Evaluation of Pulse Velocity Tests Made with Portland Cement Association Soniscopes

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●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

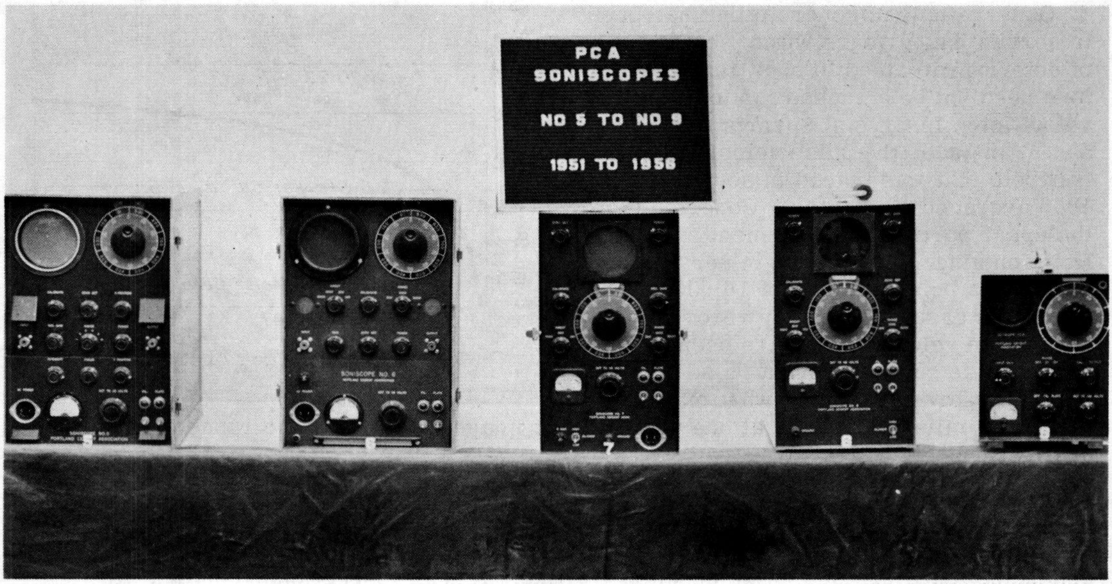

Figure 1. PCA soniscopes.

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.

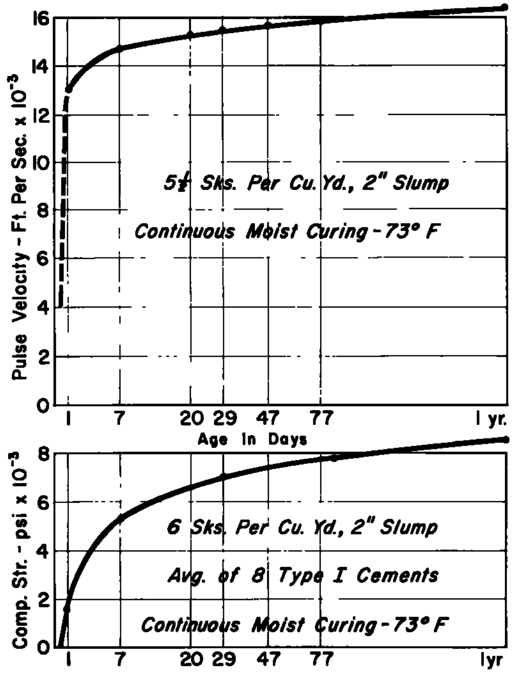

Figure 2. Effect of curing.

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-

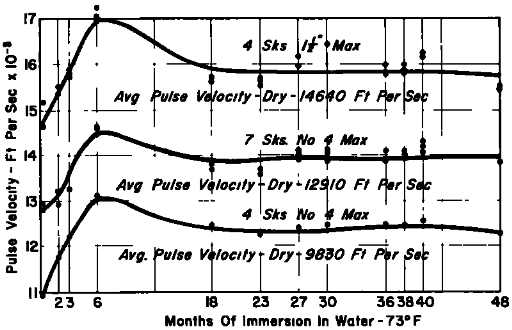

Figure 3. Effect of absorbed moisture.

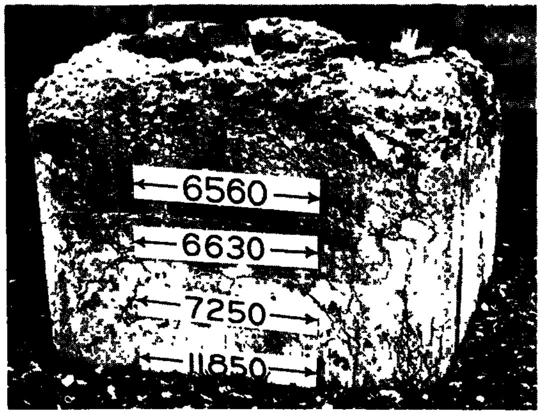

Figure 4. Pulse velocity in terms of deterioration.

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.

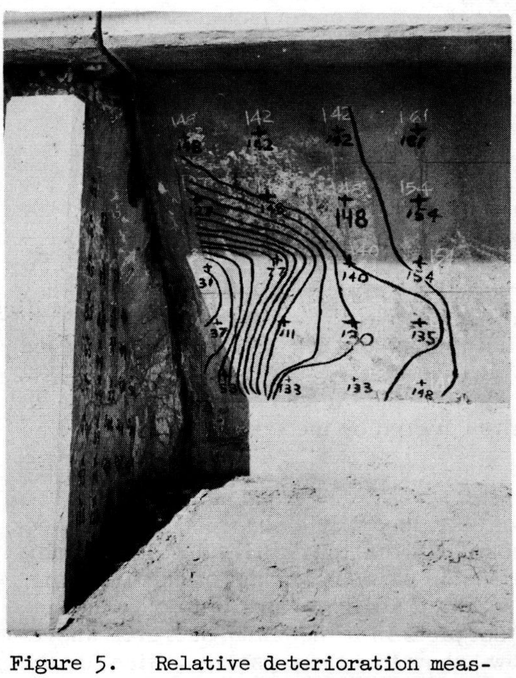

Figure 5. Relative deterioration measured by pulse velocity.

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.

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