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

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

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

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

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

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

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

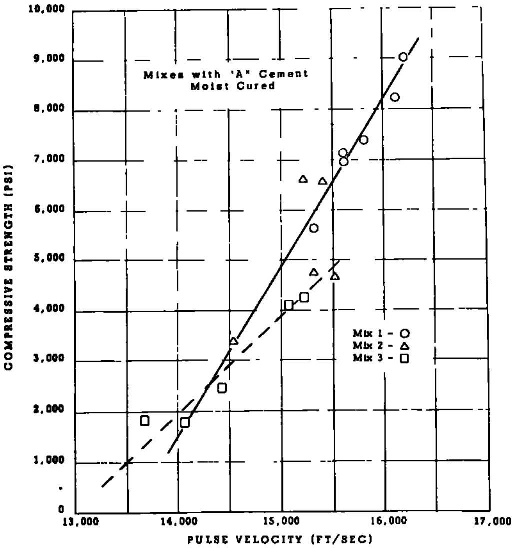

Figure 1. Compressive strength vs pulse velocity.

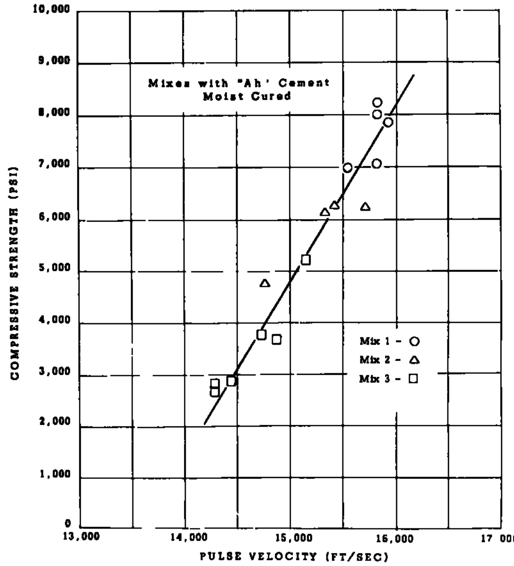

Figure 2. Compressive strength vs pulse velocity.

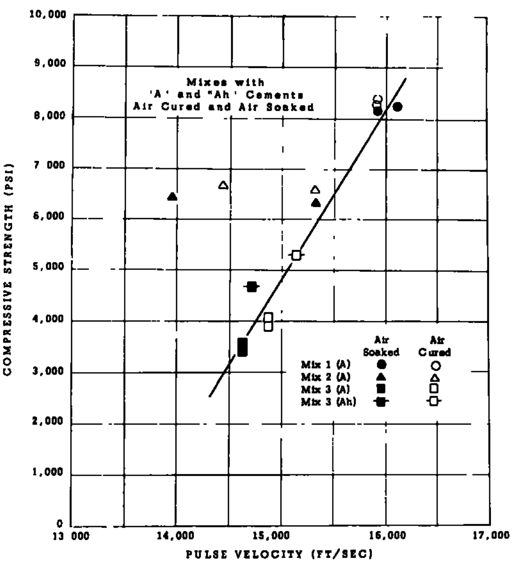

Figure 3. Compressive strength vs pulse velocity.

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

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

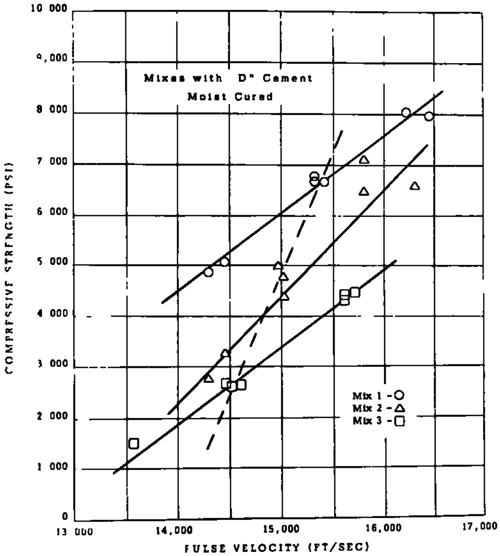

Figure 4. Compressive strength vs pulse velocity.

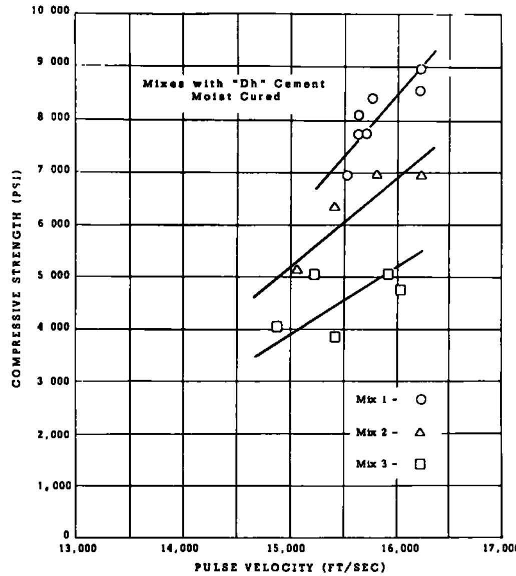

Figure 5. Compressive strength vs pulse velocity.

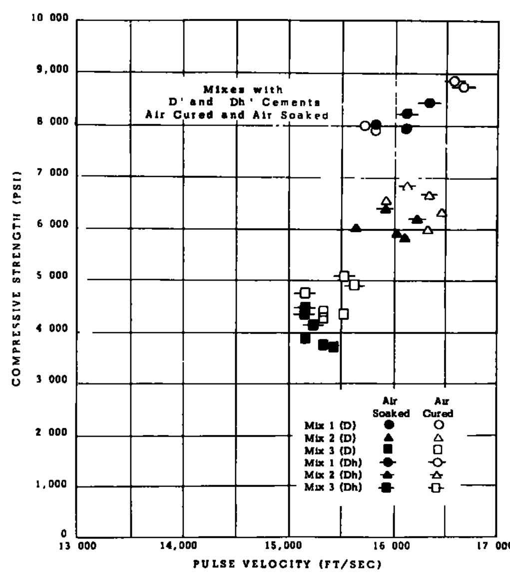

Figure 6. Compressive strength vs pulse velocity.

MATERIALS AND PROCEDURES

Four portland cements were used in the concretes made for this study. Two, identified as cements A and D, were Type I cements. The other two, identified as cements Ah and Dh, were ground from the same clinkers, respectively, but were ground to the fineness of Type III cements. One aggregate, a sand and gravel from the south-central United States, was used in all mixes. Three different water-cement ratios, $4\frac{1}{2}$ gallons per sack, 6 gallons per sack, and 8 gallons per sack were employed. Mixes with these water-cement ratios are identified as Mixes 1, 2, and 3, respectively.

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

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

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

COMPARISON OF PULSE VELOCITIES WITH COMPRESSIVE STRENGTHS

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

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

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

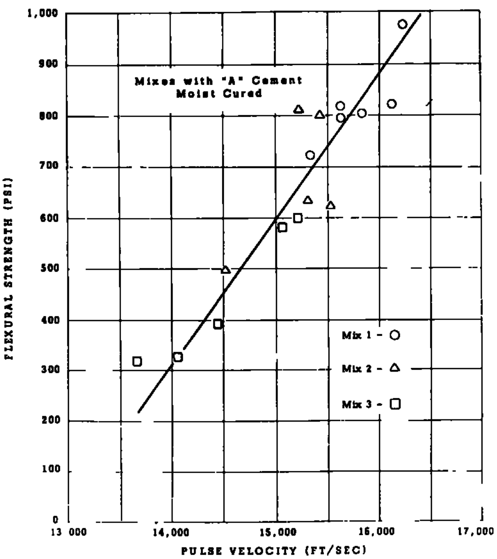

Figure 7. Flexural strength vs pulse velocity.

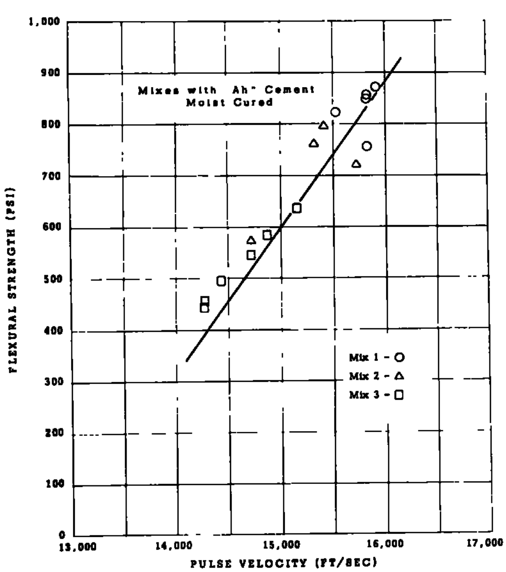

Figure 8. Flexural strength vs pulse velocity.

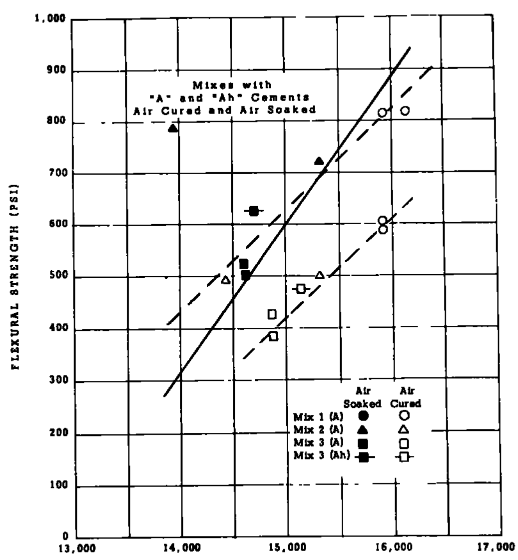

Figure 9. Flexural strength vs pulse velocity.

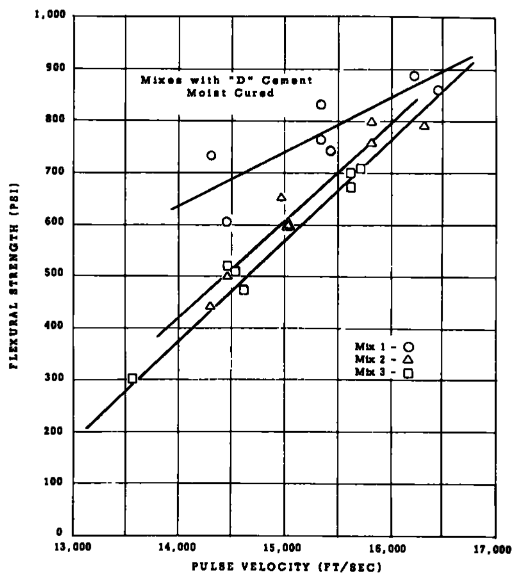

Figure 10. Flexural strength vs pulse velocity.

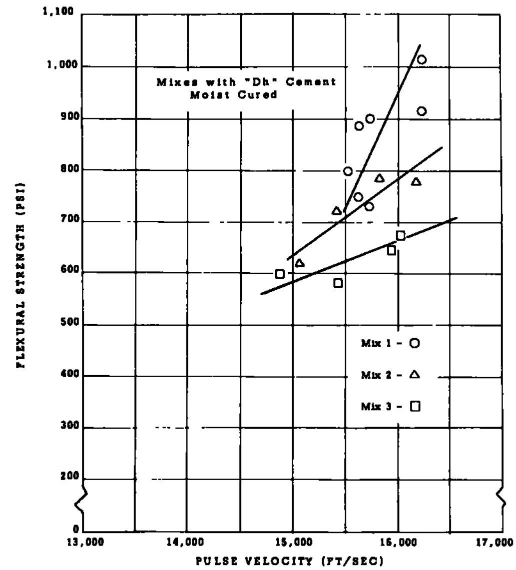

Figure 11. Flexural strength vs pulse velocity.

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

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

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

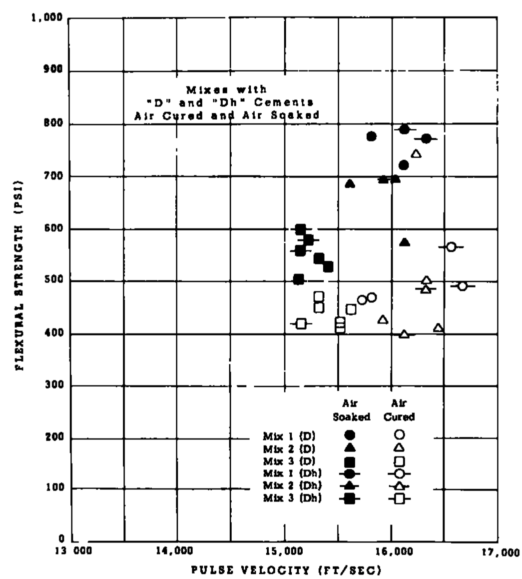

Figure 12. Flexural strength vs pulse velocity.

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

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

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

COMPARISON OF PULSE VELOCITIES WITH FLEXURAL STRENGTHS

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

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

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

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

SUMMARY

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

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

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

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

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