# IMPACT AND PENETRATION TESTS OF PORTLAND CEMENT CONCRETE

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Tests using a rebound device (Schmidt hammer) and a penetration device (Windsor probe test system) were performed at 4 ages on mortar specimens and on concretes made with 3 coarse aggregates and with 2 maximum sizes of aggregate. Cylinders, 6 by 12 in., also were cast and tested at the same ages. Comparisons of the test methods were made of their ability to detect significant differences in batches of concrete, aggregates, sizes of aggregates, successive ages of concrete, and top and bottom of test slabs. Results showed that more significant differences among concrete specimens were detected by the cylinder tests than by either hammer or probe measurements. Based on this study and others, it appears that, although both the Swiss hammer and the Windsor probe test system show a correlation with compressive strength, neither is sufficiently precise to give accurate compressive strength values. Either instrument can be used to investigate relative quality of different areas of concrete and to survey areas of deteriorated concrete. The Swiss hammer, however, is cheaper than the Windsor probe test system, less destructive to the concrete surface, and capable of providing a much greater number of tests in a given area.

•IN MARCH and April 1968, a test program was conducted in the laboratory of the Bureau of Public Roads (now Federal Highway Administration), the prime purpose of which was to study the extent to which the Windsor probe test system and the Schmidt hammer could be used to determine the strength of concrete and to determine the relative usefulness of the 2 methods. A full report on this research is to be published soon (1).

In general, our conclusions agree with those of other researchers. Although both rebound and probe measurements show a correlation with compressive strength, neither provides a precise determination of strength. Either can be used to assess relative strengths in different concretes or different areas of the same concrete, to survey a concrete surface to find areas of low strength or of deteriorated concrete, and to determine when it is safe to remove forms. For any of the uses to which both can be put, however, the Schmidt hammer has an advantage because of the larger number of tests that can be made on a given area, lower cost per test, and nondestructiveness.

## SCHMIDT HAMMER

The Schmidt hammer was developed in Switzerland about 1950 (2, 3, 4) and has become a popular instrument for making rebound measurements. Essentially, the hammer measures some property of the surface layer of the concrete that has been referred to by terms such as surface hardness or coefficient of restitution, and the rebound readings are affected by the surface condition of the concrete. Although the readings are relative, some investigators have reported that, when the instrument is properly calibrated against the compressive strength of test specimens for the conditions of a particular concrete, indications of compressive strength within 15 percent can be obtained (5). The instrument can be used to check uniformity of concrete quality, to locate deteriorated areas or areas of low strength, and to determine when forms may be removed.

The Schmidt hammer consists of a steel plunger and a tension spring in a tubular frame. When the head of the device is pressed against the surface of the concrete, the hammer is retracted against the force of the spring; and when the head is completely retracted, the spring is automatically released. The hammer is driven against the concrete and rebounds. The rebound distance is indicated by a pointer on a scale 75 mm long that is graduated from 0 to 100. The rebound readings are termed R-values. The test has to be made on a smooth spot free from honeycomb, and, if necessary, a spot is prepared by smoothing with silicon carbide stone.

For any selected area, several rebound readings may be taken, and their average may be used in estimating the compressive strength, if desired. The manufacturer furnishes a graph showing a relationship between compressive strength of the concrete and rebound readings based on data from tests conducted at the Swiss Federal Materials Testing and Experimental Institute.

## WINDSOR PROBE TEST SYSTEM

The Windsor probe test system has been developed more recently. The development of the instrument began about 1964 as a joint undertaking of the Port of New York Authority and the Windsor Machinery Company of Connecticut. The device consists of a special driving unit or gun into which is inserted a hardened alloy probe that is driven into the concrete by the firing of a powder charge (Fig. 1). The manufacturer states that the penetration of the probe reflects "the precise compressive strength in a localized area."

The measurement on which the test is based is the length of probe projecting from the surface of the concrete. The lengths of individual probes may be measured by using a device supplied with the instrument, or the average of the 3 probes fired in a triangular pattern may be measured by using a mechanical averaging device also supplied. The mechanical averaging device consists of 2 triangular plates and a depth gage. One of the plates slips over the 3 probes and rests on the surface of the concrete. The other plate fits over the top of the 3 probes, and the depth gage is inserted through a hole in the center of this plate to measure a mechanical average of the exposed height of the 3 probes. The bottom plate has a $^3/_{16}$-in. circle inscribed in its center; and, if the tip of the gage rod falls outside this circle because of uneven height of the 3 probes and consequent tipping of the top plate, the measurement is rejected. This device is supposed to reject groups of 3 measurements for which the within-group coefficient of variation is greater than 3 percent.

To translate probe measurements to strength measurements, the manufacturer supplies a set of 5 calibration curves, each curve corresponding to a specified Mohs' hardness for the coarse aggregate used in the concrete.

## TEST PROGRAM

The test program was designed to include the effect of the following variables: (a) type of coarse aggregate—crushed limestone, crushed traprock, river gravel, and mortar with no coarse aggregate; (b) size of coarse aggregate—1-in. to No. 4 and 2-in. to No. 4; and (c) age of curing (strength level)—3, 7, 14, and 28 days. The physical properties of the 3 coarse aggregates are as follows:

| Property | Limestone | Traprock | Gravel |
|---|---|---|---|
| Absorption, percent | 0.4 | 0.7 | 1.0 |
| Bulk specific gravity (dry) | 2.76 | 2.96 | 2.55 |
| Soundness (sodium sulfate), percent loss | 0.2 | 0.4 | 1.4 |
| Los Angeles abrasion, percent loss | 21 | 16 | 31 |

The gravel was composed of 36 percent quartz, 26 percent quartzite, 22 percent sandstone, 13 percent chert and flint, and 3 percent miscellaneous rock types.

All concrete was designed to have a cement factor of 6 ± 0.1 bag/yd$^3$, an air content of 6 ± 0.5 percent, and a slump of 3 ± 0.5 in. The fine aggregate fraction was 43 percent by volume of the total aggregate for all concrete containing 1-in. aggregate and 36 percent by volume in the case of concrete containing 2-in. aggregate. The water content was varied to produce the desired slump.

For each type of concrete, 6 batches were made, and from each batch one 16- by

20- by 8-in. slab and six 6- by 12-in. cylinders were cast. The slabs were consolidated by vibration and finished with a wooden float. All specimens were moist-cured in the molds for 24 hours, then removed from the molds, and stored in the moist room until the time of test.

Probe, rebound, and cylinder tests were made at 3, 7, 14, and 28 days after casting. At each age 18 individual probe tests and 9 compressive tests on cylinders were made according to the following pattern. Six probes were fired into the top and 6 probes into the bottom of 1 slab; then 3 probes were fired into the top and 3 into the bottom of a second slab. The 6 cylinders from the batch corresponding to the first slab and 3 of the cylinders from the second batch were broken at the same time. At a later age, 3 more probes were fired into the top and bottom of the second slab, which had only 3 probes, and 6 each into the top and bottom of another slab. Three companion cylinders for the second slab and all 6 cylinders accompanying the third slab were broken. The probes were fired in a triangular pattern by using the triangular plate furnished with the instrument (Fig. 1).

Before the probe and cylinder compression tests were made, Schmidt hammer tests were made on both slabs and cylinders. On the slabs, 100 rebound readings were taken: 20 each on the top and bottom of the slab, 20 around the sides near the top of the slab, 20 around the sides near the bottom of the slab, and 20 around the sides half-way between the top and bottom. On the slabs that were tested at 2 ages, 100 rebound readings were taken at each of the 2 ages. On the cylinders, 60 readings were taken: 20 near the top of the side, 20 around the middle, and 20 near the bottom. The cylinders were placed in a testing machine and subjected to a load of 10,000 $lb/ft^3$, just sufficient to hold them firm, while rebound tests were being made.

In this study, as in tests conducted at the National Ready Mixed Concrete Association (6), it was found that considerable deflection of the probes as well as differences in penetration often resulted from the probes striking coarse aggregate particles, making it impossible, in many cases, to use the mechanical averaging device or causing the device to fall in the reject region. Because most of these probe tests were considered to be valid tests, the individual probe measurements were used instead of averages. When the within-group coefficients of variation were calculated for all groups for which there were 3 usable probes, 96 out of 128, or exactly 75 percent, had coefficients of variation greater than 3 percent. Four measurements 90 deg apart around the probe were made with a micrometer caliper, and these 4 measurements were averaged to give the individual probe readings.

## DATA

Tables 1, 2, 3, and 4 give averages, standard deviations, and coefficients of variation for the compressive strengths of the cylinders, the rebound values, and the probe measurements respectively for the different aggregates, different sizes of aggregates, and different ages. For the cylinders and probes (Tables 1 and 4), the averages are based on 9 measurements each, 6 from one batch of concrete and 3 from another. Rebound values given in Table 2 are based on 20 measurements each, all on the same slab. In each case this was the slab that was tested at only 1 age. Rebound readings on the slabs that were tested at 2 ages were not used except for comparisons among batches and to obtain figures based on 9 measurements for comparison with cylinders and probes.

Table 3 gives the figures based on those 9 rebound measurements. For this analysis, 6 rebound numbers were selected at random (by using a table of random numbers) from the 20 on the slab for which 6 probes and 6 cylinders were available. Three rebound numbers were also selected at random from the 20 on the slab for which 3 probe measurements and 3 cylinder strengths were obtained. Those 9 rebound numbers were averaged and are the basis for the averages, standard deviations, and coefficients of variation given in Table 3. The standard deviations given in Tables 1, 3, and 4 are larger than they would be if based on only single batches because of some significant differences between the 2 batches tested at the same age, but comparisons among the 3 sets of figures are on the same basis.

Figure 1. Windsor probe test device.

Table 1. Average compressive strength, standard deviation, and coefficient of variation for 9 cylinders.

| Aggregate | Maximum Size (in.) | Age (day) | Compressive Strength (psi) | Standard Deviation (psi) | Coefficient of Variation (percent) |
|---|---|---|---|---|---|
| Gravel | 1 | 3 | 3,216 | 31 | 1.0 |
| Limestone | 1 | 3 | 2,953 | 282 | 9.6 |
| Traprock | 1 | 3 | 3,031 | 66 | 2.2 |
| Gravel | 1 | 7 | 4,252 | 134 | 3.1 |
| Limestone | 1 | 7 | 4,441 | 168 | 3.8 |
| Traprock | 1 | 7 | 4,422 | 76 | 1.7 |
| Limestone | 1 | 14 | 5,096 | 91 | 1.8 |
| Traprock | 1 | 14 | 5,240 | 63 | 1.2 |
| Gravel | 1 | 28 | 5,462 | 71 | 1.3 |
| Limestone | 1 | 28 | 6,040 | 100 | 1.7 |
| Traprock | 1 | 28 | 5,689 | 70 | 1.2 |
| Limestone | 2 | 3 | 3,101 | 38 | 1.2 |
| Traprock | 2 | 3 | 2,950 | 62 | 2.1 |
| Limestone | 2 | 7 | 4,354 | 91 | 2.1 |
| Traprock | 2 | 7 | 3,879 | 96 | 2.5 |
| Limestone | 2 | 14 | 4,797 | 141 | 2.9 |
| Traprock | 2 | 14 | 4,371 | 124 | 2.7 |
| Limestone | 2 | 28 | 5,476 | 169 | 3.1 |
| Traprock | 2 | 28 | 5,108 | 130 | 2.5 |
| Mortar | - | 7 | 4,343 | 155 | 3.6 |
| Mortar | - | 14 | 4,834 | 100 | 2.1 |
| Mortar | - | 28 | 5,614 | 107 | 1.9 |

Table 2. Average value, standard deviation, and coefficient of variation for 20 rebound measurements.

| Aggregate | Maximum Size (in.) | Age (day) | Side of Slab | R-Value | Standard Deviation | Coefficient of Variation (percent) |
|---|---|---|---|---|---|---|
| Gravel | 1 | 3 | Top | 25.4 | 1.8 | 7.0 |
| | | | Bottom | 28.5 | 3.2 | 11.2 |
| Limestone | 1 | 3 | Top | 23.5 | 1.8 | 7.6 |
| | | | Bottom | 26.6 | 3.4 | 12.8 |
| Traprock | 1 | 3 | Top | 20.7 | 2.4 | 11.7 |
| | | | Bottom | 25.4 | 3.5 | 13.9 |
| Gravel | 1 | 7 | Top | 28.3 | 2.2 | 7.6 |
| | | | Bottom | 31.0 | 1.7 | 5.4 |
| Limestone | 1 | 7 | Top | 29.0 | 2.1 | 7.2 |
| | | | Bottom | 31.7 | 2.7 | 8.4 |
| Traprock | 1 | 7 | Top | 25.3 | 2.8 | 10.9 |
| | | | Bottom | 29.0 | 2.5 | 8.5 |
| Limestone | 1 | 14 | Top | 28.3 | 2.8 | 10.1 |
| | | | Bottom | 33.5 | 2.7 | 8.1 |
| Traprock | 1 | 14 | Top | 28.0 | 1.7 | 6.1 |
| | | | Bottom | 32.6 | 3.1 | 9.6 |
| Gravel | 1 | 28 | Top | 30.2 | 2.5 | 8.3 |
| | | | Bottom | 37.1 | 3.6 | 9.8 |
| Limestone | 1 | 28 | Top | 31.2 | 1.6 | 5.2 |
| | | | Bottom | 36.4 | 4.3 | 11.8 |
| Traprock | 1 | 28 | Top | 27.4 | 2.0 | 7.2 |
| | | | Bottom | 34.1 | 4.3 | 12.5 |
| Limestone | 2 | 3 | Top | 24.4 | 2.6 | 10.8 |
| | | | Bottom | 28.4 | 5.1 | 17.9 |
| Traprock | 2 | 3 | Top | 20.3 | 1.9 | 9.2 |
| | | | Bottom | 22.6 | 2.8 | 12.3 |
| Limestone | 2 | 7 | Top | 25.0 | 2.3 | 9.2 |
| | | | Bottom | 29.2 | 3.4 | 11.8 |
| Traprock | 2 | 7 | Top | 24.0 | 1.7 | 6.9 |
| | | | Bottom | 27.4 | 4.8 | 17.6 |
| Limestone | 2 | 14 | Top | 27.2 | 2.3 | 8.4 |
| | | | Bottom | 32.6 | 4.6 | 14.0 |
| Traprock | 2 | 14 | Top | 23.8 | 2.8 | 11.6 |
| | | | Bottom | 26.8 | 3.3 | 12.4 |
| Limestone | 2 | 28 | Top | 29.4 | 1.6 | 5.5 |
| | | | Bottom | 33.4 | 2.3 | 7.0 |
| Traprock | 2 | 28 | Top | 25.3 | 2.2 | 8.6 |
| | | | Bottom | 31.1 | 3.2 | 10.2 |
| Mortar | | 7 | Top | 26.0 | 1.7 | 6.7 |
| | | | Bottom | 27.6 | 1.2 | 4.3 |
| Mortar | | 14 | Top | 25.5 | 1.7 | 6.9 |
| | | | Bottom | 29.8 | 0.8 | 2.8 |
| Mortar | | 28 | Top | 26.8 | 2.5 | 9.4 |
| | | | Bottom | 32.4 | 1.7 | 5.2 |

**Table 3. Average value, standard deviation, and coefficient of variation for 9 rebound measurements.**

| Aggregate | Maximum Size (in.) | Age (day) | Side of Slab | R-Value | Standard Deviation | Coefficient of Variation (percent) |
|---|---|---|---|---|---|---|
| Gravel | 1 | 3 | Top | 24.8 | 2.0 | 8.0 |
| | | | Bottom | 28.2 | 2.4 | 8.6 |
| Limestone | 1 | 3 | Top | 25.6 | 3.2 | 12.3 |
| | | | Bottom | 26.6 | 4.0 | 15.1 |
| Traprock | 1 | 3 | Top | 20.4 | 2.7 | 13.0 |
| | | | Bottom | 25.6 | 2.7 | 10.5 |
| Gravel | 1 | 7 | Top | 28.2 | 1.8 | 6.3 |
| | | | Bottom | 31.2 | 1.6 | 4.9 |
| Limestone | 1 | 7 | Top | 28.2 | 2.3 | 8.1 |
| | | | Bottom | 31.4 | 2.6 | 8.3 |
| Traprock | 1 | 7 | Top | 25.0 | 1.9 | 7.5 |
| | | | Bottom | 29.7 | 4.6 | 15.5 |
| Limestone | 1 | 14 | Top | 29.4 | 1.3 | 4.5 |
| | | | Bottom | 34.0 | 2.0 | 5.9 |
| Traprock | 1 | 14 | Top | 28.0 | 1.7 | 5.9 |
| | | | Bottom | 32.9 | 2.0 | 6.2 |
| Gravel | 1 | 28 | Top | 31.0 | 2.8 | 9.0 |
| | | | Bottom | 37.0 | 3.0 | 8.2 |
| Limestone | 1 | 28 | Top | 31.0 | 1.9 | 6.2 |
| | | | Bottom | 36.8 | 3.7 | 10.1 |
| Traprock | 1 | 28 | Top | 28.3 | 3.2 | 11.2 |
| | | | Bottom | 35.6 | 5.2 | 14.5 |
| Limestone | 2 | 3 | Top | 23.3 | 1.9 | 8.0 |
| | | | Bottom | 27.0 | 7.0 | 26.0 |
| Traprock | 2 | 3 | Top | 19.9 | 2.4 | 12.1 |
| | | | Bottom | 27.9 | 3.1 | 13.4 |
| Limestone | 2 | 7 | Top | 25.8 | 1.8 | 6.9 |
| | | | Bottom | 29.8 | 2.9 | 9.9 |
| Traprock | 2 | 7 | Top | 23.8 | 2.9 | 12.2 |
| | | | Bottom | 26.3 | 3.2 | 12.3 |
| Limestone | 2 | 14 | Top | 28.0 | 2.2 | 8.0 |
| | | | Bottom | 33.2 | 5.7 | 17.0 |
| Traprock | 2 | 14 | Top | 24.7 | 2.8 | 11.2 |
| | | | Bottom | 28.1 | 4.4 | 15.8 |
| Limestone | 2 | 28 | Top | 29.2 | 2.4 | 8.4 |
| | | | Bottom | 33.1 | 3.4 | 10.4 |
| Traprock | 2 | 28 | Top | 25.6 | 2.0 | 7.9 |
| | | | Bottom | 30.7 | 3.1 | 10.2 |
| Mortar | | 7 | Top | 25.3 | 1.9 | 7.7 |
| | | | Bottom | 27.9 | 1.2 | 4.2 |
| Mortar | | 14 | Top | 26.0 | 1.5 | 5.8 |
| | | | Bottom | 30.4 | 0.9 | 2.9 |
| Mortar | | 28 | Top | 27.4 | 3.2 | 11.7 |
| | | | Bottom | 31.9 | 2.3 | 7.1 |

**Table 4. Average penetration, standard deviation, and coefficient of variation for probe measurements.**

| Aggregate | Maximum Size (in.) | Age (day) | Side of Slab | Number of Probes | Penetration (in.) | Standard Deviation (in.) | Coefficient of Variation (percent) |
|---|---|---|---|---|---|---|---|
| Gravel | 1 | 3 | Top | 9 | 1.730 | 0.171 | 9.9 |
| | | | Bottom | 9 | 1.871 | 0.153 | 8.2 |
| Limestone | 1 | 3 | Top | 9 | 1.564 | 0.054 | 3.4 |
| | | | Bottom | 9 | 1.631 | 0.106 | 6.5 |
| Traprock | 1 | 3 | Top | 9 | 1.622 | 0.102 | 6.3 |
| | | | Bottom | 9 | 1.835 | 0.080 | 4.4 |
| Gravel | 1 | 7 | Top | 9 | 1.814 | 0.084 | 4.6 |
| | | | Bottom | 9 | 1.955 | 0.102 | 5.3 |
| Limestone | 1 | 7 | Top | 9 | 1.797 | 0.058 | 3.2 |
| | | | Bottom | 9 | 1.829 | 0.114 | 6.2 |
| Traprock | 1 | 7 | Top | 9 | 1.849 | 0.151 | 8.2 |
| | | | Bottom | 9 | 1.964 | 0.094 | 4.8 |
| Limestone | 1 | 14 | Top | 9 | 1.852 | 0.113 | 6.1 |
| | | | Bottom | 9 | 2.012 | 0.112 | 5.6 |
| Traprock | 1 | 14 | Top | 9 | 1.825 | 0.073 | 4.0 |
| | | | Bottom | 9 | 2.098 | 0.076 | 3.6 |
| Gravel | 1 | 28 | Top | 9 | 1.987 | 0.166 | 5.8 |
| | | | Bottom | 9 | 2.086 | 0.069 | 3.3 |
| Limestone | 1 | 28 | Top | 9 | 1.923 | 0.126 | 6.6 |
| | | | Bottom | 9 | 2.034 | 0.082 | 4.0 |
| Traprock | 1 | 28 | Top | 9 | 1.965 | 0.115 | 5.9 |
| | | | Bottom | 9 | 2.064 | 0.048 | 2.3 |
| Limestone | 2 | 3 | Top | 9 | 1.728 | 0.260 | 15.1 |
| | | | Bottom | 9 | 1.858 | 0.100 | 5.4 |
| Traprock | 2 | 3 | Top | 9 | 1.694 | 0.147 | 8.7 |
| | | | Bottom | 9 | 1.906 | 0.124 | 6.5 |
| Limestone | 2 | 7 | Top | 9 | 1.906 | 0.073 | 3.8 |
| | | | Bottom | 9 | 2.008 | 0.130 | 6.5 |
| Traprock | 2 | 7 | Top | 7 | 1.807 | 0.134 | 7.4 |
| | | | Bottom | 6 | 1.843 | 0.113 | 6.1 |
| Limestone | 2 | 14 | Top | 9 | 1.894 | 0.107 | 5.7 |
| | | | Bottom | 9 | 2.027 | 0.131 | 6.4 |
| Traprock | 2 | 14 | Top | 8 | 1.972 | 0.159 | 8.1 |
| | | | Bottom | 8 | 1.966 | 0.137 | 7.0 |
| Limestone | 2 | 28 | Top | 9 | 2.049 | 0.124 | 6.1 |
| | | | Bottom | 8 | 2.007 | 0.114 | 5.7 |
| Traprock | 2 | 28 | Top | 9 | 2.005 | 0.192 | 9.6 |
| | | | Bottom | 9 | 2.150 | 0.133 | 6.2 |
| Mortar | | 7 | Top | 9 | 1.512 | 0.108 | 7.1 |
| | | | Bottom | 9 | 1.657 | 0.061 | 3.7 |
| Mortar | | 14 | Top | 9 | 1.595 | 0.101 | 6.3 |
| | | | Bottom | 9 | 1.802 | 0.030 | 1.7 |
| Mortar | | 28 | Top | 9 | 1.701 | 0.071 | 4.2 |
| | | | Bottom | 9 | 1.844 | 0.047 | 2.5 |

For the gravel aggregate, not enough of the larger sizes was available and concretes were made only with the 1-in. top size. Also no data are given for the gravel aggregate at the age of 14 days. Considerable difficulty was experienced with the probe tests for this concrete at this age. Many of the probes bounced out or broke and had to be reshot. Only 11 measurable probes were finally obtained, and there was doubt as to their validity. The rebound and cylinder data could have been used, but it was decided to eliminate all data for the gravel concrete at 14 days.

No data are given for mortar at 3 days. There was difficulty with the probes penetrating too deeply. We made an effort to overcome this difficulty by air-drying the slabs and cylinders. Thus, because the treatment of the 3-day mortar slabs and cylinders was different from that of the concrete and of the mortar specimens at later ages, the 3-day mortar data were all eliminated.

Data are given in Tables 2, 3, and 4 for both top and bottom of the slabs because there were significant differences between top and bottom for both rebound and probe measurements. For compressive strengths of cylinders, of course, there is no differentiation between top and bottom, although rebound measurements taken on the sides of the cylinders showed higher readings near the bottom than near the top.

A column for the number of probes is given in Table 4 because there were a few cases with the 2-in. aggregate where 9 usable probes were not available. Frequently probes would break or bounce out and have to be reshot. The triangular device spaces the probes approximately 7 in. apart, and individual probes cannot be driven closer without danger of interfering with one another. When a probe fails, the usual procedure is to turn the triangular plate around, fit it over the good probes, and fire another one on the other side of the 2 good ones from the unusable one. In some cases the result was that 9 measurable probes were not obtained. In one case, a single probe that was measured and recorded was so far from the other two that it was eliminated.

All of the tests in this investigation were conducted in the laboratory, and the cylinder strengths were quite uniform. With the exception of the 1-in. limestone at 3 days, all of the calculated standard deviations were under 200 psi and the coefficients of variation were under 4 percent. In fact, 17 out of the 22 coefficients of variation were under 3 percent, and that represents excellent laboratory control according to ACI 214. A pooled value for the standard deviation, excluding the 3-day, 1-in. limestone, was 107 psi based on 189 cylinders.

The large standard deviation for the 1-in. limestone at 3 days was produced by the fact that the 3 cylinders from the second batch of concrete all tested significantly higher than the 6 from the first batch. The averages were 3,323 psi with a coefficient of variation of 2.3 percent and 2,768 psi with a coefficient of variation of 1.4 percent respectively.

The data given in Table 2 based on 20 rebound measurements indicate that the presence of coarse aggregate in the mixes caused more scatter in the results. The pooled standard deviation for the mortar mixes was 1.7 based on 54 rebound numbers; that for the concretes was 2.9 based on 342 rebound numbers. Coefficients of variation for all groups ranged from 2.8 to 17.9 percent.

The probe data (Table 4) indicate that the standard deviations were relatively constant over all the conditions within a given size of aggregate. The standard deviations were 0.143 based on 136 probes for the 2-in. top size, 0.105 based on 198 probes for the 1-in. top size, and 0.075 based on 54 probes for the mortar. Coefficients of variation ranged from 1.7 to 15.1 percent.

Comparison of the coefficients of variations given in the tables shows that the coefficients for the probe measurements were generally lower than those for rebound numbers, whether the latter were based on 9 or 20 measurements. It appears that the use of 20 measurements from 1 slab or 9 measurements from 2 slabs did not make any difference in the coefficients of variation for rebound numbers. Exactly half (22 out of 44) of the coefficients for the 9-probe averages were numerically equal to or larger than those for the 20-probe averages. The coefficients for the cylinders (Table 1) were generally lower than those for either the probe measurements or rebound numbers.

## COMPARISONS OF BATCHES

Table 5 gives a summary of the results of comparisons of different concretes. Comparisons are based on the t-test for significant difference between averages (7) at the 95 percent confidence level.

There were significant differences between the concrete in the 2 batches, as indicated by the cylinders, that were not revealed by either the rebound or the probe measurements. The most consistent differences, based on cylinder strengths (Table 5), were for the 3-day concrete for all 3 aggregates with 1-in. top size and for the mortar specimen. For the rebound readings, there were only 3 significant differences out of 44 possible when 9 readings were used, and the 10 did not in general correspond with differences shown by the cylinders. For the probes, only 1 out of 42 possible differences showed a t-value beyond 95 percent, and this is no more than would be expected by chance.

## COMPARISONS OF AGGREGATES

All comparisons of cylinders except two were highly significant. The 2 exceptions are limestone versus traprock at the 2 earliest ages. The direction of the differences in this instance is interesting. For comparisons between the gravel and the other 2 aggregates, the gravel concretes were the stronger at 3 days; but both the limestone and traprock showed higher strengths than the gravel at 7 and 28 days. For comparisons of limestone versus traprock with 1-in. top size, there was no significant difference for the 2 earlier ages; the traprock showed higher strength at 14 days, and the limestone showed higher strength at 28 days. For the 2-in. top size, however, the limestone showed significantly higher strength than the traprock at all 4 ages.

For the rebound numbers, 17 out of the 28 comparisons showed significant differences. Of these differences, 10 were on the top sides of the slabs and 7 were on the bottom. For the probe measurements, there were only 7 significant differences out of a possible 28. Neither the hammer nor the probes consistently showed the differences in the same direction as those shown by the cylinder averages. The rebound numbers agreed with the cylinders in showing the 2-in. limestone concrete to have higher values than those of the traprock with the same top size at 3, 14, and 28 days, and the gravel higher than the traprock at 3 days. However, they disagreed with the cylinders in showing higher values for the 1-in. gravel than for the traprock at 7 and 28 days. The probes agreed with the others as to significance and direction of the difference in only 1 case, and 6 of the 7 indicated significant differences were on the bottom of the slabs.

## COMPARISONS OF 1- AND 2-IN. AGGREGATE

In comparisons of concretes made with the 2 different maximum sizes, significant differences shown by the cylinders were not shown so consistently by either rebound or probe measurements. There were 6 out of a possible 8 significant differences, the 2 exceptions being for the limestone at the 2 earlier ages. In all cases of significant difference, the concrete without the larger size fraction showed greater strength.

The rebound numbers agreed with the cylinder strengths in all cases where the difference was significant for both. Differences for the rebound numbers were significant on both sides of the slab, the 1-in. size showing higher readings for the limestone at 7 and 28 days and for the traprock at 14 and 28 days.

However, the probe measurements were contradictory to the other two. Of the 7 cases where the difference was significant based on the probe measurements, 5 showed less penetration for the 2-in. aggregate than for the 1-in. This is undoubtedly related to the increased number of instances of probes striking large pieces of aggregate.

## COMPARISONS OF SUCCESSIVE AGES

Differences among averages for successive ages of test showed increases of strength with age for all 3 types of test; but for the rebound and probe measurements, there were cases where there was no significant difference. For the rebound numbers, 11 out of the 30 differences were not significant. For the probes, 19 out of 30 differences were not significant.

Table 5. Number of comparisons having significant differences at 95 percent confidence level.

| | Cylinders | | Probes | | Rebound | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | 9 Values | | 20 Values | |
| Item Compared | Number | Differences | Number | Differences | Number | Differences | Number | Differences |
| Batches | 22 | 9 | 43 | 1 | 44 | 3 | 44 | 10 |
| Top versus bottom | — | — | 22 | 12 | 22 | 15 | 22 | 22 |
| Aggregates | 14 | 12 | 28 | 7 | 28 | 12 | 28 | 17 |
| 1 in. versus 2 in. | 8 | 6 | 16 | 7 | 16 | 7 | 16 | 9 |
| Successive ages | | | | | | | | |
| 3 to 7 days | 5 | 5 | 10 | 4 | 10 | 8 | 10 | 8 |
| 7 to 14 days | 5 | 5 | 8 | 3 | 10 | 4 | 10 | 6 |
| 14 to 28 days | 5 | 5 | 10 | 4 | 10 | 0 | 10 | 5 |
| Total | 59 | 42 | 137 | 38 | 140 | 39 | 140 | 77 |

Figure 2. Regression curve and confidence limits for rebound values.

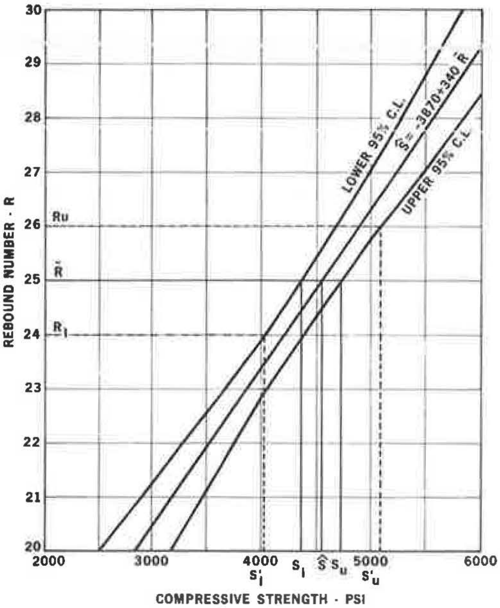
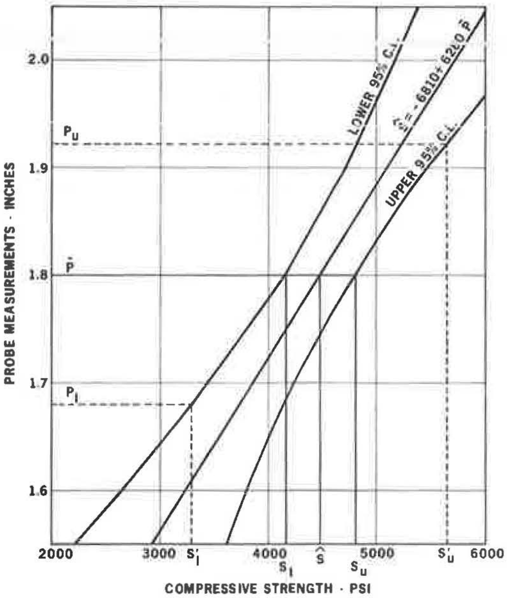


Figure 3. Regression curve and confidence limits for probe measurements.



## COMPARISONS OF TOP AND BOTTOM OF SLABS

Comparisons between measurements on the top and on the bottom of the same slab showed a highly significant difference for rebound numbers in every case, with the readings being higher on the bottom than on the top. For the probes, no significant difference was detected in 10 out of the 22 cases. The rebound tests also showed significant differences between top and bottom of cylinders.

## SUMMARY OF SIGNIFICANT DIFFERENCES

Table 5 gives the number of significant differences for each of the 3 test methods. Rebound numbers are also given for 9 measurements selected at random from the 40 measurements on the appropriate slab. Not all of the differences investigated are expected to be significant, but the significant differences shown by the compressive tests on the cylinders may be taken as representative of differences in strength that actually existed and used as a criterion with which to compare results of the other 2 methods of test, excluding comparisons between top and bottom, which were not available for the cylinders. The percentage of comparisons that were significant is as follows:

| Test Method | Percent |
|---|---|
| Cylinders | 71 |
| Probes | 23 |
| Rebound | |
| 9 values | 39 |
| 20 values | 47 |

## PREDICTION OF COMPRESSIVE STRENGTH FROM REBOUND MEASUREMENTS

Figure 2 shows a regression curve and confidence limits for compressive strengths versus rebound numbers. The confidence limits are 95 percent limits for the location of the fitted line, calculated in the manner described by Natrella (7, Ch. 5).

The confidence interval for the line as a whole is used instead of the confidence interval for points on the line because the line is a calibration line that will be used repeatedly for prediction purposes. Natrella gives a further discussion of this point (7, pp. 5-15 to 5-16).

When a regression curve is plotted or calculated with 2 sets of measurements such as this, 2 conditions must be met: The data used in the relationship must fit a common regression line, and the precision (that is, the scatter about the line) must be about the same for all the sets of data used. For the rebound numbers, as for the probe measurements, the largest available group of data that fulfilled these conditions was used. Also, because no differentiation between sides was possible for cylinders and usually only 1 side of a concrete slab is accessible, data from the top sides only were used.

Data shown in Figure 2 are based on the measurements of the slabs and cylinders made with traprock aggregate with both top sizes. For both the rebound measurements and the cylinders, the standard deviations were reasonably uniform over the range of strengths and conditions. Also, the individual regression lines for the 1- and 2-in. traprock were sufficiently close together so that the data could be plotted together and 1 regression line drawn.

The regression line is based on 16 plotted points obtained as follows: For each age for each type of concrete (1- or 2-in. aggregate), 2 values for rebound measurements were obtained by averaging the 20 rebound numbers on the top side of each of the 2 slabs tested at that age. These values were paired with the averages of 3 cylinder strengths from the corresponding batches of concrete. Three cylinders were used because only 3 were available from the batches for which the slabs were tested at 2 ages. For the batches that were tested at only 1 age, 3 of the 6 cylinders were selected at random for averaging.

Figure 2 also shows the 95 percent confidence band for the location of the fitted line and illustrates the use of the line predicting compressive strength of the same type of concrete made with the same materials. If an average rebound reading, $\bar{R}$ in Figure 3, is 25, the horizontal line from $\bar{R}$ intersects the prediction line at a point indicating an average compressive strength, S, of 4,530 psi. The confidence interval, assuming no error in the rebound average, is from $S_l = 4,350$ psi to $S_u = 4,710$psi, a range of 360 psi.

To calculate a confidence band for the rebound measurements, we obtained an estimate of the standard deviation of individual rebound numbers from the 16 sets of 20 measurements obtained on the top side of the slabs made with traprock. This estimate obtained was 2.23, based on 320 measurements. Dividing by 20 to give the standard deviation of averages of 20 and multiplying by ±1.96 to give the 95 percent confidence limits give approximately ±1.0 for the confidence band. The horizontal lines from $\bar{R}_l = 24$ and $\bar{R}_u = 26$ intersect the confidence limits for points on the line at $S_l' = 4,010$ psi and $S_u' = 5,070$ psi, a range of 1,060 psi. The combined probabilities give a confidence of approximately 90 percent for this range.

## PREDICTION OF COMPRESSIVE STRENGTH FROM PROBE MEASUREMENTS

Figure 3 shows the results of corresponding calculations of the regression line and confidence limits for the probe measurements. In this case the individual regression lines for all 3 aggregates for the 1-in. size were sufficiently close together so that 1 regression line could be fitted to all 3 sets of data. The averages of the 3 probe measurements that were fired into the slabs tested at 2 ages and the averages of 3 selected at random from the 6 fired into the slabs tested at only 1 age were paired with the corresponding averages of 3 cylinders to give 22 pairs of values for plotting and calculating the line.

The confidence band for the average of probes was obtained from an estimate of the standard deviation from the 99 probes fired into the top of the slabs made with the 1-in. aggregate; within-batch deviations were used. This estimate was 0.109 in. Dividing by 3 to get the standard deviation of averages of 3 and multiplying by ±1.96 give ±0.12 in. for the 95 percent confidence band. A value of 1.8 for the average of 3 probes gives $\hat{S} = 4,490$ psi for the estimated strength. The final confidence band for the strength resulting from both the confidence band for points on the line and the confidence band for the probe measurements is from $S_l' = 3,290$ psi to $S_u' = 5,650$ psi, a range of 2,360 psi.

## PREDICTION OF STRENGTHS USING MANUFACTURERS' CURVES

The Schmidt hammer and the Windsor probe system are both supplied with curves or tables showing a relation between compressive strength and rebound number or inches of exposed probe respectively. The curve supplied with the Schmidt hammer was calculated from tests made by the Swiss Federal Materials Testing and Experimental Institute on approximately 550 concrete cubes; the values are reduced by 10 percent to compensate for the higher strength results obtained from cubes. The manufacturers of the Windsor probe system provide a set of curves based on different Mohs' hardness of the aggregates. No information on the source, character, or number of tests on which these curves are based is given, and no limits of uncertainty are indicated. Information supplied with the Schmidt hammer states that the curve supplied is based on "average" concrete and conditions, but for any sizable application it is advisable to develop a new calibration curve for the particular conditions on the job. In the NRMCA study mentioned previously (6) and in our tests, manufacturer's curves for the Schmidt hammer were not used.

For the Windsor probe system, NRMCA found that its laboratory curves fit the data much better than did the manufacturer's curves. In a study conducted by the Louisiana Department of Highways (8) in which the chert aggregate used was considered to have a Mohs' hardness of 7, it was found that the manufacturers' curve would have caused a considerable overestimation of the strength, compared to that obtained on the cylinders. In the current study, there is some doubt about the appropriate number for Mohs' hardness, but none of the manufacturer's curves fitted the data as well as the lines calculated from the data.

## MEASUREMENTS REQUIRED TO DETECT DIFFERENCES IN STRENGTH

Assessment of the effectiveness of different methods of measuring strength may be made by determining the number of specimens required to detect the true average strength within given limits with a given probability. The following data are based on the requirement of detecting a difference from true strength of 200 psi with an $\alpha$ error of 0.10 and a $\beta$ error of 0.10. This means that the averages of a group of tests would show a significant difference from an assumed true strength 1 time in 10 when the actual difference is 0 psi and 9 times in 10 when the actual difference is 200 psi or greater. The number of measurements required depends on the standard deviation of the measurements involved.

For the cylinders in this investigation, all the standard deviations for aggregate-age combinations except one were less than 200 psi (Table 1). These were carefully prepared, well-cured, laboratory cylinders. Two hundred psi represents a coefficient of variation of 5 percent for 4,000-psi concrete. If 200 psi is taken as a standard deviation for cylinders and the $\alpha$ and $\beta$ errors described earlier are used, approximately 8 cylinders would be required to detect the true strength within 200 psi with a probability of 90 percent. The sample sizes given in this section are taken from a curve based on Table A-12C of Dixon and Massey (9).

To determine the number of measurements required to detect a psi difference for rebound and probe measurements, one has to take into account not only the standard deviation of the measurements but also the slope of the calibration curve used to convert the measurements to psi. For our rebound measurements, the slope of the calibration curve (Fig. 2) is 336 psi per rebound number. The published manufacturer's curve, although not linear, is very nearly so in the middle range and has a slope of approximately 200 psi per rebound number in the range from about 3,000 to 5,000 psi. Using 340 for the slope and 2.2 for the standard deviation of rebound numbers (as given earlier for our data) would require about 120 rebound measurements to detect the average strength within 200 psi. For tests for which the slope of the calibration curve is 200, as given by the manufacturer's curve, the number would be about 50.

For the probe measurements, the slope of the line for 1-in. aggregate shown in Figure 3 is 6,280 psi per inch of probe. Using 6,300 for the slope and 0.1-in. for the standard deviation would require about 85 probes to detect the average strength within 200 psi. The manufacturer's curves have slopes that range from 6,750 psi per inch of probe for Mohs' hardness 3 to 8,700 for 7. For data from concretes that fit these calibration curves, the approximate number of measurements required to determine the strength within 200 psi would be 100 for Mohs' hardness 3 and 160 for 7.

## CONCLUSIONS

The following conclusions are based on analysis of the probe, rebound, and cylinder data from this study.

1. Coefficients of variation for both rebound and probe measurements were generally higher than those obtained from compression tests of companion cylinders.
2. Coefficients of variation for probe measurements were generally lower than those for rebound numbers.
3. The variance of rebound numbers was increased by the presence of coarse aggregate. The standard deviation was 1.7 for the mortar tests and 2.9 based on data from all the concretes.
4. For probe tests, the standard deviations were relatively constant for a given size of aggregate: 0.75 in. for mortar, 0.105 in. for all tests for 1-in. top size, and 0.143 in. for 2-in. top size.
5. Significant differences between batches of the same concrete tested at the same age were shown by the cylinders and to some extent by the rebound numbers but were not shown by the probe measurements. The number of significant differences between batches revealed by rebound numbers increased when 20 instead of 9 measurements per slab were used.

6. Significant differences between concretes made with different aggregates were shown by the cylinder tests except for limestone versus traprock at 3 and 7 days. For the rebound numbers, 17 out of 28 of the comparisons of aggregates showed a significant difference; and, for the probe measurements, only 7 out of 28 were significant. In a number of cases where differences were significant for both the cylinders and one of the other methods of test, there was a disagreement on the direction of the difference.

7. For comparisons between 1- and 2-in. aggregates, the cylinders showed significant differences for all cases except the limestone at 3 and 7 days, and the rebound numbers showed significant differences except at 3 and 14 days for the limestone and at 7 days for the traprock. In both cases, all significant differences indicated higher strength for the 1-in. maximum size. The probe measurements showed no significant differences on either side of the slabs for the limestone at 14 days and the traprock at 3 and 28 days and on one side of the slabs for the limestone at 3 and 28 days and the traprock at 7 days. However, of the 7 significant differences shown by probe measurements, 5 indicated higher strength for the 2-in. maximum size.

8. All 3 methods of test showed significant increases of strength at successive ages. However, significant differences were not shown in 11 out of 30 cases for the rebound numbers and 17 out of 28 for the probes.

9. Both rebound and probe measurements showed significant differences between top and bottom of the slabs, with the bottom being stronger. The rebound numbers showed highly significant differences in every case, but 10 out of the 22 comparisons were not significant with the probes.

10. Comparisons of the numbers of significant differences detected by the 3 methods for the 7 types of comparisons show that comparisons of the averages of 9 cylinders in every case detected more significant differences than did either the rebound or probe measurements; comparisons using the averages of 9 rebound numbers did as well as or better than comparisons using 9 probes in detecting significant differences in 6 out of the 7 types of comparison; and comparisons using the average of 20 rebound numbers did better than comparisons using 9 probes in all cases.

11. The calibration curve for rebound numbers based on the data for traprock indicated that an average rebound number of 25 obtained from 20 measurements corresponded to approximately 4,530 ± 530 psi with a 90 percent confidence.

12. The calibration curve for probe measurements based on the data for the 1-in. maximum size for all 3 aggregates indicated that an average probe measurement of 1.8 in. obtained from 3 measurements corresponded to approximately 4,490 ± 1,180 psi with a 90 percent confidence.

13. To use either the Schmidt hammer or the Windsor probe system to predict compressive strength, one should develop calibration curves by using the materials and mix designs to be used on the job. Curves supplied by the manufacturers cannot be relied on.

14. Confidence limits for points on the curve calculated from the calibration data should be placed about the curves, and variation of the basic measurements (rebound numbers or probe measurements) together with the confidence interval should be considered when the curves are used.

15. If curves based on an error of 10 percent (probability of making the error of assessing a difference when none exists) are used, the number of tests required to detect the true strength of concrete within 200 psi 90 percent of the time is as follows: 8 cylinders, assuming a standard deviation of 200 psi; 120 rebound measurements, assuming a standard deviation of 2.2 and a slope of the calibration curve of 240 psi per rebound (a calibration curve with a slope of 200 psi such as that published from the manufacturer's data would require about 50 rebound measurements); and 85 probe measurements, assuming a standard deviation of 0.1 in. and a slope of the calibration curve of 6,300 psi per inch of probe (for the manufacturer's curves with slopes ranging from 6,750 to 8,700 psi per inch, 100 to 160 probes would be needed).

16. Considerable difficulty was experienced in using the mechanical averaging device supplied with the Windsor probe test system. Best results are obtained by measuring all probes individually.

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