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Rapid Tests for Aggregate and Concrete

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Rapid Tests for Aggregate and Concrete

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Contents

Use of Swiss Hammer for Estimating Compressive Strength of Hardened Concrete

WILLIAM E. GRIEB, Physical Research Engineer, Bureau of Public Roads

A simple and portable instrument for use in estimating the compressive strength of hardened concrete in place has been developed recently by a Swiss engineer. The device, popularly known as the Swiss hammer, is designed for field use and is not intended as a substitute for control testing. It is being used in the field to gage increases in concrete strength with age and in locating low strength areas when laboratory tests of control concrete cylinders or other conditions indicate that such areas might exist. It is also useful in surveys of old structures. The test results given in this report show that factors such as surface smoothness, surface moisture condition, and type of coarse aggregate affect the strength values obtained by the use of the device.

● A SIMPLE, quick nondestructive test method for estimating the compressive strength of hardened concrete in place has been developed by a Swiss engineer, Ernest Schmidt. The device consists of a steel plunger or hammer, free to travel in a tubular frame. When the head of the hammer is pressed against the surface of the concrete, the hammer is retracted into the frame against the force of a tension spring. When the head is completely retracted, the spring is automatically released, driving the hammer against the concrete. A small sliding pointer indicates the rebound of the hammer on a graduated scale. The scale is 75 mm in length, and reads from zero to 100 in equally-spaced divisions. The amount of this rebound "R" was found by the inventor to be related to the compressive strength of concrete.

A number of research organizations have made a study of the performance of the Swiss hammer both in the laboratory and in the field. The consensus of their reports is that the empirical relationships between hammer rebound and strength are affected by moisture conditions of the concrete and type of aggregate thus limiting the usefulness of the hammer to cases where an approximation of strength is all that is required. These reports, however, do not include sufficient data to determine fully the capabilities of this instrument.

TESTING PROCEDURE

The surface of the concrete selected for test should be smooth and free from any rough spots or honeycomb. A surface produced by form work or troweling is usually satisfactory. When necessary, a smooth surface may be prepared by rubbing with a carborundum stone an area approximately 2 in. in diameter. A suitable stone is furnished in the carrying case of the apparatus.

In performing the test, the hammer is held perpendicular to the surface of the concrete and pressed against it until the hammer is released an strikes the surface of the concrete. While the device is still pressed firmly against the concrete, a button on the side of the instrument is pressed which locks the pointer in position. This permits removing the device to facilitate reading the amount of rebound. The apparatus is shown in Figure 1.

For any selected area, five or more rebound readings are taken and the average of these readings is used to estimate the compressive strength. Areas where the reinforcing steel is known to be close to the surface, or where the coarse aggregate is exposed, are avoided.

The manufacturer of the instrument furnished a graph showing the relationship between the compressive strength of the concrete and the rebound readings. This graph

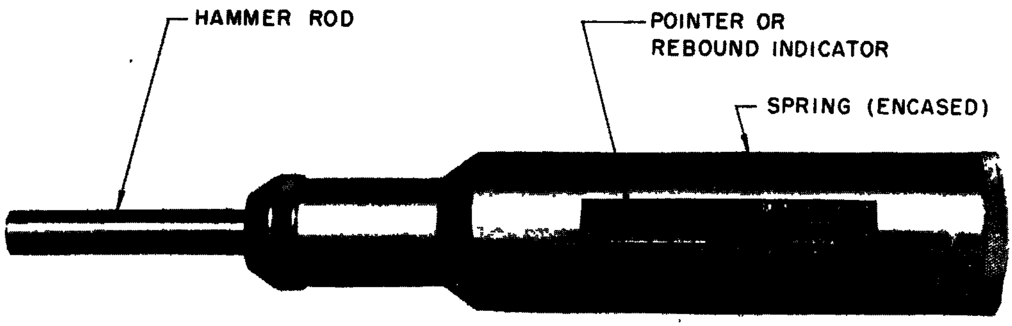

Figure 1. Swiss rebound hammer.

is shown in Figure 2. The data for establishing the relationship represented by the curve in Figure 2 were based on tests by the Swiss Federal Testing Laboratory. This curve for estimating the compressive strength shows values of rebound obtained when the hammer is held in a horizontal position against a vertical concrete surface. For other than horizontal positions of the hammer, a correction factor should be applied to the rebound readings before using the curve for estimating the strength of the concrete. A chart giving these correction factors was furnished by the manufacturer.

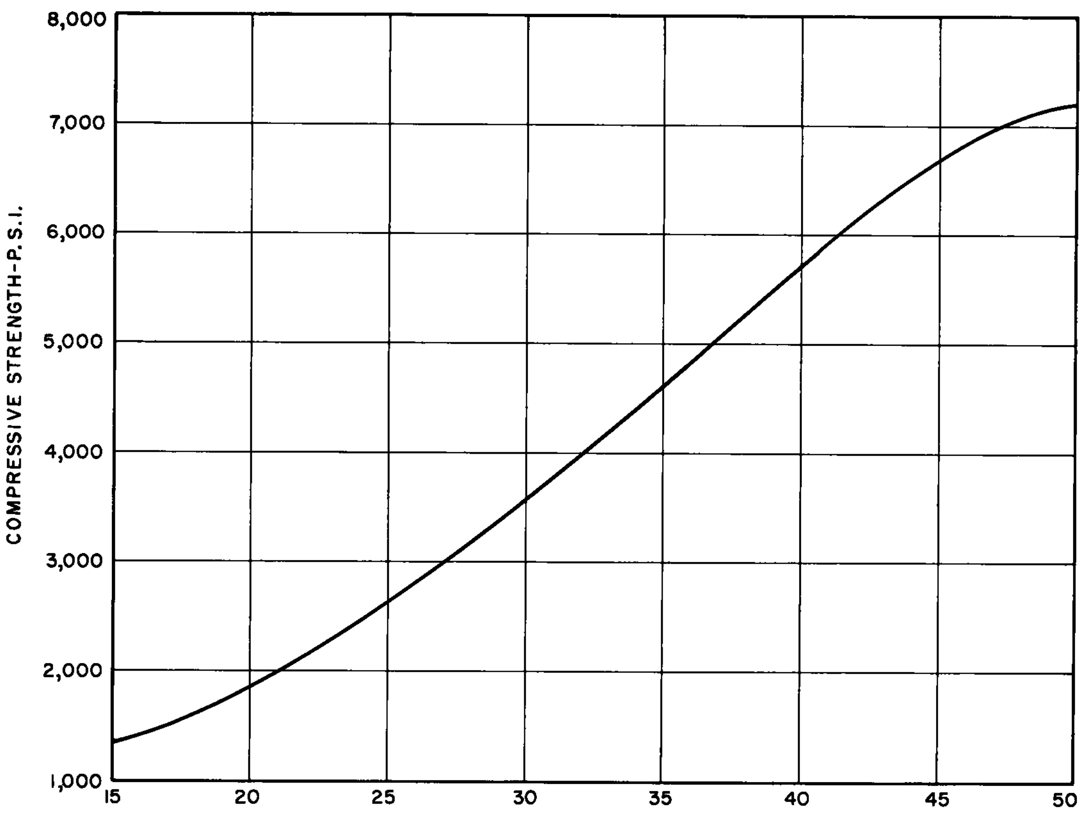

Figure 2. Relation between compressive strength and rebound readings as determined by manufacturer.

These factors vary with the angle from the horizontal and the amount of the rebound. For example with a rebound reading of 30, the corrections applied are as follows:

Angle from horizontal (degrees upward)	Correction factor
90	-6
60	-5
30	-3
0	0
(downward)	
30	+2
60	+3
90	+4

As the rebound reading increased, the correction factor decreased.

LABORATORY TESTS

To determine the value of the Swiss hammer as a tool for use in estimating the strength of concrete used in highway construction three series of laboratory tests were made as well as numerous associated studies.

Series 1

The specimens used in this series were 6- by 12-in. cylinders submitted from var-

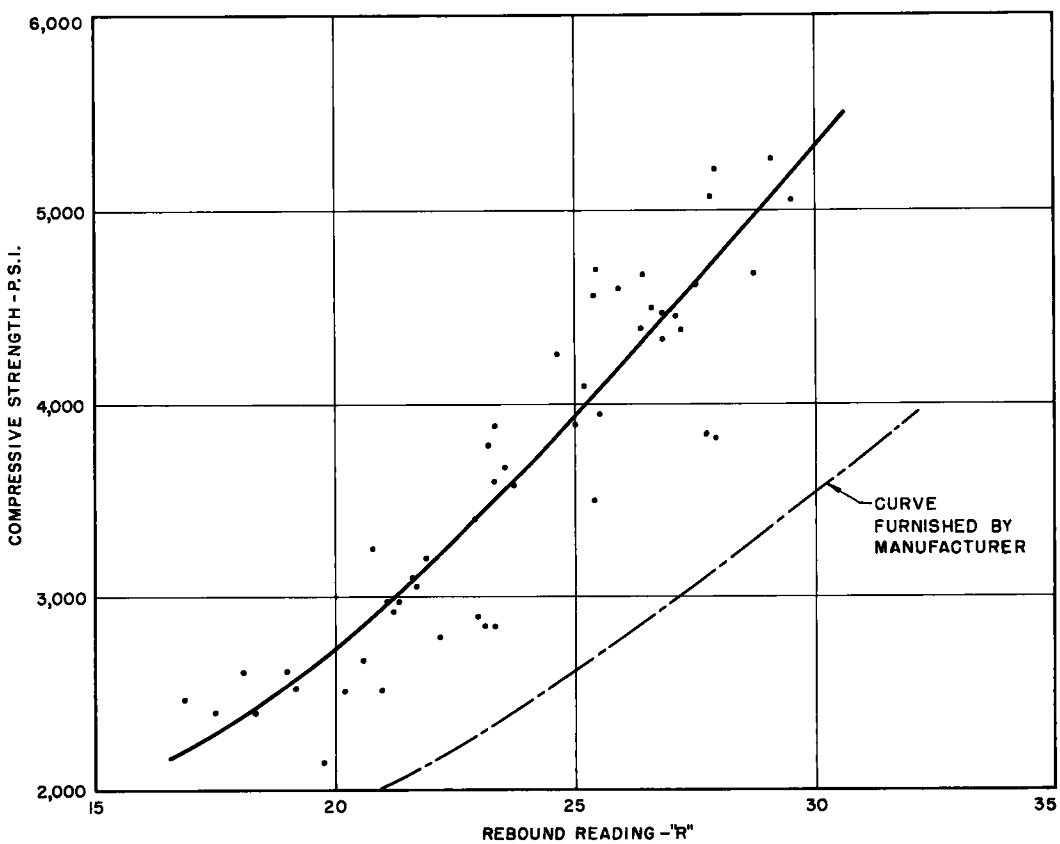

Figure 3. Relation between compressive strength and rebound readings on 6x12-in. concrete cylinders--series 1.

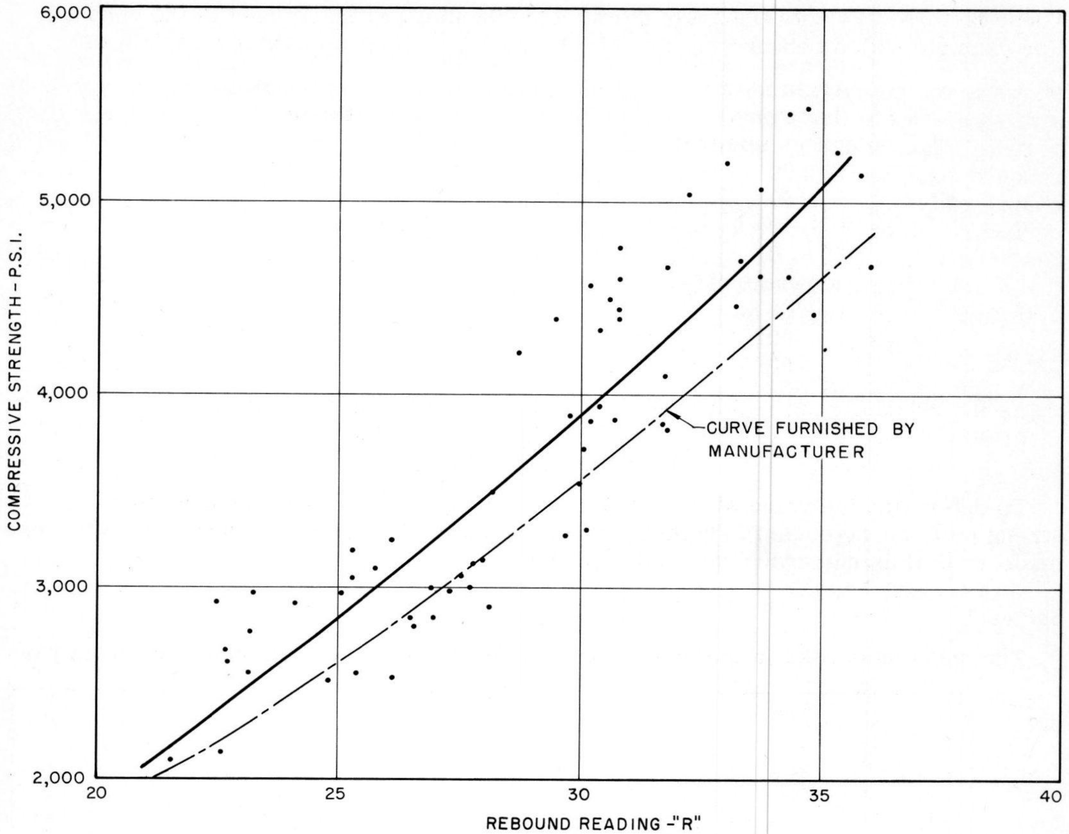

Figure 4. Relation between compressive strength and rebound readings on 6x12-in. concrete cylinders--series 2.

Figure 5. The Swiss hammer as used in the laboratory in series 2.

ious field projects. The concretes covered a wide variation in mixes and materials. All tests were made on specimens in a moist condition. Rebound readings were taken on the sides of the cylinders just prior to tests for compressive strength. The cylinders were tested in a vertical position with the side of the cylinder resting against an 8- by 12-in. machined steel plate which in turn was supported by a wall of the laboratory. The hammer was held horizontal and perpendicular to the side of the cylinder. Usually 12 readings were taken on the side of each cylinder, three readings on each quadrant, one reading 1 in. from the top, one at the center, and the other 1 in. from the bottom. Immediately after the rebound readings were taken, the cylinders were tested for compressive strength in a 400,000-lb hydraulic testing machine.

The results of the impact hammer and compressive strength tests on these cylinders are shown in Figure 3. The curve represents the average relation between the rebound readings and the actual compressive strength. The strengths as shown by this curve are approximately 50 percent higher than the compressive strengths corresponding to the same rebound readings as shown in the curve furnished with the hammer (Fig. 2). For example, the compressive strength for a rebound reading of 20 as determined from the curve for this series of tests would be 2,750 psi as compared to 1,850 from the curve in Figure 2. For a rebound reading of 30, the compressive strength from Figure 3 would be 5,300 psi as compared to only 3,600 psi from Figure 2 for the same rebound reading.

The results of these tests indicated that the concrete cylinders held in the manner described did not have enough mass or rigidity to give reliable rebound readings and that some of the energy from the blow may have been absorbed by movement of the cylinders.

Series 2

A second series of tests was made on another group of 6- by 12-in. cylinders sub-

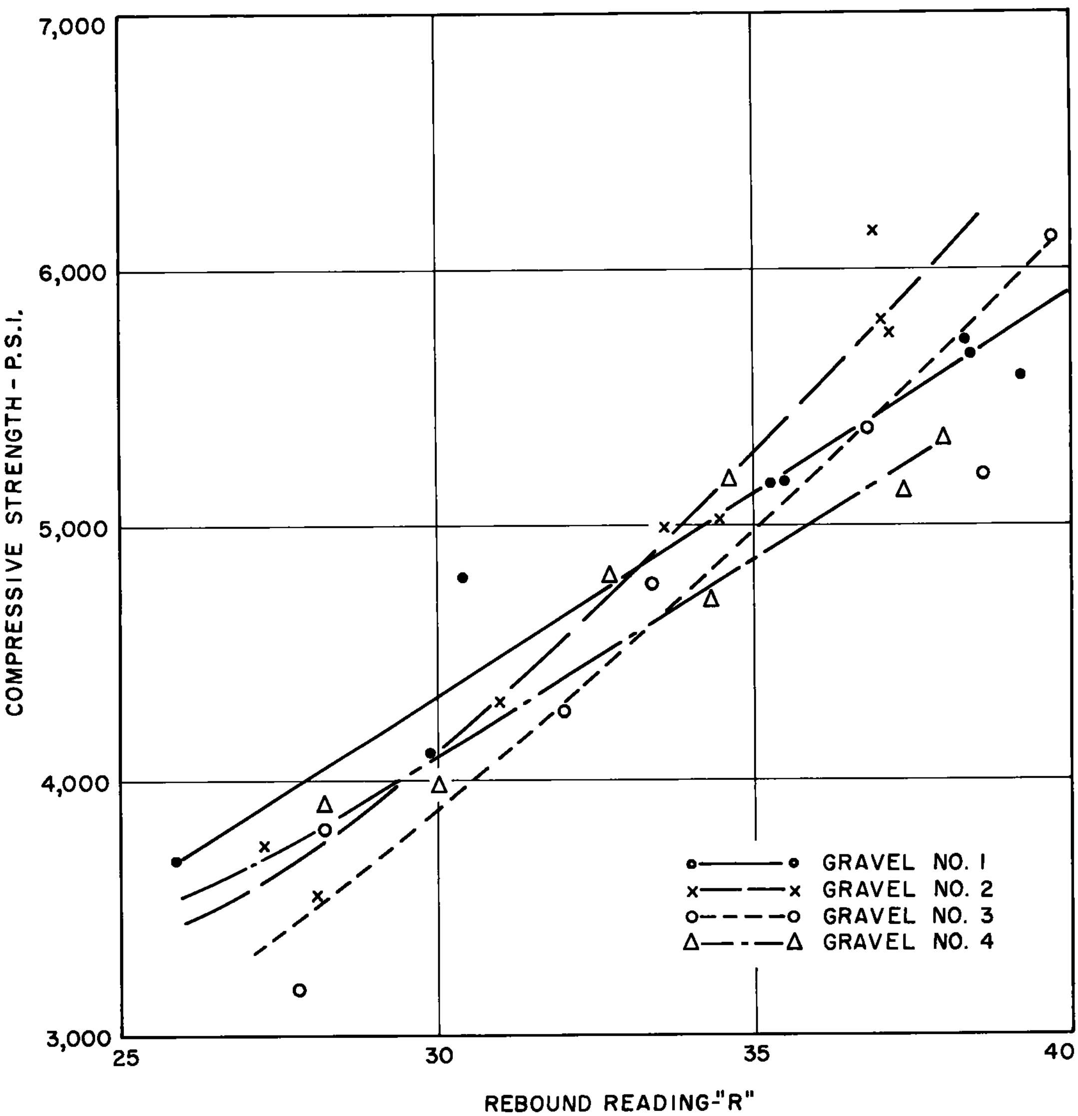

Figure 6. Effect of gravel from different sources on rebound readings of 6x12-in. concrete cylinders--series 3A.

mitted from projects under construction. To hold the cylinder firmly while the reading were taken with the hammer, each cylinder was put in the compression testing machine and a small load applied. A load of approximately 300 psi was found sufficient. Tests showed that greater loads had no effect on the rebound readings. After the rebound readings were taken the cylinders were tested for compressive strength.

The results of these tests are shown in Figure 4. The compressive strength for any rebound reading as determined from the curve in Figure 4 is approximately 12 percent higher than the compressive strength based on the curve submitted by the manufacturer of the hammer. Figure 5 shows the Swiss hammer being used in the laboratory in series 2.

Series 3

In series 3, the effect of type of coarse aggregate on the rebound-compressive strength relation was studied. All of the concrete cylinders were made in the laboratory and were tested as described in series 2. In the first part of the series (series 3A) four different gravels were used in making the cylinders tested. The results of the tests on these specimens are shown in Figure 6. The spread in compressive strength between the curves representing the concrete prepared with the four gravel coarse aggregates varied from 250 to 600 psi.

In the second part of this series comparisons were made between concrete prepared with a siliceous gravel or crushed limestone. The curves showing the average relation between rebound readings and compressive strength for concrete containing these aggregates are shown in Figure 7. The curve for the concrete prepared with crushed stone aggregate indicated about 25 percent greater strength for a given rebound reading than for the concrete prepared with gravel.

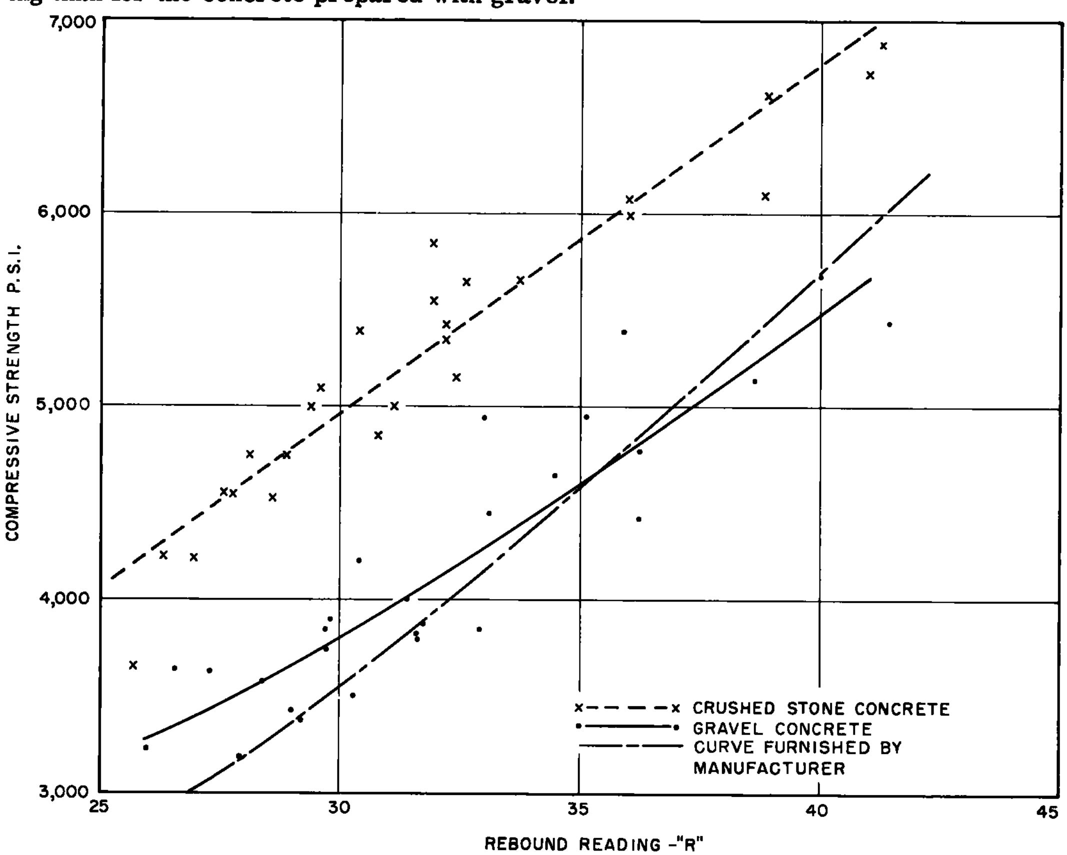

Figure 7. Effect of type of coarse aggregate on rebound readings of 6x12-in. concrete cylinders--series 3B.

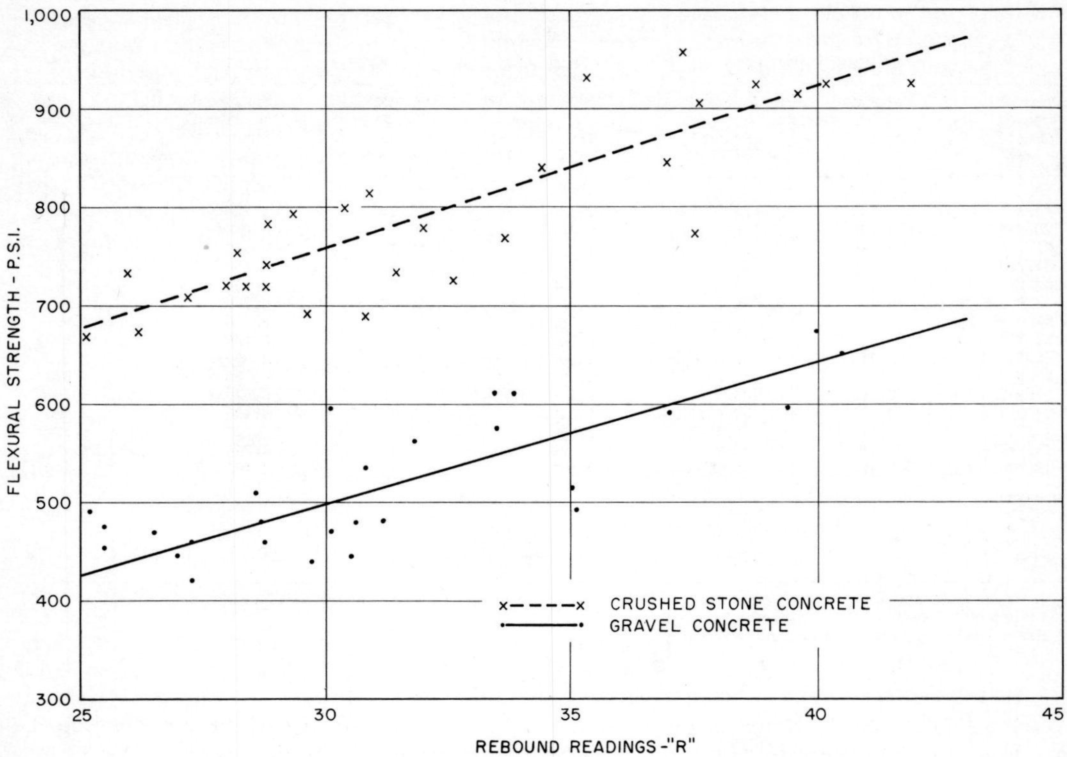

Figure 8. Relation between flexural strength and rebound readings on 6x6x21-in. concrete beams as influenced by type of aggregate.

The curve for the relation between rebound readings and compressive strength for the gravel concrete corresponds very closely to that furnished by the manufacturer and shown in Figure 2.

These tests show that type of coarse aggregate is a governing factor in the rebound-compressive strength relation. This means, that the Swiss hammer is of most value in making comparative tests on concrete prepared with the same coarse aggregate. If comparisons between concretes prepared with different aggregates are desired, curves for the rebound-compressive strength relation for each aggregate should be obtained.

ASSOCIATED TESTS

Rebound readings were taken on the top and bottom of cylinders as cast prior to capping as well as on the sides. The readings were taken as described in series 1. There was considerable difference in the readings on the top, bottom, and sides of the same cylinder. The results are shown in Table 1. This table also shows the estimated compressive strengths which correspond to these readings, taken from the curve furnished by the manufacturer (Fig. 2), and the actual compressive strength of the concrete.

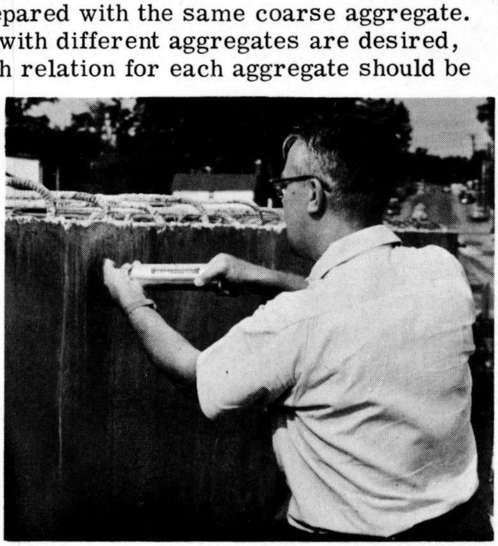

Figure 9. Swiss hammer being used in the field.

The average of the readings taken on the bottoms of all of the cylinders was 23 percent higher than the average of the

TABLE 1

REBOUND READINGS ON TOP, BOTTOM, AND SIDE OF 6- BY 12-IN. CYLINDERS

Average Rebound Reading on Side[1]	Estimated Compressive Strength[2] (psi)	Average Rebound Reading on Top[1]	Estimated Compressive Strength[2] (psi)	Average Rebound Reading on Bottom[1]	Estimated Compressive Strength[2] (psi)	Actual Compressive Strength[3] (psi)
18 3	1,640	20.8	1,960	24 2	2,480	2,410
19.2	1,750	22.2	2,160	23.8	2,420	3,210
20.8	1,960	21.8	2,100	27.4	3,050	3,250
21.3	2,040	21.6	2,050	29.4	3,420	2,980
21.3	2,040	22.0	2,130	25.4	2,690	3,290
22.2	2,160	22.0	2,130	29.2	3,380	2,800
22.8	2,250	24.3	2,500	26.9	2,960	3,080
23.0	2,280	23.5	2,360	27.4	3,050	2,950
23.5	2,360	24.9	2,600	28.0	3,160	3,270
25.6	2,730	26.0	2,800	30.6	3,650	3,900
26.9	2,960	31.0	3,730	34.8	4,560	3,870
26.9	2,960	26.5	2,890	30.2	3,570	4,180
27.9	3,140	30.0	3,530	32.8	4,120	3,800
28.0	3,160	27.0	2,980	33.8	4,340	4,790
28.7	3,290	29.2	3,380	33.8	4,340	4,700
29.4	3,420	32.2	3,980	35.8	4,780	4,200
Average:						
24.1	2,510	25.3	2,700	29.6	3,500	3,540
Ratio to Reading on Side:						
100%		105%		123%		

[1] Each rebound value on side is average of 12 readings, values on top and bottom are average of 5 readings.
[2] Estimated values from curve shown in Figure 2.
[3] Results of strength tests on cylinders.

readings taken on the sides of the cylinders whereas the average of the readings on the top was only 5 percent higher. An explanation for some of this difference could be a difference between the quality of the concrete in the top and bottom of the cylinder. It is also possible that the cylinders were in a more rigid position when the readings were taken on the top and bottom than they were when readings were taken on the side.

Rebound readings were taken on a few cylinders in a dry condition and then on the same cylinders after immersion in water for 24 hours. The readings on the cylinders in a dry condition in all cases were larger than those in a moist condition. The results of these tests are shown in Table 2. The estimated compressive strengths from the manufacturer's curve are also shown in this table.

A study was made to determine if the rebound readings increased with age as the compressive strength increased. Of 12 concrete cylinders made from the same batch of concrete, 4 were tested at an age of 5 days, 4 at 10 days and 4 at 20 days. The results of these tests are shown in Table 3. The estimated compressive strength and the actual compressive strength of this concrete are also shown. The increase in rebound values was approximately proportional to the increase in the actual compressive strength.

Studies were made of the uniformity of the concrete in 6- by 6- by 21-in. beams, and rebound readings were made on the sides, top, bottom, and ends of 29 beams. Five tests were made on the ends of each beam and 10 tests on each of the other faces. Average values for the entire groups of beams were as follows:

Face of Beam	Rebound Value
Side	25.5
Top	23.6
Bottom	26.1
End	28.2

It is believed that these values correctly reflect slight differences between the quality of the concrete in different faces of the beams. With consideration given to the tendency of concrete to "bleed," the bottom of a beam should be more dense and have a higher rebound reading than the sides or the top. The rebound tests at the ends of the beams were made on a concrete specimen with a depth of 21 in., 3½ times the depth of concrete at any other point, and this may be the reason for the greater readings.

A study was also made of the relationship between "R" readings taken on the ends of 6- by 6- by 21-in. beams and readings taken on the sides of 6- by 12-in. cylinders. A beam and a corresponding cylinder were made from the same batch of concrete. Half of the total number of specimens contained gravel coarse aggregate and the other half contained crushed stone. The readings were taken on the beams held against the wall whereas the readings on the cylinders were taken with them in the testing machine with a small load as described under series 2. The beams were tested for flexural strength after the rebound readings were made.

The rebound values are shown in Table 4 for both beams and cylinders together with the actual compressive strength of the cylinders and the flexural strengths of the beams. The average of all of the rebound readings on the cylinders for gravel concrete was

TABLE 2

REBOUND READINGS ON DRY CYLINDERS AND ON CYLINDERS AFTER 24 HOURS IMMERSION IN WATER

Average Rebound Reading, Dry	Estimated Compressive Strength[1] (psi)	Average Rebound Reading, Wet	Estimated Compressive Strength[1] (psi)
26.8	2,940	25.0	2,620
27.7	3,100	27.3	3,040
27.8	3,120	26.9	2,960
28.3	3,220	26.0	2,800
28.7	3,280	26.9	2,960
29.4	3,420	26.3	2,860
34.7	4,540	30.5	3,630
35.1	4,620	32.8	4,120
35.8	4,780	32.5	4,050
37.6	5,170	34.4	4,470
Average: 31.2	3,820	28.9	3,350

Each value is average of 12 readings.

Approximate age of cylinders dry, was 14 days. Specimens were then immersed in water 24 hours.

[1]Estimated values from curve shown in Figure 2.

TABLE 3

REBOUND READINGS ON CYLINDERS TESTED AT VARIOUS AGES

Age at Test (Days)	Average Rebound Reading[1]	Estimated Compressive Strength[2] (psi)	Actual Compressive Strength[3] (psi)
5	21.9	2,110	3,410
10	25.0	2,620	3,920
20	28.3	3,220	4,800

[1] Each rebound reading is average of 12 readings on each of four cylinders.
[2] Estimated values from curve shown in Figure 2.
[3] Results of strenth tests on cylinders.

TABLE 4

RELATION BETWEEN REBOUND READINGS ON CYLINDERS AND BEAMS

Gravel Concrete				Stone Concrete			
Rebound Reading		Actual	M. of R.	Rebound Reading		Actual	M. of R.
Side of Cylinders[1]	End of Beams[1]	Comp. Str of Cyl. (psi)	of Beams (psi)	Side of Cylinders[1]	End of Beams[1]	Comp. Str. of Cyl. (psi)	of Beams (psi)
24 6	25.5	2,920	475	24.4	26 2	4,020	675
25.3	23.5	2,380	450	25 7	25.1	3,660	670
26.0	25.5	3,220	455	26.3	27 2	4,220	710
26.6	27.0	3,640	445	27 1	26 0	4,230	735
26.8	25.2	2,450	490	27.6	28 0	4,560	720
27.3	27.3	3,630	460	27.8	28 8	4,550	740
27.9	28.6	3,190	510	28.1	28.8	4,760	720
28.4	26.5	3,570	470	28 6	28.8	4,520	785
29.0	27.3	3,420	420	28 9	28 2	4,740	755
29.2	28.7	3,380	480	29 4	29 6	4,990	690
29.7	28.8	3,740	460	29.6	28 4	5,090	720
29.7	30.7	3,840	470	30.4	32 6	5,400	725
29.8	29.7	3,900	440	30 8	30 4	4,850	800
30.3	31.1	3,490	480	31 1	29 3	4,990	795
30.4	30.5	4,200	445	31 9	31.4	5,540	735
31.4	30.6	3,990	480	31 9	33.6	5,840	770
31.6	30.6	3,820	480	32.2	32.0	5,360	780
31.6	31.8	3,790	560	32.2	34.4	5,430	840
31.7	30.8	3,880	535	32.4	31.9	5,140	815
32 9	30.1	3,860	595	32 6	31.8	5,650	690
33.0	35.0	4,950	515	33.7	35.3	5,660	930
33.1	33.4	4,450	610	36.0	37.3	6,010	955
34.5	33.5	4,640	575	36 0	37 6	6,080	905
35.2	35.1	4,960	490	38 8	37 5	6,100	775
35.9	37.0	5,400	590	38.8	38.8	6,330	925
36.2	40.0	4,780	675	39 1	36.9	6,620	845
36.2	33.8	4,420	610	40 9	40.2	6,740	925
38 6	39.4	5,140	595	41 2	39.6	6,890	915
41.4	40.5	5,440	650	43 7	41 9	7,090	925
Average:							
31.2	30.9	3,950	515	32 3	32 3	5,350	790

[1] Each value is average of 10 or 12 readings.

TABLE 5

FIELD TESTS USING SWISS HAMMER—"R" READINGS ON BEAMS FOR POST-TENSIONED BRIDGE

Beam 5 Age 8 Days		Beam 5 Age 16 Days		Beam 2 Age 35 Days		Beam 4 Age 21 Days		Beam 4[2] Age 29 Days	
35	33	44	33	31	36	38	38	41	39
36	35	47[1]	36	39	36	38	43	42	37
39	36	44	34	40	36	38	39	40	38
37	31	43	39	41	36	36	34	39	43
37	51[1]	38	37	38	35	37	40	40	43
44[1]	37	37	42	37	45[1]	35	38	38	47
34	30	44	34	39	34	40	47[1]	40	37
41	30	36	38	38	34	35	38	38	37
36	38	37	41	40	34	40	38	38	44
34	33	36	34	37	37	36	48[1]	41	45
33	35	35	34	48[1]	38	38	35	39	38
34	37	38	37	41	37	28[1]	42	40	39
35	31	41	38	36		40		41	
33	36	37	36	36		38		37	
39	40	42	39	40		38		42	
Average:									
35.2		38.1		37.0		38.0		40 1	
Estimated comp. str. (psi)									
4,640		5,280		5,040		5,260		5,720	
Actual comp. str. of control cyl. (psi)									
3,700		4,100		4,600		4,600		4,700	
Ratio of est. str. to control spec.									
125%		129%		110%		114%		122%	

[1] Readings not included in average.
[2] Readings taken after beam had been stressed.

31.2, as compared to 30.9 for the beams made with gravel concrete. The average rebound reading was 32.3 for both cylinders and beams made from stone concrete.

There appears to be a definite relation between rebound readings taken on the ends of the beams and the flexural strength for this series of tests. This relation is shown in Figure 8.

The Swiss hammer could be used to estimate the flexural strength of paving concrete. Readings taken on control beams would indicate increases in flexural strength with age. From these readings, the age at which flexural strength tests should be made to meet specification requirements may be determined. This would reduce the number of control beams necessary.

FIELD TESTS

The Swiss hammer was used to estimate the strength of several concrete structures in the field. In one case, tests were made on three beam sections cast for post tensioning for use in a concrete bridge. Readings were taken on all of the beams prior to stressing and on one beam after stressing.

The concrete used in the beams was made with gravel aggregate. Each beam was approximately 3 ft wide by 3 ft deep by 75 ft long. Rebound readings were taken along the length of the beam at intervals of approximately 3 ft from one end to the center. Three readings were taken at each location, one 5 to 10 in. from the top, one at the center and the other about 10 in. from the bottom. The beams were cured with wet burlap on the job, and were in a moist condition when readings were taken. Figure 9 shows the hammer being used on these beams.

Concrete cylinders for control were cast at the same time the beams were made. These were stored on the job for 5 days then taken to a laboratory for moist storage and testing.

The rebound readings on the beams, the estimated compressive strength of the concrete in each beam as obtained using the curve furnished by the manufacturer (Fig. 2), and the actual strengths of the test cylinders are shown in Table 5. The average estimated compressive strengths of the beams from the rebound readings was approximately 20 percent greater than the average compressive strength of the test cylinders. Differences in curing and testing procedures or in materials used may account for this variation.

The individual rebound readings show very little variation from the average. Only a few of the readings were not included in the average. These were excluded because the hammer had probably been held against a piece of exposed aggregate or where there was a thin layer of mortar over a void.

The Swiss hammer was also used on the piers of a bridge which were about 2½ years old. The average compressive strength at 28 days of control test cylinders was reported as 4,500 psi. The average estimated compressive strength of this concrete at 2½ years as determined from the rebound readings given in Table 6 and use of the curve in Figure 2 was 5,660 psi.

The reconstruction of a 38 year old bridge offered an excellent opportunity to try the Swiss hammer on concrete in place and on specimens secured for tests in the laboratory. This concrete was in good condition. Swiss hammer readings were taken at four locations on the vertical face of the hand rail of the bridge. The average of all rebound readings was 40.9, and reference to Figure 2 showed this value to indicate a compressive strength of 5,850 psi.

Three prisms approximately 6 in. square and 9 in. high were sawed from the hand rail at about the same location where the rebound readings were taken. After these specimens had been prepared for tests for compressive strength, they were placed under a small load in the testing machine. Rebound readings taken of these specimens had an average value of 41.2, corresponding to an estimated compressive strength of 5,980 psi. The actual compressive strength of the three prisms corrected for H/D averaged 5,470 psi.

In two of the three trials of the Swiss hammer on concrete structures, direct com-

TABLE 6

FIELD TESTS USING SWISS HAMMER—"R" READINGS ON BRIDGE PIER[1]

West Pier	Center Pier East Side	Center Pier West Side	East Pier
41	42	37	39
41	42	31	37
42	48	43	35
42	43	37	35
42	40	38	39
41	40	38	40
42	38	43	40
44	44	50	40
39	48	42	34
43	32	34	36
38	43	34	38
40	36	41	32
42	38	42	38
41	36	39	36
46	41	40	46
41	41	40	38
Average:			
41.6	40.8	39.3	37.7
Estimated comp. str. in psi			
6,030	5,870	5,550	4,200

[1] Concrete approximately 2½ years old. Compressive strength of control cylinders at 28 days, 4,500 psi

parisons could be made between the actual compressive strength of test specimens representing the concrete and the compressive strength as determined from the rebound reading and use of the curve given in Figure 2. In both cases, the rebound reading indicated a strength 10 to 20 percent higher than was obtained by test of the specimens. It is apparent that the curve given in Figure 2 should be used with reservations. For the best determinations, a curve should be prepared showing the relation between strength and rebound reading for concrete of the same type and composition as that which will be inspected.

Considerable wear was found on the face of the striking rod of the Swiss hammer after making the tests described in this report. Check tests made in the laboratory showed little effect on the indicated reading from this wear. However, for extended use it would be desirable to have a harder wearing surface on the face of the hammer.

Factors Affecting Results of Tests Using Swiss Hammer

In using the Swiss hammer, there are a number of factors which affect the readings, and these should be considered in interpreting the results. Some of these are:

1. Condition of the surface of the concrete. Readings taken on a polished surface are high, whereas readings taken on a rough surface (such as a broomed surface) are low.
2. Moisture condition on the concrete. Concrete in a moist condition gives a lower reading than concrete in a dry condition.
3. Type of coarse aggregate. The type of coarse aggregate used and possibly the composition of the concrete affect the amount of rebound.

The Value of the Swiss Hammer

The Swiss hammer provides a quick and inexpensive method for checking the uniformity and estimating the strength of hardened concrete. It is not intended as a substitute for control test cylinders; nor is it intended to give an accurate measure of the compressive strength of the concrete. It is valuable for use in the field for "trouble shooting," to determine whether test cores are needed and where they should be drilled. It may be used to determine the rate of increase in strength of concrete and may also be used to determine when forms can be removed or loads applied. It may also be used to estimate the extent of damage done to structures by freezing or by fire, and the quality of the concrete in old structures.

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Discussion

R. E. PHILLEO, Department of the Army, Civil Works Engineering Division, Concrete Branch—The paper "Study of the Use of the Swiss Hammer for Estimating Compressive Strength of Hardened Concrete" by W. E. Grieb, which was sponsored by Committee B-3, has been reviewed by a member of the committee. His generally favorable review contains the following specific comments.

Are the curves of Figure 6 least square curves? One would get a better idea of the true differences represented in Figure 6 if the data were analyzed more fully. For example, an analysis of variance would be in order to show if the means for the four gravels were significantly different. In addition, one could find out if there was justification for drawing four separate lines on Figure 6. It would be of interest to know if the 24-hr immersion mentioned in connection with Table 2 had any effect on the actual compressive strenth. Also, it has been suggested that the proportional increase shown in Table 3 might not continue for conditions at later ages. The effect of carbonation, for example, could cause a change in the relationship.

A word of caution should be mentioned, because if the surface condition of the concrete is poorer than the interior, hammer readings could be misleading.

W. E. GRIEB, Closure—The purpose of the four curves in Figure 6 is to show the small range in the rebound-compressive strength relationship of four different gravels. The four gravels were from different locations; however, three of them had similar mineral compositions. The data for each curve were limited to seven cylinders.

The rebound readings shown in Table 2 were taken on the cylinders prior to capping and no compressive strength tests were made on those cylinders at the time rebound readings were taken. However, compressive strength tests made in the laboratory on dry cylinders and on similar cylinders which were immersed in water for 24 hr usually showed higher compressive strength for the dry cylinders.

Reference was made to the method of supporting the beam while the rebound readings were taken. The bearing areas both on the table and against the wall and the mass of concrete was much larger for the beams than it was for the cylinders. The beams appeared to have enough rigidity to give reliable rebound readings, but the cylinders did not.

It is agreed that some types of disintegration naturally progress inwardly and the rebound readings on that concrete may be in error. However, the instrument under discussion is only intended to estimate the compressive strength.

Rapid Freezing and Thawing Test for Aggregate

R. H. BRINK, Division of Physical Research, Bureau of Public Roads

This report describes a freezing and thawing procedure which requires about the same test period as the sulfate soundness test. The accelerated action of this test resulted from the use of a water-alcohol solution as the freezing medium rather than water. A home-type freezer was found to be suitable for conducting such a freezing and thawing procedure. The results of freezing and thawing 27 different materials by the water-alcohol method showed that 16 cycles of the method are equal in severity to 5 cycles of the sulfate soundness tests and are much more severe than 50 cycles of freezing and thawing in water. Freezing and thawing in the water-alcohol solution, however, resulted in a different order of soundness being indicated for the various materials than when water was used. The results of the sulfate soundness test did not correlate closely with any of the freezing and thawing procedures.

●THE RESISTANCE of aggregates to natural freezing and thawing is a property which is difficult to evaluate properly in the laboratory. The test most frequently applied to aggregates for this purpose is an accelerated soundness test in which the crystallization of sodium or magnesium sulfate is used to simulate the action of ice formation in aggregate pore spaces. Although the results of this test show a general correlation with the performance of aggregates in service, numerous instances of disagreement with known service records have resulted in considerable loss of confidence in the method. The sulfate soundness test, however, continues to be used extensively because of the short test period and the inexpensive equipment required as compared to most laboratory freezing and thawing procedures.

Further justification for using the sulfate soundness test is frequently based on the fact that laboratory freezing and thawing, per se, does not guarantee a correct evaluation of the durability of an aggregate. Freezing and thawing in the laboratory is generally designed to be more severe than that occurring in nature in order to obtain results in a reasonable length of time. The greater severity of laboratory freezing and thawing not only hastens disintegration, but for some aggregates may cause disintegration which would not occur under most service conditions. At the present time there is no single freezing and thawing procedure which is generally recognized as being suitable for evaluating all aggregates for use under all conditions of exposure. The current AASHO method for freezing and thawing of aggregates, T 103, is specified by only three of the seven state highway departments which include such a test for aggregates in their standard specifications. The remaining four states have developed other procedures which presumably provide more satisfactory results for the aggregates in their particular areas.

PURPOSE OF STUDY

Although there is often difficulty in interpreting the results of a freezing and thawing test, such results usually command greater confidence than those obtained by the sulfate soundness test. Some specifications, for example, permit the use of an aggregate failing the sulfate soundness test provided it passes a freezing and thawing test. In such instances, it is evident that the sulfate soundness test would not be specified at all if a freezing and thawing procedure was available which could be performed as easily and quickly and did not require expensive refrigeration equipment. The primary purpose of this investigation was to study the feasibility of using a procedure and equipment which meet these requirements.

The Standard Specifications of the Iowa State Highway Commission contain a requirement regarding the soundness of concrete aggregates which is based on 16 cycles of freezing and thawing in water containing 0. 5 percent alcohol. In most other procedures

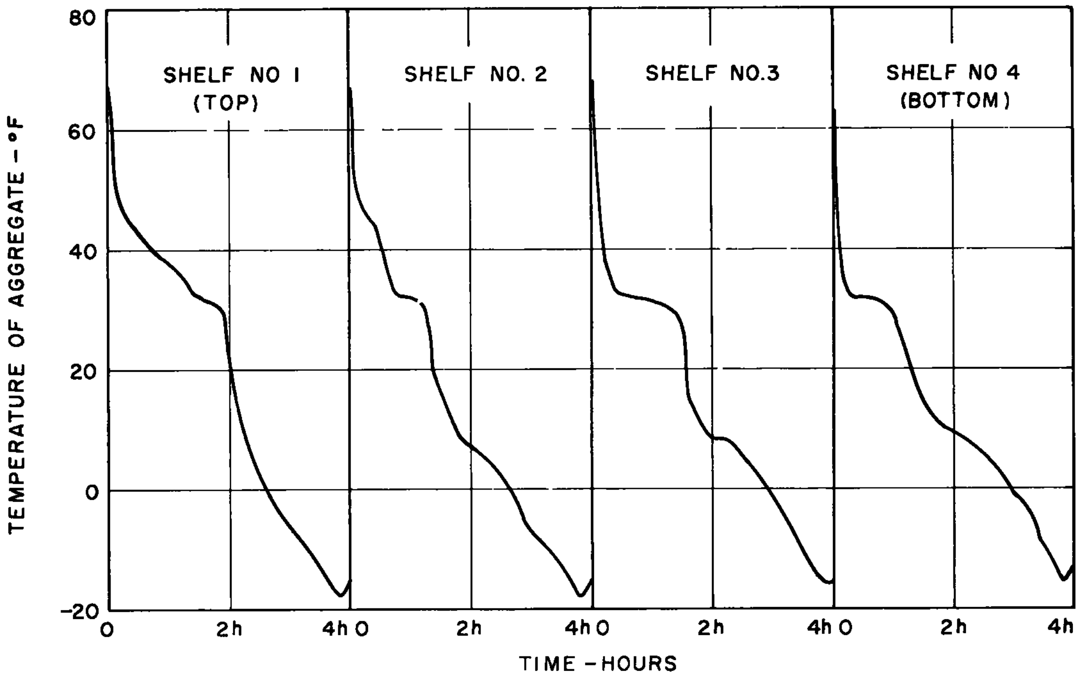

Figure 1. Cooling rate of 25-cu ft home freezer. Freezer loaded with 24 pans containing 1,000 gm samples in $\frac{1}{4}$ in. of water.

TABLE 1

ABSORPTION AND SULFATE SOUNDNESS LOSS OF AGGREGATES

BPR Lab. No.	Type of Rock	Absorption: 24 Hours (%)	Absorption: Vacuum Saturated for 15 min (%)	Loss of 1- to ¾-in. Material After 5 Cycles of Sodium Sulfate Soundness Test: Through ¾-in. sieve (%)	Loss of 1- to ¾-in. Material After 5 Cycles of Sodium Sulfate Soundness Test: Through ⅜-in. sieve (%)
70124	Limestone	0.6	0.4	4.7	1.3
78266	do	2.4	2.6	36 1	12.4
79826	Sandstone	2.2	2.6	33.7	26.6
81967	do	5.9	8.3	90.1	74.5
83888	Peridotite	0.6	0.5	13.7	5.2
89805	Limestone	2.5	3.9	28.9	14.0
89812	do	0.9	1 1	13.2	4.2
89813	do	1.3	1 6	17.9	6.4
89918	do	1.7	2.0	19.1	11.8
89889	Dunite	0.3	0.2	1.7	0.3
89892	Limestone	1.9	2.4	16.5	4.6
89988	do	0.9	0.9	49.0	20.4
Stock	Dolomite	0.2	0.3	4.1	0.5
94544	Limestone	0.5	0.4	11.5	6.1
N-74	Light Limestone	7.4	9.2	66.8	28.9
N-74	Dark Limestone	5.7	6.2	71.5	38.4
N-92	Limestone	1.8	2.9	2.5	1.0
N-127	Serpentine Diopside Garnet	1.3	1.1	4.9	1.4
N-162	Dolomite	3.3	3.6	11.1	8.5
N-163	do	3.7	4.0	25.6	11.1
N-164	Limestone	3.8	4.1	25.8	8.8
N-165	do	1.3	1.1	44.1	9.9
N-166	do	2.2	1.8	55.2	20.5
N-167	do	0.7	0.7	15.5	3.9
N-168	do	0.4	0.4	2.1	1.8
N-169	Dolomite	0.9	1.0	9.3	1.4
N-419	Gneiss Granite Schist	0.4	0.5	1.8	0.6

TABLE 2

FREEZING AND THAWING OF AGGREGATES BY METHOD A[1]
(Samples arranged in order of increasing loss on the 3/8- inch sieve after 50 cycles)

BPR No.	Type of Rock	Loss of 1-in. to 3/4-in. Material (%) 3/4-in. Sieve 16 Cycles	3/4-in. Sieve 25 Cycles	3/4-in. Sieve 50 Cycles	3/8-in. Sieve 16 Cycles	3/8-in. Sieve 25 Cycles	3/8-in. Sieve 50 Cycles	No. 8 Sieve 16 Cycles	No. 8 Sieve 25 Cycles	No. 8 Sieve 50 Cycles
Stock	Dolomite	1.8	5.0	5.0	0.0	0.0	0.1	0.0	0.0	0.1
N-419	Gneiss Schist Granite	1.0	1.0	1.6	0.1	0.2	0.2	0.1	0.2	0.2
N-169	Dolomite	2.9	2.9	2.9	0.1	0.3	0.5	0.1	0.2	0.4
89812	Limestone	2.7	5.4	5.5	0.0	0.3	0.5	0.0	0.2	0.3
89892	do	0.6	1.5	3.0	0.1	0.3	0.6	0.0	0.3	0.5
N-92	do	2.8	5.6	6.8	0.0	0.4	0.6	0.0	0.1	0.3
N-168	do	0.2	0.4	1.3	0.2	0.4	0.6	0.2	0.4	0.6
83888	Peridotite	2.3	2.3	2.7	0.1	0.4	0.7	0.0	0.4	0.7
70124	Limestone	5.0	7.6	9.3	0.0	0.4	0.8	0.0	0.2	0.4
N-127	Serpentine Diopside Garnet	3.1	4.3	6.7	0.1	0.5	0.9	0.0	0.3	0.5
N-163	Dolomite	1.2	5.5	5.6	0.2	0.6	1.0	0.0	0.3	0.5
89889	Dunite	5.3	6.5	9.0	0.4	0.7	1.0	0.3	0.4	0.7
N-167	Limestone	0.4	0.4	1.2	0.1	0.4	1.2	0.0	0.1	0.3
N-165	do	2.1	4.3	7.2	0.2	0.8	1.7	0.0	0.3	0.7
79826	Sandstone	3.2	3.6	3.6	0.7	1.3	1.7	0.5	1.1	1.5
89805	Limestone	3.9	3.9	7.3	0.3	1.0	1.8	0.2	0.6	1.0
N-162	Dolomite	0.4	2.7	7.0	0.1	0.7	1.9	0.0	0.4	0.8
89813	Limestone	2.2	5.8	10.2	0.6	1.5	2.7	0.1	0.7	1.1
78266	do	6.2	11.9	22.9	0.3	1.2	3.1	0.0	0.6	1.0
94544	do	1.9	3.1	12.2	0.5	1.0	3.2	0.0	0.5	1.8
N-164	do	5.1	10.6	21.7	0.6	2.3	4.3	0.0	1.0	1.6
89988	do	1.5	3.9	20.6	0.5	1.5	6.9	0.1	1.0	3.7
N-166	do	1.2	4.2	11.2	0.2	1.3	10.8	0.0	0.7	1.2
89918	do	7.2	13.5	27.4	2.8	5.6	12.4	0.9	2.1	4.4
81967	Sandstone	5.7	16.9	38.4	2.0	9.0	18.8	1.6	7.3	18.5
N-74	Light Limestone	30.8	43.5	65.7	13.1	21.5	36.9	6.3	9.3	13.7
N-74	Dark Limestone	45.8	76.2	89.5	15.7	41.0	67.9	3.8	11 4	22.7

[1] Samples were vacuum saturated before test for 15 minutes, frozen in 1/4 in. of water at a temperature between -10 to 20 F, and thawed in water at 70±5 F.

where plain water is used, at least 50 cycles of freezing and thawing are considered necessary to permit positive identification of sound materials. A test requiring only 16 cycles and conducted with freezing equipment capable of obtaining at least 3 cycles per day, requires about the same testing time as that necessary to perform 5 cycles of the sulfate soundness test. In this study, freezing equipment capable of completing 3 cycles per day was used to test 27 different materials by the Iowa alcohol-water method and two other freezing and thawing procedures, thus providing comparative data by which the relative severity of the three methods can be determined. The accelerated soundness test using sodium sulfate was also performed on these same materials.

REFRIGERATION EQUIPMENT

The refrigeration equipment used for these tests was a 25-cu ft vertical-type home freezer. The freezer had four shelves, each containing cooling coils, and readily accessible through a door at the front of the unit. Temperature was controlled by a thermostat having seven settings. The temperatures corresponding to these settings ranged from a high of 10 F to a low of about -15 F. Using the coldest setting, the time required to cool samples of aggregate from 70 F to -15 F is shown in Figure 1. The temperatures plotted were measured by means of thermocouples placed at the

TABLE 3

FREEZING AND THAWING OF AGGREGATES BY METHOD B[1]
(Samples arranged in order of increasing loss on the $^3/_8$-inch sieve after 16 cycles)

BPR No	Type of Rock	Loss of 1-in. to $^3/_4$-in. Material (%)								
		$^3/_4$-in. Sieve			$^3/_8$-in. Sieve			No. 8 Sieve		
		16 Cycles	25 Cycles	50 Cycles	16 Cycles	25 Cycles	50 Cycles	16 Cycles	25 Cycles	50 Cycles
N-419	Gneiss Granite Schist	0.0	2.3	2.3	0.0	0.2	0.2	0.0	0.2	0.2
N-168	Limestone	0.9	0.9	2.8	0.3	0.9	1.4	0.3	0.9	1.3
Stock	Dolomite	3.2	5.1	7.1	0.3	0.3	1.2	0.2	0.2	0.4
89892	Limestone	0.4	0.4	0.7	0.3	0.4	0.7	0.3	0.4	0.6
89889	Dunite	0.6	0.9	4.9	0.6	0.9	1.1	0.6	0.9	1.1
83888	Peridotite	10.6	10.8	10.9	0.7	0.7	1.6	0.5	1.0	1.5
N-92	Limestone	3.1	4.3	8.5	0.9	1.7	3.8	0.5	1.1	2.9
79826	Sandstone	2.6	6.5	18.5	1.0	3.0	7.5	1.0	2.9	7.2
N-169	Dolomite	3.2	3.2	8.2	1.5	1.9	2.5	0.6	1.0	1.6
70124	Limestone	6.6	6.6	26.4	2.4	3.6	8.6	2.1	3.3	7.2
N-127	Serpentine Diopside Garnet	8.8	8.8	15.7	2.6	5.6	10.3	2.0	4.1	8.8
94544	Limestone	4.4	7.1	13.7	3.5	4.5	6.9	2.7	3.9	6.4
81967	Sandstone	15.6	32.1	61.5	5.6	17.7	45.4	5.3	16.6	44.2
89813	Limestone	16.4	21.7	34.8	5.7	8.4	15.2	3.9	5.3	9.1
89805	do	7.6	10.2	17.9	6.9	8.4	10.5	5.3	6.6	8.2
N-167	do	14.6	29.3	54.8	7.5	14.0	34.1	3.7	8.4	26.2
N-167	Dolomite	26.7	40.8	59.2	8.5	15.9	39.2	5.8	12.8	35.2
89812	Limestone	18.2	21.8	31.9	8.6	9.9	17.2	5.6	6.9	11.2
89988	do	16.0	24.6	49.2	10.0	14.0	30.4	8.6	12.1	25.4
N-165	do	38.6	58.5	88.9	16.1	27.7	59.8	9.9	17.9	44.1
89918	do	40.5	45.9	52.1	17.5	21.6	32.6	12.0	14.1	21.6
78266	do	33.7	50.7	76.2	17.6	23.8	41.8	13.1	17.3	32.8
N-166	do	29.7	55.1	88.4	18.4	33.0	66.8	14.7	28.1	61.9
N-162	Dolomite	42.1	59.1	91.5	24.8	41.4	75.9	22.3	38.7	74.2
N-74	Light Limestone	59.1	77.5	94.9	30.5	48.3	83.2	22.5	34.4	67.3
N-164	do	66.1	81.8	100.0	31.3	48.8	89.9	20.3	38.5	85.9
N-74	Dark Limestone	82.4	89.1	96.7	64.4	74.1	89.1	43.7	60.8	83.2

[1] Samples were vacuum saturated before test for 15 minutes, frozen in $^1/_4$ in. of a 0.5 percent alcohol solution at a temperature between -10 and -20 F, and thawed in the same solution at 70±5 F.

center of 1- to $^3/_4$-in. particles stored in $^1/_4$ in. of water. The freezer was initially at -15 F and was fully loaded with 24 pans each containing 1,000 gm of material at room temperature. Under these conditions, the temperature of the particles was reduced to below 0 F after 3 hours, but between $3^1/_2$ and 4 hours was necessary to cool the samples to -15 F.

TESTING PROCEDURES

In the tests reported here under methods A, B, and C, only two cycles of freezing and thawing were obtained each 24 hours because of limited personnel. Samples remained in the freezer for 6 hours during the working day and 16 hours overnight. The thawing period was about 1 hour. It was demonstrated in later tests that it was practical to obtain 3 cycles of freezing and thawing in 24 hours by using two $3^1/_2$-hour freezing and three $^1/_2$-hour thawing periods during the working day. All samples consisted of approximately 1,000 gm of 1- to $^3/_4$-in. material which had been originally ovendried. All freezing was done at -15±5 F and all thawing at 70±5 F in a circulating bath. Otherwise, the three procedures covered by this report had the following distinguishing features:

Method A. Samples were saturated with water before test by first being subjected

TABLE 4

FREEZING AND THAWING OF AGGREGATES BY METHOD C[1]
(Samples arranged in order of increasing loss on the ⅜-inch sieve after 50 cycles)

BPR No.	Type of Rock	Loss of 1-in to ¾-in. Material (%) ¾-in. Sieve 16 Cycles	¾-in. Sieve 25 Cycles	¾-in. Sieve 50 Cycles	⅜-in. Sieve 16 Cycles	⅜-in. Sieve 25 Cycles	⅜-in. Sieve 50 Cycles	No. 8 Sieve 16 Cycles	No. 8 Sieve 25 Cycles	No. 8 Sieve 50 Cycles
N-127	Serpentine Diopside Garnet	2.2	2.2	2.4	0.0	0.0	0.2	0.0	0.0	0.1
N-419	Gneiss Granite Schist	0.0	0 1	1.2	0.0	0.1	0.2	0 0	0.1	0.2
Stock	Dolomite	3.1	3 9	3.9	0.1	0 1	0.2	0.1	0.1	0.1
N-92	Limestone	1.2	1.4	1.6	0.1	0.2	0.3	0.1	0 2	0 3
N-163	Dolomite	1.9	3.9	4 8	0.1	0.3	0.3	0.0	0 1	0.1
70124	Limestone	3.3	3.7	3.7	0.3	0.3	0.3	0.1	0.1	0.1
N-168	do	0.0	0.2	1 3	0.0	0.2	0.4	0.0	0.2	0.4
89892	do	0.0	0.3	1.6	0.0	0.3	0.4	0.0	0.2	0.4
89805	do	0.0	0.3	2.1	0.0	0.3	0.4	0.0	0.3	0.4
N-162	Dolomite	1.3	2.9	7.6	0.1	0.3	0.4	0.0	0.2	0.2
N-169	do	0.2	1.2	1.2	0.2	0.3	0.4	0.2	0 2	0.4
N-167	Limestone	3.0	3.1	9.9	0.1	0.3	0.5	0.0	0.1	0.2
89812	do	1 1	1.2	1.3	0.3	0.3	0.5	0.3	0.3	0.5
89889	Dunite	1.5	2.9	3.7	0.4	0.5	0.7	0.3	0 4	0.6
79826	Sandstone	1.3	1 3	3.0	0.5	0.5	0.9	0.3	0.4	0.8
N-164	Limestone	3.1	3.1	4.1	0.0	0.9	1.1	0.0	0 6	0.6
N-166	do	1.7	4 8	6.1	0.4	0.7	1.4	0.2	0.4	0.6
N-165	do	0.2	0.7	4.1	0.2	0.7	1.6	0.0	0.4	0.6
78266	do	4.9	6.9	10.6	0.2	0.7	1.6	0.1	0.4	0.7
83888	Peridotite	0.6	1.1	1.7	0.6	0 9	1.6	0.6	0.9	1.6
89813	Limestone	3.8	5.2	8 5	2.2	2.2	2.7	0 1	1.5	2.0
94544	do	8.2	8 6	10.0	1.6	2.1	3.1	0.7	1.0	1.9
89918	do	1.9	4.5	5.3	1.1	1.9	3.6	0.7	1.1	2.1
81967	Sandstone	6.7	8.8	9 6	0.9	2.7	4.5	0.7	2.6	4.4
89988	Limestone	2.7	4.1	10.8	0.7	1.1	5.4	0.4	0.9	3.2
N-74	Light Limestone	5.9	9.6	16.6	2 3	4.3	7.9	1.0	2.8	5.2
N-74	Dark Limestone	6.0	12.1	31.1	3 3	5.7	13.6	1.9	3.4	6.7

[1] Samples were saturated for 24 hours before test, frozen in air at a temperature between -10 and -20 F and thawed in water at 70±5 F.

to an air pressure reduced to about 1 in. of mercury and then submerged in water for 15 minutes while the vacuum was maintained. Samples were frozen in 8- by 12-in. pans containing ¼ in. of water. Thawing was done in water.

Method B. Samples were vacuum-saturated with water as in method A, but were frozen in 8- by 12-in. pans containing ¼ in. of the alcohol-water mixture (0.5 percent alcohol). Thawing was done in this same alcohol-water mixture.

Method C. Samples were saturated before test by being submerged in water at atmospheric pressure for 24 hours. Samples were frozen in air using sieves as containers and were thawed in water.

DISCUSSION OF RESULTS

Table 1 shows the absorption and sodium sulfate soundness losses for each of the materials used in this study. Their resistance to freezing and thawing was determined after 16, 25, and 50 cycles by measuring losses through the ¾-in., ⅜-in., and No. 8 sieves. These losses by methods A, B, and C are shown in Tables 2, 3, and 4 respectively.

Although each of the freezing methods used in this study is patterned after a procedure followed by a state highway laboratory, the specification limit prescribed by

TABLE 5

RELATIVE SEVERITY OF THREE METHODS OF FREEZING AND THAWING

BPR No.	Type of Rock	Loss on 3/8-in. Sieve After 50 Cycles of Method C	Number of Cycles Equivalent to 50 Cycles of Method C[1]	
			Method A	Method B
N-92	Limestone	0.3	22	5
70124	do	0.3	22	3
N-168	do	0.4	25	17
89892	do	0.4	33	25
89805	do	0 4	17	1
N-167	do	0.5	28	1
89812	do	0.5	50	1
N-164	do	1.1	19	1
N-166	do	1.4	26	1
N-165	do	1.6	48	2
78266	do	1.6	30	2
89813	do	2.7	50	8
94544	do	3.1	48	14
89918	do	3.6	19	3
89988	do	5.4	45	9
N-74Light	do	7.9	9	4
N-74 Dark	do	13.6	6	3
Stock	Dolomite	0 2	100	10
N-163	do	0.3	18	1
N-162	do	0.4	17	1
N-169	do	0.4	37	4
Average (21 carbonate-type rocks)			32	6
N-127	Serpentine Diopside Garnet	0.2	18	2
N-419	Gneiss Granite Schist	0.2	25	25
83888	Peridotite	1.6	100+	50
89889	Dunite	0.7	25	19
79826	Sandstone	0.9	19	14
81967	do	4.5	19	13
Average (6 miscellaneous-type rocks)			34	20
Average (27 samples)			32	9

[1] This value is the number of cycles required to produce the same loss on the 3/8-in. sieve as 50 cycles by method C, as estimated by consideration of the losses obtained at 16, 25, and 50 cycles.

that state is not necessarily applicable to the results obtained here. For example, in the case of method B, the Iowa specifications make provision for testing a sample graded down to the No. 4 sieve with the loss to be determined on a No. 8 sieve. The loss on a No. 8 sieve will tend to be greater for such a graded sample than for 1-in. to 3/4-in. material of the same quality such as used in this study because many of the particles in the graded test sample will be closer in size to the sieve used for determining the loss. However, these results do provide a means of directly comparing the severity of each of the three freezing and thawing procedures. In Table 5, this comparison is made in terms of the equivalent number of cycles of methods A and B which would produce the same destructive effect as 50 cycles of method C. Considering the entire group of 27 samples, method A (freezing in water) required about two-thirds and method B (freezing in alcohol-water) about one-fifth the number of cycles required by method C (freezing in air) to produce the same action. The greater severity of method B over methods A and C was more pronounced for the carbonate-type rocks than the miscellaneous types, although the limited number of samples in this latter group precludes drawing a general conclusion to that effect. Comparisons for individual samples also indicate that the relative severity of the three methods varies considerably for different materials.

Since the rates of freezing and thawing were the same for the three procedures covered by this report, it might be expected that differences in degree of saturation of the particles during freezing would account for differences in destructive effect of the three methods. It is reasonable, for example, to attribute the low losses obtained by method C, where freezing was done in air, to the reduced amount of water in the aggregate as a result of partial drying taking place in the freezer. The greater severity of method B where alcohol was used, as compared to methods A and C, is believed to result from the increased absorption caused by the alcohol. It was determined, for example, that the absorption of aggregates which had been subjected to several cycles of freezing and thawing in the 0. 5 percent water-alcohol mixture was greater than the absorption of similar samples which had been frozen in plain water. Alcohol did not, however, increase the absorption of aggregates when they were simply immersed in the mixture without freezing.

It is of interest to compare the relative order of soundness of the 27 samples as determined by each freezing and thawing procedure. To help visualize this comparison, losses of all materials by the three methods were plotted in Figure 2, the samples being arranged from left to right in order of increasing loss by method A. It is evident that arranging the samples according to their losses by either of the other methods would have produced a different order. The difference in order of soundness found by comparing results obtained by methods A and C could result from sampling variations or the general lack of preciseness which is common to any freezing and thawing method. However, the difference between results obtained by method B compared to method A or C is sufficiently great to preclude an explanation based entirely on such factors. It is possible that the different order of soundness found by method B is related to the relatively advanced state of disintegration of many samples after 16 cycles of this method as compared to 50 cycles of the other methods. Another possibility is

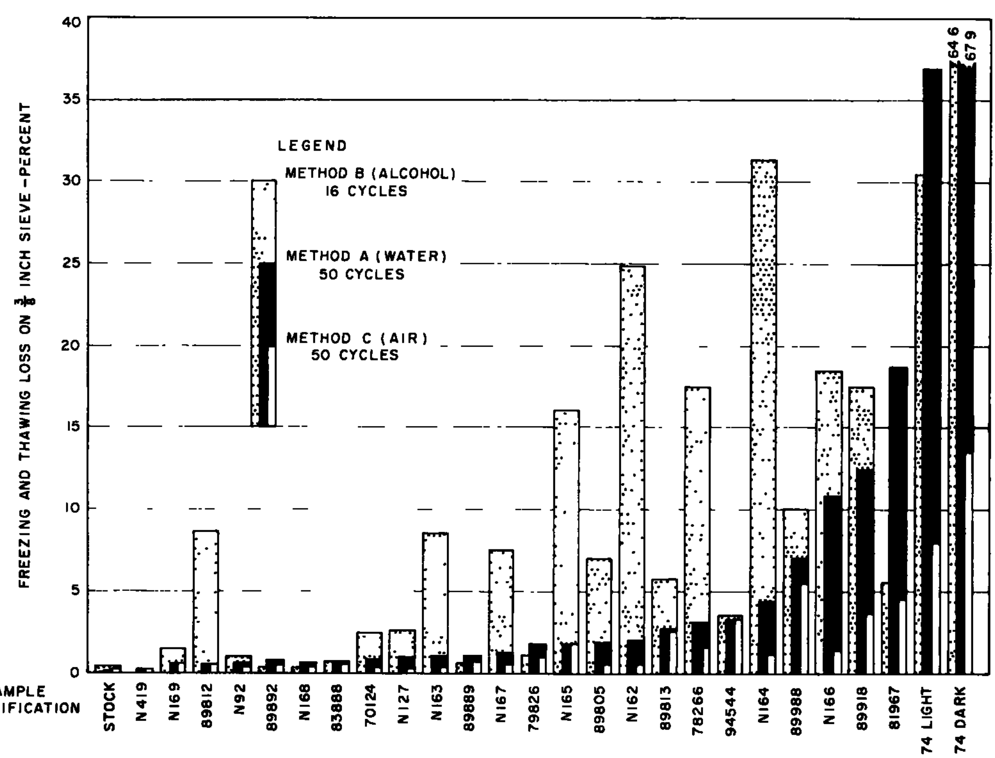

Figure 2. Comparison of freezing and thawing loss by methods A, B and C. Samples arranged from left to right in order of increasing loss by method A.

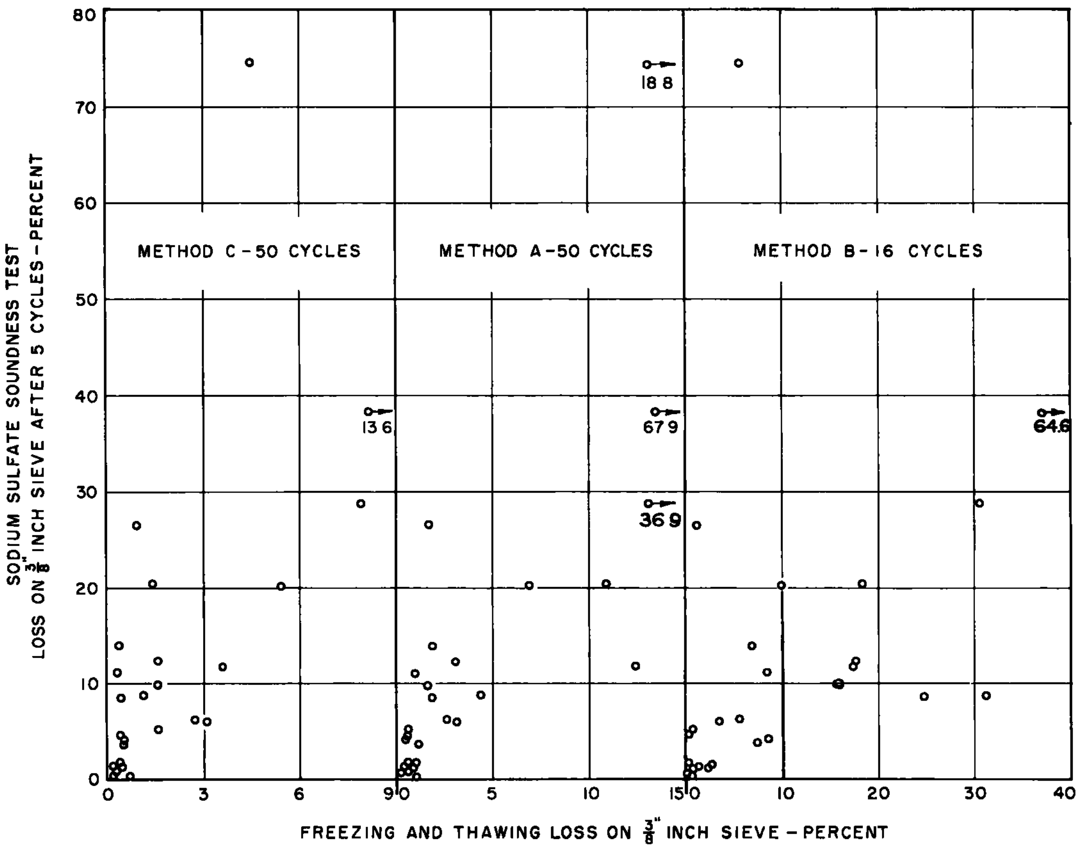

Figure 3. Relation between the losses by the sulfate soundness test and freezing and thawing methods A, B and C.

that the alcohol method may be introducing some destructive process in the freezing and thawing procedure which is inherently different than that involved in methods A and C.

This possibility raises the question of agreement of the findings of the alcohol-water method with the service record of the materials tested. To determine this, the submitters of the samples were asked to furnish information of the behavior of the materials in service. Replies were obtained for 22 of the 27 materials. Of these 22 materials for which dependable service records were obtained, 12 were rated as either unsound or questionable and had losses by method B of 5. 7 percent or more. Of the 10 materials rated as sound, 9 had losses by method B of 3. 5 percent or less and one had a loss of 7. 5 percent. Hence, in all but one instance, a good separation was made between sound and questionable materials.

Although the feasibility of substituting a freezing and thawing procedure for the sulfate soundness test should not hinge on obtaining good correlation between the two types of test, a comparison between results obtained by the sulfate method and those obtained by methods A, B, and C is made in Figure 3. The horizontal scales were adjusted so that except for a few points, the plotted values occupy about the same horizontal distance for each of the three freezing and thawing methods. Losses obtained after 5 cycles of the sulfate test greatly exceeded the losses obtained by methods A and C but were approximately equal in magnitude to those obtained by method B. However, it is apparent from the scattering of points in Figure 3 that the sulfate test does not correlate closely with any of the freezing and thawing methods used in this study.

The results of this study should not be interpreted as a recommendation that the alcohol-water method of freezing and thawing aggregates be blindly substituted for the sulfate soundness test as a method of judging the durability of aggregates. It is sufficient for the purpose of this study that those having the responsibility of selecting sound materials be made aware of the existence of such a procedure as well as the availability of inexpensive equipment for its rapid performance. By thus demonstrating the procedure, it is hoped that others will be moved to investigate the suitability of such a method, or some modification of it, for use with the materials with which they are immediately concerned.

CONCLUSIONS

1. A home-type freezing unit proved satisfactory for rapid freezing and thawing tests of aggregates. Three cycles per day were possible with a minimum freezing temperature between -10 and -15 F.
2. Sixteen cycles of method B, which involved freezing and thawing in a 0.5 percent alcohol-water solution, was equally as effective as 5 cycles of the sodium sulfate test, but was much more destructive than 50 cycles of method A with freezing and thawing in plain water, or method C, with freezing in air and thawing in water.
3. The order of soundness of the materials used in this study was significantly different when determined by method B and either method A or C. However, the losses obtained by method B were in reasonable agreement with the service records of the 22 materials for which such information was available. The results of the sulfate soundness test did not correlate closely with the results obtained by any of the freezing and thawing procedures.

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