to 4 microseconds, which would be suitable for concrete testing. It has internal timing circuits which appear to be capable of measuring time intervals to an accuracy of 1 microsecond or better. It also provides a trigger pulse, either positive or negative, of 100 volts amplitude. A video amplifier is available. It seems likely that all that would be required to convert this instrument into a device similar to the soniscope would be two suitable transducers and a small unit containing a high-voltage power supply and a thyratron capable of energizing the transmitting transducer. The thyratron would, itself, be fired by the trigger pulse from the oscilloscope. Perhaps some additional amplification of the received signal might also be required.

Repetitive-Blow Devices

Instruments in this category combine the cathode-ray oscilloscope presentation of the soniscope and similar devices with the physical-blow techniques of the electronic interval timer and similar devices. One such instrument has been developed in the Laboratories du Batiment et des Travaux Publics, in Paris, by Chefdeville and Dawance (*6*). The transmitter is a small hammer held by a spring and released at the rate of five times per second by a motor-driven cam. The force of the blow, thus, is constant. The receiver is of the magnetostrictive type, a nickel rod biased by a magnet. Sensitivity is reported to be good and impulse response excellent.

As shown in Figure 10, the hammer does not strike the concrete directly but, rather, an anvil which is in contact with the concrete. A dectector on the anvil generates a signal which causes the trace of the oscilloscope to commence its sweep before the impulse reaches the concrete. Apparently, it is common to make a small hole in the concrete into which the anvil is inserted. The time-measuring system is quite similar to that used in the late models of the soniscope. Rotation of a dial causes a step, rather than a strobe, to move along the trace. When the step has reached the initial point of the received signal the reading of the dial indicates the elapsed time between signals.

The range of this device is given as 1½ to

7 feet. A later publication indicates that two hammers are now available, one having a repetition rate of four blows per second and a range of 5 meters, and the other a rate of one blow per second and a range up to 20 or 30 meters. From the figure shown in the description of this testing technique, it is believed that the instrument is used primarily along surfaces rather than through masses.

It should be noted here that these investigators have also developed an instrument for laboratory use which appears to be quite similar to the soniscope and the ultrasonic concrete tester. It consists of two quartz transducers, one of which is triggered by a 1,000-volt pulse of 10 microseconds duration at a rate of 160 pulses per second. The second acts as a receiver. The transmitted and received signals are shown on the trace of a cathode ray oscilloscope along with a timing wave having a period of 5 microseconds. The number of cycles of this wave appearing between transmitted and received signals may be counted as a measure of the transit time involved. The maximum range of the instrument is reported to be about 2 feet, doubtless due to the high resonant frequency of the transducer crystals. The frequency standard which generates the timing wave is reported to be "not too stable." For this reason, the apparatus cannot be used in conjunction with a gasoline-engine generator and has not been employed in field testing.

Finally, this organization has experimented with a device, intended for use over extreme ranges, in which an explosive force initiates the energy front. No results of these experiments have been reported.

The development of another similar repetitive blow device has recently been reported by Minnick and Meyers (*23*). This instrument, referred to only as "pulse-velocity equipment," appears to be similar to that discussed above. The hammer blow is applied at the rate of three times per second. The anvil is a 1-foot steel rod. The pickup is believed to be a phonograph crystal, but this has not been substantiated. The time-measuring unit is in the form of a calibrated delay. The device consists of two relatively small units, shown in Figure 11, which may be operated from 100 to 130 volts, 60 cycle A.C., or from a conventional 6-volt, lead-acid storage battery. A 120 ampere-hour battery provides 4 hours of

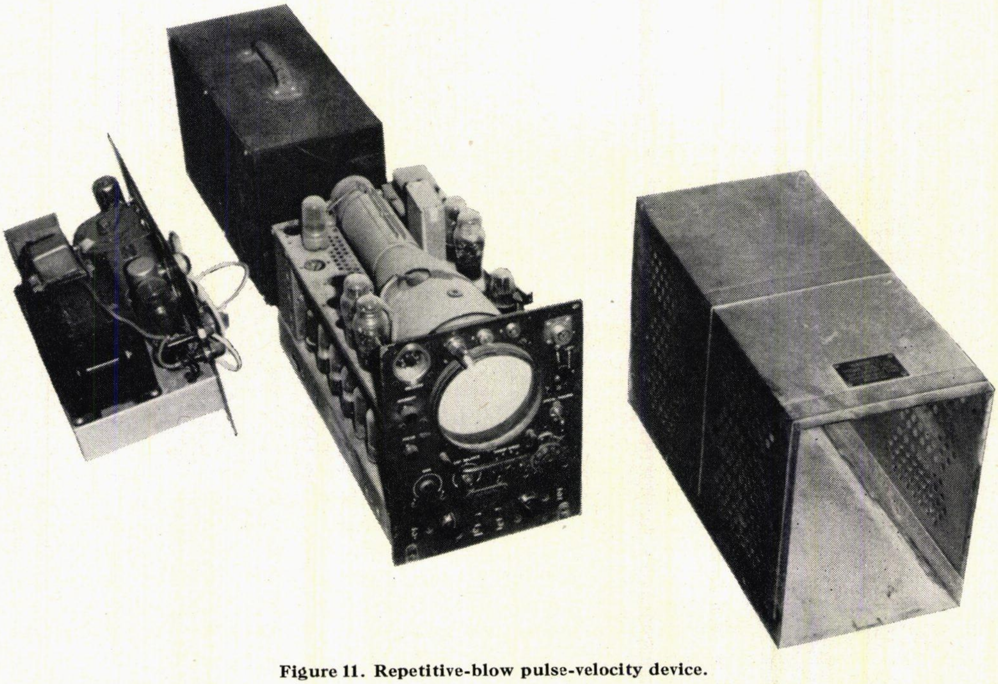

Figure 11. Repetitive-blow pulse-velocity device.

continuous service from a full charge. Minnick reports, in correspondence with the author, that this device has been used only in a limited degree on concrete specimens in the laboratory. It was built for, and has been used primarily in connection with, field testing of stabilized soils. From the available description, however, it would appear that it is as well adapted to the testing of concrete as are other similar devices.

The instrument reported by Chefdeville and Dawance may be available through a Belgian laboratory, the address of which is not known. The instrument of Minnick and Meyers is not presently available on a commercial basis.

It seems almost certain that other devices have been developed for making pulse-velocity measurements on concrete in other countries. Reports have reached the author of such work in Germany, Italy, Sweden, and possibly Spain. At the present time, however, no definite information is available concerning either the instruments or the work accomplished. In view of the surprising grouping into three categories of the numerous instruments described above, it might be suspected that these others would be quite similar to some of those previously mentioned.

COMPARISON OF RESULTS OF THE VARIOUS INSTRUMENTS

Having examined the several devices developed for the purpose of measuring pulse velocities through concrete, a direct comparison of these devices as they perform in testing would be of value. Unfortunately, such comparisons are not widely available and it is not likely that they soon will be. Information is available, however, on two comparisons which may be of interest.

The first of these is a comparison of results obtained on the same concrete when tested with several instruments of the same type operated by a number of different operators. The instrument involved was the soniscope. The results were recently reported by Mather (*21*). In this study three different soniscopes, all built by different agencies and operated by as many as five different operators, were used in making measurements on concrete, both in the field and in the laboratory. From these tests, it was concluded that the reproducibility of results obtained through uncracked concrete, using various operators and soniscopes, was within 2 percent for massive structures and, with care, might be kept within 1 percent. Wider variation is to be expected for path lengths in the order of a foot or less. In the case of cracked concrete, however, widely variable results were obtained with different soniscopes, the variation being as high as 20 percent. Such variations had been found in the past by others. It is possible that the very fact that these variations occur may be an important indication of the quality of the concrete. It was also concluded from these results that, in cases where the same concrete was tested over a period of time, consecutive velocity variations of less than 2 percent are probably not significant, while such variations greater than 5 percent are probably significant.

The other available comparison involved two different instruments, the soniscope and the Bureau of Reclamation's microtimer. These tests were made by West and the author in 1949 and reported by West (*29*). They recovered a period of approximately 6 weeks and included only field testing of concrete in or associated with dams. In those cases where it was possible to make a direct comparison between the two instruments, the test results agreed within 5 percent. Greater deviations occurred where the concrete had suffered serious disintegration and cracking and in locations where the microtimer was used to measure through the mass of concrete rather than along the surface. In many of these cases, the velocity measured by the microtimer was considerably higher than that measured by the soniscope. It is believed that the greater amplitude of the pulse used with the microtimer and the much-lower modulation frequency of this pulse permitted it to span some of the smaller cracks, while the signal from the soniscope was required to pass around such cracks.

It should be observed that both types of equipment, those involving a hammer blow and those of a more-complex electronic nature, have certain advantages and disadvantages. Several of the hammer blow devices may be operated from a battery power supply, making the availability of power in the field a noncritical item. The impact generated by even a light hammer blow is many times greater than that generated by a crystal transducer. The hammer-blow devices are generally smaller and lighter than the electronic devices and may be handled with greater ease in the field. They may also require less extensive maintenance, although in the past this has not been a serious problem with the other type of instrument. The hammer-blow device is ideally suited to measurements along concrete surfaces and may, with some difficulty, be modified for use through mass concrete.

The electronic devices have the advantage over the single-hammer-blow instruments of visual presentation of the test signals. In this way, the operator may be quite certain when the received signal is adequate to justify measurement and when it is not. It is believed that this is one of the great disadvantages of the single-blow technique, in that the deterioration of the wave front in passing through the concrete may not be observed and may result in the measurement of an abnormally long transit time. It has been observed by several investigators that the measured time, using a hammer-blow technique, is to some degree a function of the force with which the blow is applied. This is a liability unless the force of this blow can be calibrated in some way. With the electronic devices, it is only necessary that the operator increase the power of the exciting voltage to his transmitter until a received signal of identifiable size is observed. No case has been observed, to the author's knowledge, in which the magnitude of the crystal-transmitter output influenced the measured transit time. It is believed that the accuracy of time measurement of the electronic devices is somewhat greater than that of the single-blow devices, because of the more-elaborate time-measuring circuits involved. The electronic devices are ideally suitable for measurement through masses of concrete and, as has been indicated, a range of 50 feet may be reached and sometimes exceeded.

Because of the low directivity of the output, particularly at the frequencies used in the transducers associated with the soniscope, the two transducers need not be on opposite sides of the member, but may be at 90 deg. to each other, or even parallel to each other, as when both are placed on the surface of a pavement slab. The range through which a vibration may be sent under this latter condition is quite limited, varying from possibly 3 to 6 feet. It has also been claimed that the electronic devices, because of the high repetition rate with which the signal is transmitted through the concrete, give a result which is actually the average of many readings, and therefore, should be more accurate than tests depending upon a single or a few hammer blows. Although these devices do require a source of alternating current, the power requirements are small and the stability of the units is such that they may be served adequately by a small gasoline-engine-driven generator.

Both types of equipment are severely affected by extraneous vibrations in the concrete under test. This is particularly notable in such structures as power houses when tests are conducted in proximity to the draft tubes. The author has observed upon occasion, however, that successful tests could be made with the electronic device when they could not be made with the hammer device. In these cases, the vibration within the structure was such that the triggering circuits of the hammer device could not be made to remain stable. The structural vibration was also picked up by the receiver of the electronic device, and appeared as a noise signal on the face of the oscilloscope. The operator, however, by careful interpretation, was sometimes able to separate the stationary received signal from the moving noise signal.

INTERPRETATIONS OF TEST RESULTS

In view of the fact that during a reasonably few years the numerous devices and techniques described above have been developed and used on a wide range of field and laboratory testing programs, it is not surprising that there are some wide differences of opinion concerning interpretation of velocity test results. Some of these differences, as well as areas in which general agreement exists, will be mentioned below.

Velocity as a Measure of Strength

After their early investigations, Long, et al., (*20*) stated that they found good agreement between dynamic modulus computed from pulse velocities through pavements and such modulus computed from the flexural resonant frequency of beams cut from the pavements. They also stated that a good relation existed between the modulus computed from resonance and the flexural strength of the concrete, and presented an equation and a curve from which they suggest flexural strength may be calculated or taken when the dynamic modulus has been calculated. Their tabulated data, however, indicate that the use of this equation, or curve, could lead to a serious error in the prediction of flexural strength, as was pointed out by Dodge (*7*) in his discussion of their paper.

Jones has reported (*11*, *12*) that he found a good correlation between pulse velocity and compressive strength provided the aggregate-cement ratio of the concrete remained constant. As a result, he has reported a series of tests (*14*) in which the velocity-strength relationship established for a number of test cubes was used to predict the compressive strength of a wall constructed from the same concrete mix from velocities measured directly through the wall.

Tests of the Ontario Hydro-Electric Power Commission reported by Cheesman (*5*) show a reasonably good relationship between compressive strength and pulse velocity in the low strength ranges, indicating that such velocity tests might be useful in evaluating the safety of removal of forms. Later tests over a wide range of mixes in connection with a large construction project were reported by Parker (*26*). These indicate linear relationship between the pulse velocity and the logarithm of compressive strength, but show that as the compressive strength increases, the lower 95-percent confidence limit becomes large indeed, until at an estimated strength of approximately 4,000 lb. this lower confidence limit is in the neighborhood of 2,000 lb. These tests indicate that, in the usual range of working strengths, possible errors in prediction of 1,000 to 2,000 psi. might result.

On all occasions where the author has had opportunity to investigate the relationship between pulse velocity and either the compressive or flexural strength of concrete, he has found a general relationship to exist but has found the variation of individual test points from this relationship to be great indeed. It is believed that the pulse velocity through concrete is probably as good a criterion of strength as are any of the other dynamic tests normally employed in the laboratory, but it is questioned whether a close relationship between strength and any dynamic test has yet been shown to exist.

Velocity as a Measure of Uniformity

Several investigators have indicated that one of the major uses of pulse-velocity techniques may lie in evaluating the uniformity of concrete in structures. Jones (*12*) has shown variations in uniformity between the bottom and top of a 4-inch cube. Most devices developed for field testing are not capable of measurements of this accuracy. In his tests of the concrete wall, however, Jones was able to differentiate between areas of "good" and "poor" concrete.

Whitehurst (*3*) has reported the location of areas, in otherwise sound structures, which appear to be of low quality, as indicated by notably low velocities, and of areas indicated to be sound in obviously very poor structures. Such variations were found in bridges and in navigation-lock structures in the United States. Parker (*26*) has reported extensive tests, involving nearly 50,000 readings, taken on a slab-and-buttress dam in which velocities were found to range from below 5,000 to over 17,000 ft. per sec. The velocities were plotted as contours on a plan of the dam and used as evidence of areas requiring major repair.

Velocity as a Measure of Setting Characteristics

Several investigators have considered the desirability of using pulse velocities as a criterion of setting time of concrete. Such investigations have met with varying success. Velocity measurements through cement paste reported by Chefdeville and Dawance (*6*) showed that velocities increased slowly from the time of mixing until initial set occurred, then rapidly through the setting period. The rate diminished as setting progressed. Tests by Whitehurst (*32*) showed similar results for concretes of very stiff consistency, having practically no slump. Jones (*11*) has reported similar results, although his tests appear to have been started after the setting process was well under way. Andersen and Nerenst (*2*) have considered the variations in pulse velocity during setting, although they experienced considerable difficulty in measuring such velocities, and have formed an hypothesis and an equation for predicting velocities at early ages.

All investigators have experienced great difficulty in successfully measuring velocities while the concrete is still in a plastic state. Some difficulty is encountered in impressing the impulse upon the concrete and the attenuation of fresh concrete is high indeed. Such devices as rubber windows in the sides of specimen forms and transducers imbedded in the fresh concrete have been tried with some success.

Cheesman (*5*) has given one interesting example of velocity tests on concrete in place in a dam at early ages. These tests were made over a 14-foot path with access to the concrete provided by windows cut from the forms. No tests were successful until the concrete was one day old. The steep rise in velocity reported by other investigators, from laboratory tests, was observed to occur between the ages of 1 and 2½ days. These tests were made on two similar sections of a gravity dam, one made of plain concrete and the other containing an admixture. Cheesman was able to observe a distinct difference in the characteristics of the two sections.

Velocity as a Measure of Dynamic Modulus

From the very beginning of this type of testing, there has been considerable discussion among investigators as to the desirability or propriety of calculating the dynamic modulus of elasticity from measured pulse velocities. Cheesman (*4*) has shown a good correlation between modulus computed from pulse velocity and that computed from flexural resonant frequency for 300 laboratory beams. His relationship, however, when plotted on rectangular coördinates, gives a straight line having a slope slightly greater than one. If the theoretical relationships upon which equations for determining modulus are based were perfectly true for concrete, the slope of the correlating line should, of course, be 1. Cheesman has also shown that the modulus computed from pulse velocity and from resonant frequency for specimens which have undergone deterioration from freezing and thawing agree closely.

Batchelder and Lewis (*3*), however, have recently reported a series of tests in which they found the changes in dynamic modulus computed from flexural resonant frequency for specimens undergoing freezing and thawing to be much greater than the changes in modulus of elasticity computed from pulse velocities through the same specimens. The difference was sometimes as great as two to one.

Most investigators who have studied this problem in Canada and the United States are in agreement that little is to be gained from computing dynamic modulus from pulse velocities. Such computation was desirable with resonant-frequency techniques in the laboratory in order that results of tests on specimens of different sizes and shapes might be compared. Since the pulse velocity is independent of size and shape of the member tested, it would appear that the pulse velocity itself is as good a criterion for comparison as any other value which might be calculated therefrom. The pulse velocity may be measured rather accurately, while the conversion of this quantity to dynamic modulus requires the use of an equation which may not be perfectly applicable, some knowledge or determination of the unit weight of the concrete, and some knowledge or determination of Poisson's ratio. Most investigators also agree that, if the dynamic modulus is to be computed, the equation relating velocity to dynamic modulus for mass concrete should be used, regardless of the size of the concrete member tested.

Velocity as a Measure of Cracking

As previously indicated, the soniscope was originally developed and was, indeed, for a short period known as a "crack detector." Leslie and Cheesman (*17*) have shown how the instrument may be used to determine the presence or absence of cracks in the interior of monolithic concrete and, in some cases, to evaluate the location and extent of such cracks. They have also shown how the depth of surface cracks may be evaluated. The Ontario Hydro-Electric Power Commission has used the soniscope extensively for this purpose in the past few years. Insofar as is known, no other organization has made extensive studies of this nature. Mitchell (*24*), however, has recently reported interesting data concerning the effect of modulation frequency on the ability to detect both air-filled and water-filled cracks.

Jones (*15*) has reported an interesting series of experiments in which the formation of cracks in concrete specimens undergoing compressive or tensile testing was studied. He observed sharp reductions in velocity which indicated that specimens tested in compression cracked internally at loads as small as a third of the ultimate. For specimens tested in tension, however, little cracking of this nature was indicated.

SUMMARY

An effort has been made to describe the several devices which have been developed for measuring pulse velocities through concrete. It has been interesting to find that of the numerous devices known, most fall into two distinct categories and the remainder into a category embracing some of the details of each of the other two. It is hoped that the formation presented concerning instrumentation and techniques will be valuable to others who are interested in entering this field of pulse velocity testing of concrete.

A brief résumé has also been offered of the interpretations which various investigators have made of pulse velocity test results. This may be most noteworthy for the wide divergence of opinion which exists in a number of cases.

These differences notwithstanding, all investigators who have stated an opinion agree that the development of these techniques has presented the student of concrete behavior with a welcome and important tool for evaluating concrete quality and performance. It is to be hoped that continuous investigation in this field will result in the resolution of many of the questions raised and will make these techniques of even greater use.

ACKNOWLEDGMENTS

The author wishes to acknowledge with appreciation the assistance of R. C. Valore, Jr., chairman of Highway Research Board Committee B-3, for his assistance in making available certain material from the library of the Bureau of Standards; the Portland Cement Association for assistance with the references; a number of the writers referred to for making available information concerning their work; and the manufacturers of several of the devices described for furnishing and permitting publication of details concerning the operation of their equipment.

REFERENCES

1. Andersen, J., Nerenst, P., and Plum, N. M., "The Non-destructive Testing of Concrete with Special Reference to the Wave Velocity Method," *Building Research Report No. 3*, The Danish National Institute of Building Research, 1950.
2. Andersen, J. and Nerenst, P., "Wave Velocity in Concrete," *Proceedings*, ACI, Vol. 48 (1952).
3. Batchelder, G. M., and Lewis, D. W., "Comparison of Dynamic Methods of Testing Concretes Subjected to Freezing and Thawing," Presented at ASTM Annual Meeting, July, 1953.
4. Cheesman, W. J., "Dynamic Testing of Concrete with the Soniscope Apparatus," *Proceedings*, HRB, Vol. 29 (1949).
5. Cheesman, W. J., "Discussion of 'Use of the Soniscope for Measuring Setting Time of Concrete'," *Proceedings*, ASTM, Vol. 51 (1951).
6. Chefdeville, J. and Dawance, G., "L'Auscultation Dynamique du Beton (Dynamic Sounding of Concrete)," Annales de L'Institut Technique du Batiment et des Travaux Publics, No. 140, July–August, 1950.
7. Dodge, A., "Discussion of 'An Instrument and a Technique for Field Determination of the Modulus of Elasticity of Concrete (Pavements)'," *Proceedings*, ACI, Vol. 41 (1945).
8. Filter, J. H. J., "Microsecond Timer Checks Concrete Beams," *Electronics*, Vol. 26, No. 10, Oct., 1953, pg. 152.
9. Gatfield, E. N., "An Apparatus for Determining the Velocity of an Ultrasonic Pulse in Engineering Materials," *Electronic Engineering*, 1952, Vol. 24, pg. 390–395.
10. Jones, R., "The Dynamic Testing of Concrete by a Supersonic Method," *Proceedings*, Third Congress of the International Association for Bridge and Structural Engineering, Liege, 13–18 September, 1948, Section II.
11. Jones, R., "A Non-destructive Method of Testing Concrete During Hardening," *Concrete and Constructional Engineering*, April, 1949.
12. Jones, R., "The Non-destructive Testing of Concrete," *Magazine of Concrete Research*, No. 2, June, 1949.
13. Jones, R., "Elasticity and Rupture of Concrete and Stone at Constant Rates of Loading," *Nature*, Vol. 165, January, 1950.
14. Jones, R., "Testing the Quality of Concrete in a Thick Wall," *Concrete and*

Constructional Engineering, November, 1950.

15. JONES, R., "A Method of Studying the Formation of Cracks in a Material Subjected to Stress," *British Journal of Applied Physics*, Vol. 3, July, 1952.
16. JONES, R., "The Testing of Concrete by an Ultrasonic Pulse Technique," *Proceedings*, HRB, Vol. 32, (1952).
17. LESLIE, J. R., AND CHEESMAN, W. J., "An Ultrasonic Method of Studying Deterioration and Cracking in Concrete Structures," *Proceedings*, ACI, Vol. 46 (1949).
18. LESLIE, J. R., "The Application of Pulse Techniques to Dynamic Testing," *Proceedings*, ASTM, Vol. 50 (1950).
19. 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).
20. LONG, B. G., KURTZ, H. J., AND SANDENAW, T. A., "An Instrument and a Technique for Field Determination of the Modulus of Elasticity of Concrete (Pavements)," *Proceedings*, ACI, Vol. 41 (1945).
21. MATHER, B., "Comparative Tests of Soniscopes for Ultrasonic Testing of Concrete," *Proceedings*, HRB, Vol. 33, (1954).
22. MEYER, R. C., "Dynamic Testing of Concrete Pavements with the Soniscope," *Proceedings*, HRB, Vol. 31 (1952).
23. MINNICK, L. JOHN, AND MEYERS, W. F., "Properties of Lime-Flyash-Soil Compositions Employed in Road Construction," *Bulletin 69*, HRB, 1953.
24. MITCHELL, L. J., "Some Experiences in Dynamic Testing of Materials," *Proceedings*, HRB, Vol. 33, (1954).
25. MORTON, P. L., "Discussion of 'An Instrument and a Technique for Field Determination of the Modolus of Elasticity of Concrete (Pavements)'," *Proceedings*, ACI, Vol. 41 (1945).
26. PARKER, W. E., "Pulse Velocity Testing of Concrete," Presented at ASTM Annual Meeting, July, 1953.
27. POWERS, T. C., "Measuring Young's Modulus of Elasticity by Means of Sonic Vibrations," *Proceedings*, ASTM, Vol. 38, Part II (1938).
28. WEST, H. H., "Determination of Young's Modulus of Elasticity for Concrete by a Velocity Method," USBR, *Materials Laboratories Report No. C-322*, September 19, 1946.
29. WEST, H. H., "Measurements of Vibration Wave Velocities through Concrete Structures," USBR, *Materials Laboratories Report No. C-468*, Nov. 10, 1949.
30. WHITEHURST, E. A., "Soniscope Tests Concrete Structures," *Proceedings*, ACI, Vol. 47 (1951).
31. WHITEHURST, E. A., "The Soniscope—A Device for Field Testing of Concrete," *Proceedings*, 37th Annual Road School, Purdue University, Engineering Reprint (JHRP) No. 71, (1951).
32. WHITEHURST, E. A., "Use of the Soniscope for Measuring Setting Time of Concrete," *Proceedings*, ASTM, Vol. 51 (1951).
33. WHITEHURST, E. A., AND YODER, E. J., "Durability Tests on Lime-Stabilized Soils," *Proceedings*, HRB, Vol. 31 (1952).
34. EISENMANN, "Untersuchung der Rissebildung des Betons Ultraschall," (Investigation of the Formation of Cracks in Concrete by Means of Ultrasonics), *Beton-Und Stahlbetonbau*, Vol. 46, No. 1, January, 1951, pp 19–20.
35. FOSS BRINK, J. AND CHRISTENSEN-DAHLSGAARD, S., "En dynamisk methode til bestemmelse af lydhastighed i faste stoffer", (A Dynamic Method for Determination of Wave Velocity in Solids), *Ingenioeren* (Copenhagen) Vol. 59, No. 2, Jan. 14, 1950, pp. 50–54.
36. GIACOMINI, A., "Contribution to Ultrasonic Measuring Techniques", (In Italian) *Ricerca Sci*, Vol. 23, January, 1953, Abstract in Phys. Abs., Vol. 56, May, 1953.
37. GRAHAM, B. L., "Hydro's Ultrasonic Eye", *Hydro News*, Vol. 35, No. 6, June, 1948, pp 10–11.
38. HARVEY, H. A., "New Surface Applied Instrument Tests Condition and Quality of Concrete". *Roads and Engineering Construction*, Vol. 90, No. 5, May, 1952, pp 77–79.
39. JONES, R., "Non-destructive Testing of Concrete", *Reinforced Concrete Review*, Vol. 2, No. 5, Jan., 1951, pp 315–321.

40. KRAUTKRAMER, J., "Non-destructive Material Testing with Ultrasonic Impulses", (In German) *Werkstoffe Korr*, Vol. 3, April, Abstract in App. Mech. Rev., Vol. 5, August, 1952.
41. KREIJGER, P. C., "Acoustic Testing of Cement and Concrete", *Cement* (Amsterdam), Vol. 3, December, 1951.
42. LEWIS, D. W., "Field Determination of the Modulus of Elasticity of Concrete Pavements", C-36-37, Part E, Joint Highway Research Project, Purdue University, *Preliminary Report No. 1*.
43. MARGARIT, A., "New Method of Measuring the Modulus of Elasticity and the Possibility of Using It on Concrete", (In Spanish), *Rev. Ciemc. Apl.*, Vol. 4, July, 1950, Abstract in *Phys. Abs.*, Vol. 54, January, 1951.
44. WESCHE, K., "Concrete Testing by Means of Ultrasonics", (In German) *Beton-Und Stahlbetonbau*, Vol. 48, No. 5, May, 1953, pp. 116–119.
45. "Machine Developed to Test Mass Concrete in Place", *Engineering News-Record*, Vol. 131, No. 15, October 7, 1943, pp 537.
46. *Bulletin*, Union of Testing and Research Laboratories for Materials and Structures (R.I.L.E.M.), No. 15, August, 1953.

Dynamic Testing of Materials

L. J. MITCHELL, *U. S. Bureau of Reclamation*

THIS paper describes dynamic tests of both sonic velocity and resonant frequency types. Sonic velocity tests were made to evaluate the effect of both air-filled and water-filled cracks on transmittal of signals through concrete. Low-frequency signals, especially those groups caused by hammer blows, showed little effect from either narrow or water-filled cracks. As would be expected, any attenuation or delay was increased as the crack size increased. An increase in the frequencies composing the signal also increased the effect of both air- and water-filled cracks.

Another series of investigations consisted of sonic-velocity measurements on masses of sand, gravel, combinations of sand or gravel with water, and freshly mixed concrete. Decreasing particle size reduced the measured sonic velocities. The presence of water in the above mixtures increased the sonic velocity in all cases. Measured velocities in this series were much below velocity of sound in air and, when compared to data presented by other investigators, led to the conclusion that the apparent velocity through a loose mass is dependent upon the character and frequency of the signal. These results led to the investigation of various pickups and circuit components which demonstrated that ordinary equipment components always produced time delay factors in the measurement. Some of these variables are caused by surface conditions, power and type of the original signals and the mounting of pickup components.

Resonant-frequency dynamic tests were compared to sonic velocities. Flexural and torsional resonant frequency testing on rock cores revealed unusual reactions. Some indications of heterogeneity and loose structure were evident even in apparently sound specimens. Irrational values of Poisson's ratio, which were frequently indicated by these cores, are discussed.

● MANY investigators have been interested in dynamic, or non-destructive, testing of materials during the past several years. We are concerned with two general methods of test which have been developed, along with special equipment for each. The first method, testing by sonic vibration or resonant frequency, has been quite useful but is applicable