NONDESTRUCTIVE TESTING OF CONCRETE BY WAVE VELOCITY METHODS: A LABORATORY AND FIELD STUDY

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An investigation was conducted to determine whether the compressive strength and modulus of elasticity of concrete could be determined from the velocity of an elastic compression wave traveling through it. The elastic wave velocities were usually determined by the seismic method. Two comparisons between seismic velocities and elastic wave velocities determined by the soniscope method are presented. A correlation between the seismic velocity and compressive strength of slabs and beams constructed of con-concrete containing San Gabriel drainage aggregate was developed. The rate of change of wave velocity to compressive strength was undesirably small. This correlation is not necessarily valid for concrete made with aggregate from other sources. It was also concluded that seismic velocities may be influenced by the presence of reinforcing steel. It was observed that changes in temperature in the 2- to 60-C range have negligible effect on the seismic velocity of concrete.

•IF THE velocity of an elastic compression wave traveling through concrete can be related to the compressive strength, modulus of elasticity, or other physical properties of the concrete, then the concrete can be tested nondestructively. Elastic wave velocity measurements can be performed more rapidly than conventional tests and, therefore, are more economical.

Jones (3), Whitehurst (6), and many other researchers have employed the soniscope method of measuring the wave velocity of concrete. Phelps and Cantor (4) employed the seismic method to measure elastic wave velocity and successfully predicted the deterioration of asphalt-overlaid concrete bridge decks.

Seismic velocity tests, similar in principle to those performed for geophysical purposes, were performed on concrete to determine the elastic wave velocities. The seismic velocity apparatus is shown in Figure 1. Travel times were measured in microseconds because the traverse lengths were shorter than 1 m and the seismic velocities are of the order of 3,000 m/sec. A DynaMetric microseismic timer, model 217, the only commercially available microseismic timer, was used throughout this investigation. A length of adhesive copper tape was attached to each test slab at the point of impact. Striking the tape with a pendulum hammer closed a circuit to start the timer and created an elastic wave that traveled through the concrete. A phonograph-needle transducer at the first station received the wave and stopped the timer. Several travel times were observed until a repeatable reading was obtained. The transducer was moved to each successive station and the process repeated. The procedure for testing rough-finished slabs in the field differed: The transducer remained at the initial station; the field impactor replaced the pendulum hammer as the impact source; the field impactor was moved to successive stations; and the repeatability criteria were relaxed. The pendulum hammer and transducer were mounted for tests on vertical surfaces. Cylinders and cores were tested in a holder that isolated them from external vibrations (1).

With the soniscope, a vibrating-sending transducer transmits elastic compression waves to the receiving transducer. The travel time is directly proportional to the phase shift of the wave between the 2 transducers. The distance between the transducers is divided by the travel time to give the wave velocity. It is preferable that a soniscope be simple to operate and have flexible diaphragm transducers to make positive contact with the concrete. A James V-Scope was used in this investigation (1, 2).

Deterioration studies were not included in this investigation because it was programmed for 1 year (July 1966 through June 1967) and because the compressive strength of concrete usually increases with age.

TEST PROGRAM

This investigation consisted of (a) a laboratory phase performed in Arcadia, California, to develop procedures and hypotheses, and (b) field investigations, performed near Happy Camp, California, to test these findings.

A group of test structures was constructed from 12 concrete mixes. It consisted of 12 slabs 1.2 by 1.8 m, 6 columns 0.6 by 0.6 by 2.4 m, 2 beams 0.4 by 0.5 by 2.1 m, 1 arch of the same dimensions as the beam with 0.2-m maximum rise, and 7 flexure beams 0.15 by 0.15 by 0.6 m. Ten of the concrete mixes contained river-run aggregate from the San Gabriel drainage. One mix contained aggregate from the Tujunga drainage. The nominal specific gravity of these aggregates was 2.65. Crestlite lightweight manufactured aggregate was used as the coarse aggregate in 1 mix. The slumps of these mixes ranged from 40 to 180 mm. The air content varied from 1.8 to 6.4 percent. Number 3 reinforcing bars were placed 50 mm beneath the surface of 2 slabs. A No. 8 reinforcing bar was partially embedded in the top of 1 flexure beam; a semicurcular section of the bar remained exposed. A No. 8 reinforcing bar was placed 50 mm below the top surface of another flexure beam.

Seismic velocity tests were performed on all the test structures except the flexure beams at 7, 28, and 133 days. The compressive strength of both cylinders cured adjacent to the slabs and 100-mm diameter cores from the test structures were determined at the same ages.

The adhesive copper tape could not be expected to adhere well to rough or dusting concrete that would probably be encountered in the field if the points of impact were not ground. This effect was determined by performing 10 seismic velocity tests on horizontal surfaces of the test structures. The points of impact were ground with a grinding bit to simulate field conditions. The seismic velocity tests were repeated by using the ground points of impact.

The possible effects of temperature on the seismic velocity of concrete was determined by testing 189-day old flexure beams first at 20 C. The beams were brought to temperature equilibrium at 60, 2, and -18 C and retested.

Seismic velocity tests were performed with the objective of locating reinforcing steel by detecting the characteristic seismic velocity of steel, approximately 5,100 m/sec. These tests were performed directly above the embedded reinforcing steel and on the exposed surface of the half-embedded No. 8 reinforcing bar.

Static modulus of elasticity tests were performed on nine 133-day old cylinders representing different batches of concrete. These tests were performed according to Texas Highway Department Method 421-A, modified by using a Testlab CE 2760 compressometer and by stopping the test at a smaller load to avoid damaging the compressometer.

The elastic wave velocity of 1 slab, 6 columns, and 9 pairs of companion cylinders was measured with the V-Scope. The concrete tested with the V-Scope ranged in age from 200 to 256 days. Both transducers were placed on the top surface of the slab. The columns and cylinders were tested by through transmission, with the transducers placed opposite each other.

Six existing bridges and 1 bridge under construction, the Indian Mill Bridge, were tested by seismic velocity and conventional methods. The seismic velocities of the deck and abutment of the Indian Mill Bridge were measured at 7 and 28 days. The compressive strength of cylinders and cores representing the structure were determined at the same time. The ages of the existing bridges ranged from 8 to 46 months. Two existing bridges were constructed of concrete containing nominally 2.65 specific gravity aggregate. The other bridges were constructed of concrete containing nominally 2.80 specific gravity aggregate.

Two pairs of comparison tests were performed on a smooth concrete curb to determine whether seismic velocity tests performed with the field impactor are more accurate than seismic velocity tests in which the point of impact had been ground. The pendulum hammer was used as the impact source for 1 test of each pair, and the field impactor was used for the other.

Figure 1. Seismic velocity apparatus.

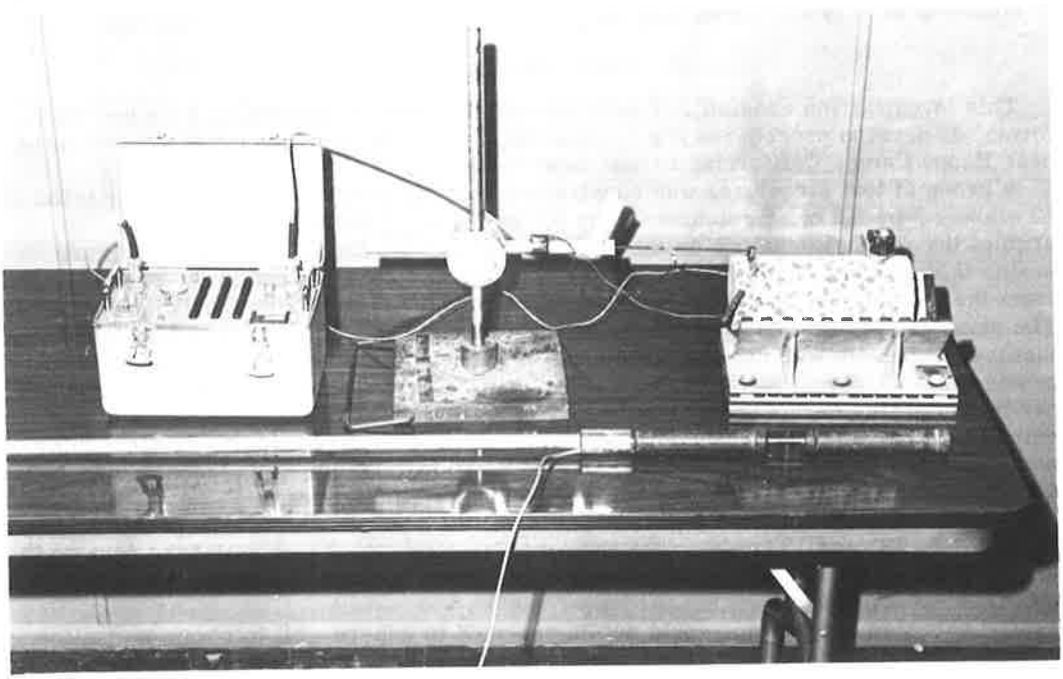
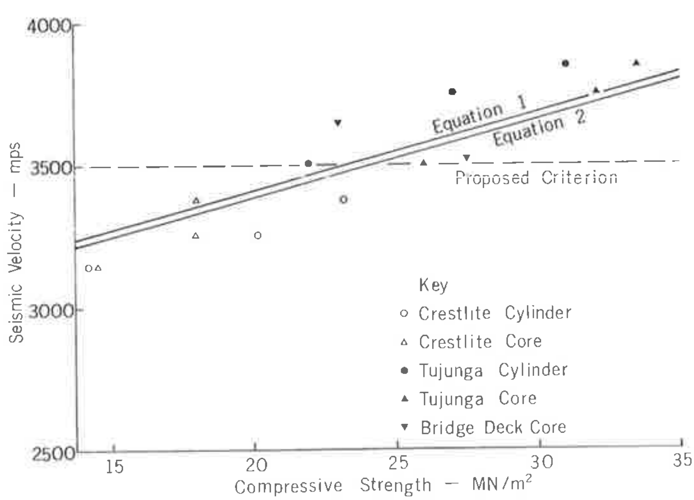


Figure 2. Seismic velocity and compressive strength relations.



RESULTS AND DISCUSSION

Horizontal Surfaces

Equations 1 and 2 were derived statistically from the results of seismic velocity and compressive strength measurements performed on the test slabs that had been constructed of San Gabriel drainage aggregate concrete.

For seismic velocity of slabs and compressive strength of cylinders,

$$SV = 3{,}050 + 22.6\ f \quad n = 30 \quad r = 0.87 \tag{1}$$

For seismic velocity of slabs and compressive strength of cores,

$$SV = 3{,}040 + 21.5\ f \quad n = 30 \quad r = 0.81 \tag{2}$$

where

SV = elastic wave velocity measured by the seismic technique, in meters per second;
r = coefficient of correlation;
n = number of data items (a data item may be the average of a maximum of 6 tests); and
f = compressive strength of concrete, in meganewtons per square meter.

Figure 2 shows the relations of seismic velocity and compressive strength of slabs constructed of concrete containing normal specific gravity aggregate and lightweight aggregate.

From Eqs. 1 and 2 and other analysis of the data from which they were derived, it is concluded that, if the seismic velocity of a slab equals or exceeds 3,500 m/sec, there is a 90 percent probability that the compressive strength will equal or exceed 20.7 MN/m^2. The 2 tests performed on bridge decks constructed of concrete containing nominally 2.65 specific gravity aggregate meet this proposed criterion. In the author's opinion, the rate of change of seismic velocity with compressive strength is undesirably low because variations in seismic velocity tests of 30 to 60 m/sec are commonplace.

Seismic velocity and compressive strength data from tests performed on bridge decks constructed from concrete containing nominally 2.80 specific gravity aggregate is represented by Eqs. 3 and 4.

For seismic velocity of Indian Mill Bridge deck and compressive strength of cylinders,

$$SV = 3{,}730 + 5.7\ f \quad n = 6 \quad r = 0.20 \tag{3}$$

For seismic velocity of bridge decks and compressive strength of cores,

$$SV = 3{,}710 + 6.3\ f \quad n = 10 \quad r = 0.15 \tag{4}$$

Only 25 percent of these results meet the 3,500 m/sec - 20.7 MN/m^2 criterion, probably because the concrete contains nominally 2.80 specific gravity aggregate. Because of the low correlation coefficient and rate of change of seismic velocity with compressive strength, neither Eq. 3 nor Eq. 4 can be used to establish a criterion for concrete containing nominally 2.80 specific gravity aggregate.

Both V-Scope transducers were placed on top of a test slab. The V-Scope velocity thus measured agreed exactly with the seismic velocity. The amplitude of the received signal was so small, however, that the author had no confidence in the result and thereafter used the V-Scope only for through transmission measurements.

Vertical Surfaces

Equations 5 and 6 were derived from the results of seismic velocity and compressive strength measurements performed on the test columns, beams, and arch.

For seismic velocity of vertical surfaces and compressive strength of cylinders,

$$SV = 2{,}960 + 15.1\ f \quad n = 25 \quad r = 0.34 \tag{5}$$

For seismic velocity of vertical surfaces and compressive strength of cores,

$$SV = 2{,}800 + 22.7\ f \quad n = 25 \quad r = 0.48 \tag{6}$$

Because of the poor seismic velocity and compressive strength correlation, no criterion was developed from the data represented by Eqs. 5 and 6. The seismic velocity of 6 of the 9 vertical surfaces did not increase with age as, in general, the slabs did. This leads the author to suspect that the seismic velocity tests performed on the vertical surfaces at 7, 28, and 133 days were not so reliable as the seismic velocity tests performed on the test slabs at the same age or on the columns at 200 to 256 days.

Seismic velocity and compressive strength data from tests performed on vertical surfaces of concrete containing nominally 2.80 specific gravity aggregate is represented by Eqs. 7 and 8.

For seismic velocity of vertical surfaces on Indian Mill Bridge deck and compressive strength of cylinders,

$$SV = 3{,}250 + 32.0\ f \quad n = 6 \quad r = 0.48 \tag{7}$$

For seismic velocity of vertical surfaces and compressive strength of cores,

$$SV = 3{,}500 + 23.8\ f \quad n = 13 \quad r = 0.51 \tag{8}$$

These seismic velocity compressive strength relationships differ significantly from those obtained during the laboratory investigations. The seismic velocity corresponding to a specific compressive strength is much higher in Eqs. 7 and 8 than in Eqs. 5 and 6, again probably because the specific gravity of the aggregate is higher.

The soniscope and seismic velocities of the columns were compared with the following result:

$$V = 1.07\ SV - 280 \quad n = 6 \quad r = 0.98 \tag{9}$$

where

V = elastic wave velocity measured by the soniscope technique, in meters per second.

The elastic wave velocities measured by these methods agree within 30 m/sec in the range of velocities measured. This agreement, in the author's opinion, substantiates the results of both tests performed at ages 200 to 256 days.

Cylinders and Cores

The seismic velocities of cylinders and cores are subject to error because of the short (less than 0.25 m) traverse length. Disturbance of the cores by high frequency vibrations during coring probably affected the seismic velocity or compressive strength of the cores or both (1). No meaningful correlation could be developed between the seismic velocity and compressive strength of individual cores and cylinders.

The soniscope and seismic velocities of companion cylinders having a 2.4 MN/m^2 maximum compressive strength variation between companion cylinders compared as follows:

For seismic velocity of first and second cylinders,

$$SV_2 = 870 + 0.72\ SV_1 \quad n = 9 \quad r = 0.57 \tag{10}$$

For soniscope velocity of first and second cylinders,

$$V_2 = 820 + 0.77\ V_1 \quad n = 9 \quad r = 0.91 \tag{11}$$

where subscripts refer to the first and second cylinder of each pair cast.

For comparison of seismic and soniscope velocities of individual cylinders,

$$SV = 67 + 0.87\ V \quad n = 18 \quad r = 0.70 \tag{12}$$

The V-Scope velocities of the pairs of companion cylinders agree with each other more closely than do the seismic velocities; the correlation coefficient of Eq. 11 is significantly higher than that of Eq. 10. The elastic wave velocity of cylinders, as measured by these 2 methods, differs significantly, discrediting one or both methods of measuring the elastic wave velocity through cylinders.

Miscellaneous Results

Dynamic elastic moduli were calculated from a relationship of the following form:

$$E_d = [(SV)^2 (1 + \nu)\ (1 - 2\nu)]/(1 - \nu)$$

where

E_d = dynamic modulus of elasticity, in giganewtons per square meter;
d = density, in kilograms per cubic meter; and
ν = Poisson's ratio.

Poisson's ratio was assumed to be 0.2 (1, 5). These dynamic moduli are compared with static secant moduli between 89 kN and maximum test load as follows: for static and dynamic moduli of elasticity,

$$E_d = 3.86 + 1.24\ E_s \quad n = 9 \quad r = 0.86 \tag{13}$$

where

E_s = static modulus of elasticity, in giganewtons per square meter.

Because elastic moduli are important to structural engineers and a theoretical relationship exists between elastic wave velocity and elastic moduli, the author suggests that further research be conducted with the objective of determining elastic constants from seismic velocity measurements. He suggests that the specimens be at least 0.6 m in length to permit more accurate velocity determination and that shear wave velocities be measured so that Poisson's ratio can be calculated.

Only the characteristic seismic velocity of the concrete was detected when seismic velocity tests were performed directly above the No. 3 reinforcing bars embedded in the slabs. Two possible reasons why the steel was not located are (a) the seismic velocity of a long slender rod is significantly less than 5,100 m/sec and (b) energy losses reduced the amplitude of the elastic wave traveling through the steel to an undetectable magnitude.

When seismic velocity tests were performed on the exposed surface of the half-embedded No. 8 reinforcing bar, seismic velocities of more than 4,880 m/sec were measured. Seismic velocity tests performed directly above the No. 8 reinforcing bar embedded in the second beam resulted in a seismic velocity of 4,150 m/sec. This velocity, which is significantly higher than that of the concrete, is thought to be "seismic velocity influenced by steel." It may be significant as a source of error in testing reinforced structures and in locating steel.

Seismic velocity tests performed on flexure beams at 60 and 2 C resulted in changes in seismic velocity from that measured at 20 C of 60 m/sec or less in 10 of 11 tests. One 180-m/sec decrease in seismic velocity was measured at 60 C. In only 2 of 6 tests at -18 C were the changes in seismic velocity 60 m/sec or less. The maximum variation at -18 C was 490 m/sec. Ice films formed on the specimens tested at -18 C and interfered with the seismic velocity tests. It is concluded that for practical purposes the seismic velocity of concrete is unaffected by temperature changes in the 2 to 60 C range and that seismic velocity tests should not be performed below freezing because of the ice difficulty.

Five of the 10 seismic velocity tests performed after grinding the point of impact differed by 60 to 180 m/sec from the seismic velocity measured before grinding the point of impact. These variations ranged from 150 (higher) to 180 m/sec (lower).

The seismic velocity measured in 1 test using the field impactor as the impact source was identical to that measured in the test using the pendulum hammer. The seismic velocity measured in the test using the field impactor as the impact source was 90 m/sec higher than that measured in the test using the pendulum hammer in the second comparison. The field impactor was used as the impact source for testing broom-finished slabs during the field portion of this investigation because using the field impactor caused less seismic velocity variation than grinding the point of impact. Another advantage of using the field impactor on broom-finished slabs is that the transducer was positioned at the initial station for the entire test. Positive contact between the transducer and the concrete could be maintained more easily in this manner.

CONCLUSIONS AND SUGGESTIONS

It is difficult to predict the compressive strength of structural concrete by wave velocity methods in practice because (a) the wave velocity versus compressive strength relationships vary greatly depending on the aggregate and (b) the rate of change of wave velocity to compressive strength was found to be smaller than desirable in comparison to the precision of wave velocity measurements.

A relation between the seismic velocity and compressive strength of concrete slabs containing San Gabriel drainage aggregate was developed. If the seismic velocity of the slabs equals or exceeds 3,500 m/sec, there is a 90 percent probability that the compressive strength equals or exceeds 20.7 MN/m^2. Although 2 field tests performed on concrete containing nominally 2.65 specific gravity aggregate support the 3,500 m/sec - 20.7 MN/m^2 criterion, the validity range of this criterion has not been determined. This criterion definitely does not apply to concrete containing nominally 2.80 specific gravity aggregate and is not necessarily applicable to concrete containing aggregate other than the rounded San Gabriel drainage aggregate. The correlation between the seismic velocity of vertical surfaces and compressive strength developed in this investigation is inadequate for engineering purposes.

The author suggests that additional research in the following 2 areas would be worthwhile:

1. Investigate the seismic velocity-compressive strength relations of major pavement structures. Each structure should contain aggregate from a single geologic source. In this way the validity range of the 3,500 m/sec - 20.7 MN/m^2 criterion can be determined or a new criterion developed or both.
2. Determine elastic constants from elastic wave velocity measurements of specimens at least 0.6 m in length. A method of nondestructively measuring the actual modulus of elasticity of concrete is expected to be valuable to structural engineers.

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