Factors Influencing Physical Properties of Soil-Cement Mixtures

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Introductory Remarks by the Chairman: Felt has presented important results of the well-conceived and thorough investigations on soil-cement accomplished by the Portland Cement Association. It is especially gratifying to notice how in the development of soil-cement general pedological principles and specific physico-chemical concepts have been utilized at an early stage, together with the more-direct approach from soils and materials engineering.

The importance of this work for a better understanding and utilization of soil-cement is obvious. Less obvious (but perhaps of even greater significance) is the fact that the basic principles developed are applicable not only to systems composed of soil and portland cement but to soil stabilization with practically all types of inorganic cementing materials.

This paper may fill another need: Some have suspected a negative attitude in the emphasis given in the papers by our nonengineering contributors to the complexity of the science of soil stabilization and to the many problems that still remain to be solved. It is well for the scientist to point out these problems and for the engineer to listen. But it is also the glory of the engineer to view and measure these problems and to solve them with his creative genius. How this is done is well demonstrated in Felt's paper.

● THE properties of compacted and hydrated soil-cement mixtures are dependent to a great extent upon the types of soil involved. Certain differences in properties and in cement reaction are due to variations in the chemical composition of the soils. For instance, lateritic clays with a relatively low silica-sesquioxide ratio (colloids low in silica and high in the sesquioxides of iron and aluminum) pulverize more readily and react more favorably with cement than do northern podzolic or chernozem clay soils which have relatively high silica-sesquioxide ratios. Laboratory studies (1, 2) and field experience have shown the differences that may occur in the properties of soil-cement mixtures made with different clay soils.

Sandy soils, too, may react differently with cement depending upon their chemical makeup and surface chemical properties. For instance, a great variance exists between the relatively poor effectiveness of cement with the A horizon (topsoil) of many podzol or podzolic soils and the much greater effectiveness of cement with the C horizon (parent material) from the same soil profile. In these soils the organic matter in the A horizon is considered to be the chief offender, as it may retard or almost completely arrest the cement reaction.

Because of the tremendous effect organic matter may have on some soil-cement mixtures, special laboratory studies (3) and field experiments have been conducted. This work has shown that sandy soils of this type may be satisfactorily treated. Soil identification and careful sampling are, of course, prerequisites to effective soil-cement testing and construction. In this connection, the Pedological system of soil identification (4) which includes information on both the physical and chemical properties of soils is recommended for soil-cement work. Additional information of value in this field is available (5, 6).

Other factors which have pronounced influence on the physical properties of soil-cement mixtures include the quantity of cement and water added; the density to which the mixture is compacted; the length of time the soil, cement, and water are mixed prior to compaction; and the degree of pulverization of the soil if it is a clay.

The purpose of this report is to show how these last-named factors influence the strength and the relative durability of soil-cement specimens as indicated by their resistance to loss in weight resulting from alternate cycles of wetting and drying and of freezing and thawing in the laboratory. Although soil-cement may be used for a number of purposes (7), this report concerns compacted soil-cement mixtures

(and cement-modified soils,[1] to a lesser extent) as used principally for base and subbase courses in highway and runway construction. It does not include data on "plastic" soil-cement, which is made with much higher water contents than the compacted type.

SCOPE OF PROGRAM

To obtain representative data, indicative of the performance of soil-cement mixtures made of different types of soil, tests were made on mixtures containing sandy, silty, and clayey soils. Seven series of tests were made to determine the influence of various factors upon the compressive strength and resistance to wetting and drying and to freezing and thawing of compacted, hydrated soil-cement mixtures. For convenience in this report these test series were identified as follows: Series 1, effect of density; Series 2, effect of molding moisture content; Series 3, effect of length of mixing time; Series 4, effect of degree of pulverization; Series 5, effect of air-entraining cement; Series 6, effect of the quantity of cement; and Series 7, effect of high early strength cement.

Data are also reported for three fine-grain soils treated with relatively low percentages of cement (cement-modified soils) and for three granular soils treated both with low percentages of cement as required for cement-modified soils and with higher percentages as required for soil-cement. These test series were designated: Series 8, properties of cement-modified fine-grain soils, and Series 9, properties of cement-modified granular soils compared with properties of granular soil-cement mixtures.

TABLE 1
GRADATION AND PHYSICAL TEST CONSTANTS[a] OF RESEARCH SOILS

Soil No.	Used in Test Series No.	Gradation - % of Total: Sand 2.0 to 0.25 mm	Sand 0.25 to 0.05 mm	Silt 0.05 to 0.005 mm	Clay 0.005 to 0.000 mm	Physical Test Constants[b]: L. L.	P. I.	S. L.	Textural Class	U. S. BPR[c] Soil Group
2a	1, 2	39	49	3	9	12	NP		Fine Sand	A-2
2a-2	3	24	49	8	19	26	11	18	Sandy Loam	A-2
2a-3	1, 2	35	46	8	11	13	NP	21	Loamy Sand	A-2
2a-4	1, 2, 3, 5	27	47	7	19	17	1	17	Sandy Loam	A-2
2a-6	6, 7	26	57	6	11	14	NP	20	Loamy Sand	A-2
4b-3	1, 2, 3,	2	17	57	24	38	13	25	Silty Clay Loam	A-4
4b-4	3	3	12	59	26	35	12	26	Silty Clay Loam	A-4
4b-5	1, 2, 3, 5	2	9	64	25	34	10	24	Silty Clay Loam	A-4
4b-6	4	2	7	67	24	37	12	20	Silty Clay Loam	A-4
4d	1, 2, 6, 7	1	8	67	24	34	14	16	Silty Clay Loam	A-4
6e	1, 2	2	10	35	53	49	26	17	Clay	A-6-7
6e-2	3	2	9	40	49	47	26	18	Clay	A-6-7
6e-4	1, 2, 3, 5	1	11	51	37	51	28	17	Silty Clay	A-6-7
7h	4, 6	8	9	36	47	37	18	16	Clay	A-7
7d	1, 2	0	14	18	68	118	83	14	Clay	A-7

[a]Obtained using Standard AASHO and ASTM Procedures
[b]L. L. = Liquid Limit
P. I. = Plasticity Index
S. L. = Shrinkage Limit
N. P. = Not Plastic
[c]Bureau of Public Roads

[1] Cement-modified soil mixtures are those which contain less cement than the quantities required to definitely harden them to produce soil-cement.

The greatest use for soil-cement mixtures is in the construction of pavement base courses. For this reason, the cement contents used with the various soils when conducting Series 1, 2, 3, 4, and 5 were in the range that would normally be used in building pavement bases. These cement contents were 6 percent and 8 percent for the sandy soil, 12 percent and 14 percent for two silty soils, 12 percent for two clay soils, and 20 percent for one very-tough clay soil. Preliminary tests using AASHO Methods T135 (wet-dry test) and T136[2] (freeze-thaw test) were made to determine the cement requirements. In conducting Series 6, 7, 8, and 9, cement contents ranging from 1½ percent to 34 percent were included in the tests.

MATERIALS AND TEST METHODS

The physical properties of the soils used in the first seven test series are listed in Table 1. Similar data for soils used in Series 8 and 9 are given in discussion of those series. The first group in Table 1 is composed of five sandy soils all identified as Soil 2a. (The numbers after the 2a, i.e., 2a-2, 2a-4, etc., indicate different samples from approximately the same area.) Second is a group of five silty soils; third is a group of four clayey soils; and fourth is a single clay soil, very-heavy textured and extremely plastic. The numbers used in identifying these soils are also the AASHO soil-group numbers, thus Soil 4b and Soil 4d are A-4 silty soils, Soil 2a is an A-2 sandy soil, etc.

Soil 2a is a brown, fine, sandy soil from South Carolina. It is a mixture of the lower A, the B, and the upper C horizons of the soil profile and contains some organic contamination from the A horizon. This contamination varied in the different samples, depending upon the percentage of A horizon soil included. As previously mentioned, organic matter has a deleterious effect upon proper cement hydration, and thus some of the soil-cement made with samples of Soil 2a hardened at a slower rate and developed less strength than did soil-cement mixtures made with other samples of soil from approximately the same location.

Soil 4b (four samples) is a dark-gray, silty soil from a well-drained area in Illinois. It is from the lower A horizon of the soil profile and contains some organic matter. The presence of these organic compounds probably has some effect on the reaction of this soil with cement. Soil 4d is a brown silty soil from Illinois. It is from the lower B and upper C horizons and reacts in a normal manner.

Soil 6e (three samples) and soil 7h are brown clay soils from Illinois, from the B and upper C horizons of the soil profile. These soils react with cement in a normal manner.

Soil 7d is a light-brown, heavy clay soil from Mississippi. It is from the B and C horizons of the soil profile and is an unusually tough clay.

Type I portland cement, used in most of these tests, was a blend of four brands purchased on the open market. The soil-cement mixture was proportioned in the laboratory on a dry-weight basis, with cement contents selected to yield certain predetermined percentages expressed on a volume basis. Cement contents are reported, unless otherwise noted, in terms of volume of loose cement (94 lb. per cu. ft.) per unit volume of compacted soil-cement mixture. Thus, a cement content of 8 percent by volume indicates that a cubic foot of compacted mixture contains 0.08 sack (7.52 lb.) of cement.

Test Methods

In most of the work, three different tests were used in evaluating the influence of various factors upon the quality of the mixture. These were the wet-dry test, the freeze-thaw test, and the compressive-strength test. Specimens for the first two of these were 4 inches in diameter and 4.6 inches high. The testing methods were in accordance with AASHO methods T135 and T136, Wetting and Drying Test and Freezing and Thawing Test, respectively, except that the specimens were not in all cases compacted according to the AASHO standard procedure (T134) specified in these methods, and in some cases the tests were continued for more than the 12 cycles specified in the AASHO procedures. The compaction procedure was varied in several instances in order that the density and moisture content of the specimens could be varied and is described under each series of tests.

Specimens for the compressive strength tests were 2 inches in diameter and 2

[2] ASTM Methods D559 and D560, respectively.

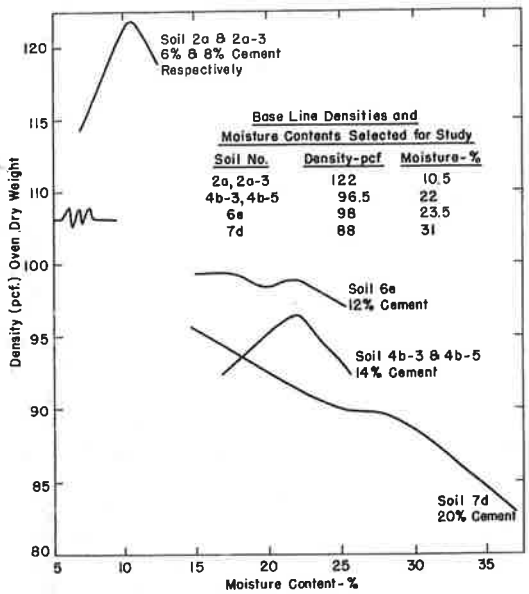

Figure 1. Moisture versus density of soil-cement mixtures used in Series 1 and 2.

inches in height. Specimens of this relatively small size were suitable as the soils used in the compressive-strength test were relatively fine textured and did not contain material retained on the No. 4 sieve. There is no AASHO standard method for making compression-test specimens of soil-cement mixtures.

Specimens were compacted from both ends using the double-piston method. A predetermined weight of mixture containing the proper moisture and cement content was placed in the cylindrical mold and compactive force applied through the pistons. When the pistons were separated by 2 inches, the specimen was at the designed density and contained the designed cement content by volume. After removing the specimens from the mold, they were stored for cement hydration in an atmosphere at 73 F. and 100 percent relative humidity. At the selected age for testing, the specimens were removed from storage, immersed in water for an hour, and then broken in a compression-testing machine.

In Series 8 and 9, liquid-limit and plastic-limit tests, bearing-ratio tests, and soniscope tests (Series 9) were made to aid in evaluating the influence of cement in modifying the soil. Test procedures for these series are described later in the report.

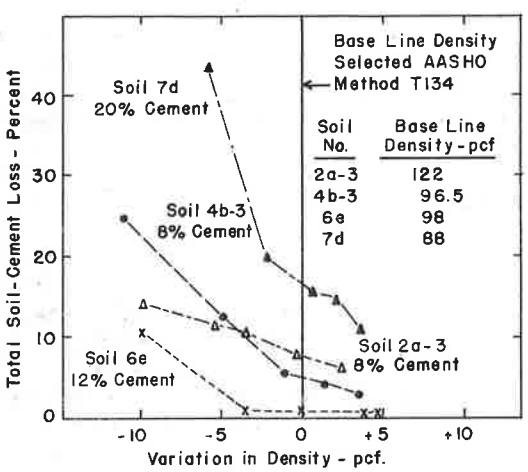

Figure 2. Effect of density on soil-cement loss from wet-dry test.

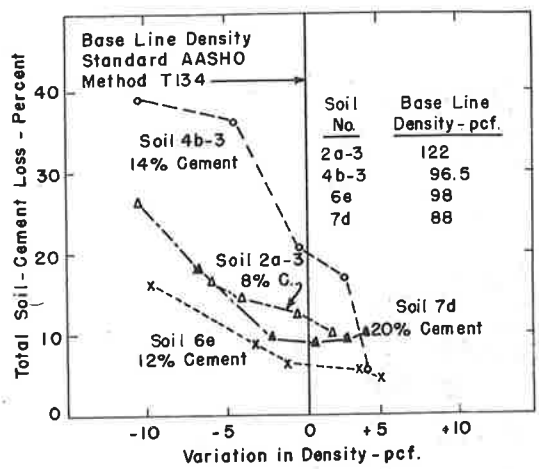

Figure 3. Effect of density on soil-cement loss from freeze-thaw test.

TEST RESULTS

Most soil-cement mixtures, when compacted in accordance with AASHO test T134, develop parabolic-shaped moisture-density curves, as shown for Soil 2a and Soil 4b in Figure 1, and a maximum density is indicated at an optimum moisture content at the peak of the curve. These values, obtained using the standard test, are called "base-line" values in Series 1 and 2, which were designed to study the effect of density and of moisture content on the properties of soil-cement mixtures.

The clay soil-cement mixtures used in the tests in Series 1 and 2 did not have parabolic-shaped moisture-density curves. These soils, because of their swelling characteristics as they become wet, tend to develop irregular moisture-density

curves of ski-slide shape, as shown for Soil 7d in Figure 1. Experience (1, 2) has shown that, when a curve of this shape is obtained, the selection of a base-line density and base-line moisture content can be done most accurately after special tests have been made. The tests which will be discussed in Series 2 are of particular value with soils of this type, as they permit the engineer to select the moisture content which produces maximum effectiveness from the cement. The base-line optimum moisture content of soil-cement mixtures which have a secondary hump in the curve, as for instance Soil 6e in Figure 1, is generally taken about 2 percentage points above the water content at the second hump; the base-line density is that obtained at this particular moisture content.

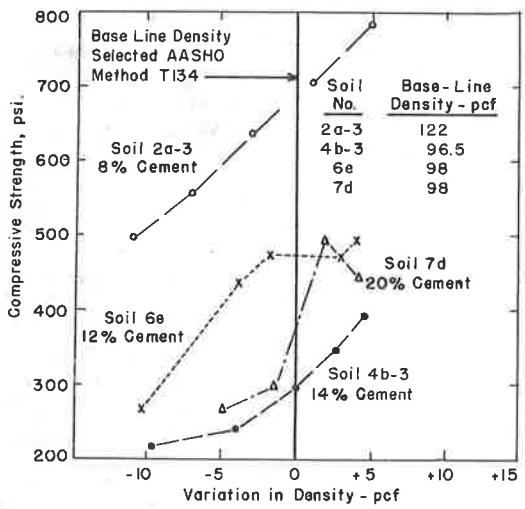

Figure 4. Effect of density on 28-day compressive strength.

Series 1: Effect of Density

Experience has shown that soil-cement mixture of good quality can be made by compacting the mixture to a density equal to that obtained by the AASHO compaction procedure. In Series 1 an investigation was made of the quality of soil-cement mixture compacted to lower and higher densities. In these tests the moisture content for each of the soil-cement mixtures was maintained constant and equal to the selected base-line moisture content. To vary the density at this moisture content, specimens for the wet-dry and freeze-thaw tests were molded according to the standard procedure, except that the number of blows of the compacting rammer per layer was changed from 25, and was set at 4, 9, 15, 20 and 50. This procedure produced specimens having a density variation of about 10 to 15 pcf. (pounds per cubic foot). Compressive-strength specimens 2 by 2 inches were then molded at densities and moisture contents equal to those of the wet-dry and freeze-thaw specimens.

Sandy Soil 2a-3, silty Soils 4b-3 and 4b-5, and clayey Soils 6e and 7d were used in the tests. Figure 1 shows the base-line densities and base-line optimum moisture contents selected for study. Figures 2, 3, and 4 show the base-line densities and also the variation in density from the base.

Results from the wet-dry test are shown in Figure 2 and from the freeze-thaw test in Figure 3. The ordinates show the weight loss from the specimens in 12 cycles of test. The effect of density is readily apparent; specimens had increasingly higher losses as the density decreased. Although all the different types of soil-cement mixture were benefited by increased density, the silty and clayey soil-cement mixtures were benefited the most. For the sand Soil 2a-3, each 1-pcf. increase in density reduced soil-cement losses about 1 percentage point. For silty Soil 4b-3 and clayey Soil 7d, however, the corresponding reduction in soil-cement losses varied from approximately 1.5 to 3.5 percentage points for each 1-pcf. increase in density in the low density range. (Soil 4b soil-cement contained 8 percent of cement in the wet-dry test, but 14 percent in the freeze-thaw test, which is critical for this soil.)

The compressive strengths of specimens molded at different densities are shown in Figure 4. Again, the value of high density is apparent. In the case of sandy Soil 2a-3, an increase in density of 1 pcf. resulted in an increase in compressive strength of approximately 20 psi. The compressive strengths of the silty and clayey soil-cements practically doubled as a result of increasing the density of these materials 10 to 15 pcf. For instance, with Soil 4b-3, at a density 5 pcf. below base-line density, the compressive strength was 235 psi., whereas at a density 5 pcf. above base-line density, the compressive strength was 400 psi. Soil-cement mixtures of clay Soils 6e and 7d showed similar performance. In general, with these soils, an

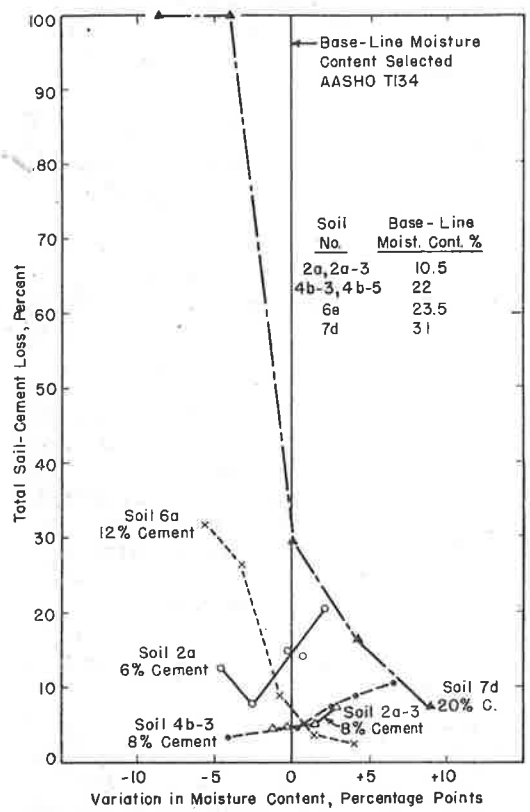

Figure 5. Effect of moisture content on soil-cement loss from wet-dry test.

increase in density of 1 pcf. in the low density range resulted in an increase in compressive strength of approximately 15 to 25 psi.

Series 2: Effect of Molding Moisture Content

To study the effect of molding moisture content on the quality of soil-cement mixtures, specimens for wet-dry and freeze-thaw tests were molded at moisture contents below and above the selected base-line moisture content, using the standard AASHO compaction procedure. Compressive strength specimens were molded at the same densities and moisture contents. Since the compactive effort was constant and the moisture content varied, the density of the specimens also varied, but the data indicate that the effect of moisture content overshadows the effect of the differences in density.

The data from the AASHO wet-dry and freeze-thaw tests are shown in Figures 5 and 6. For convenience, the data in Figure 6 are considered first; it is apparent from these data that soil-cement mixtures made of silty Soil 4b-3 and 4b-5 and clayey Soil 7d had much-less resistance to alternate freezing and thawing when they were compacted at moisture contents less than the base-line moisture contents. As seen in Figure 5, this was true in the wet-dry test for soil-cements of clay Soils 6e and 7d, but the soil-cement mixture made of Soil 4b was not affected significantly. (Soil 4b mixture contained only 8 percent of cement in the wet-dry test, but 14 percent of cement in the freeze-thaw test, which is critical for this soil.)

It is apparent from these data that to obtain high-quality mixtures from silty and clayey soils, the mixtures must be compacted at or above, never below, the AASHO T134 optimum moisture content when they are compacted to AASHO density. These data have been corroborated by other tests at the Portland Cement Association and are in agreement with results obtained by other investigators (2).

The effect of molding moisture content

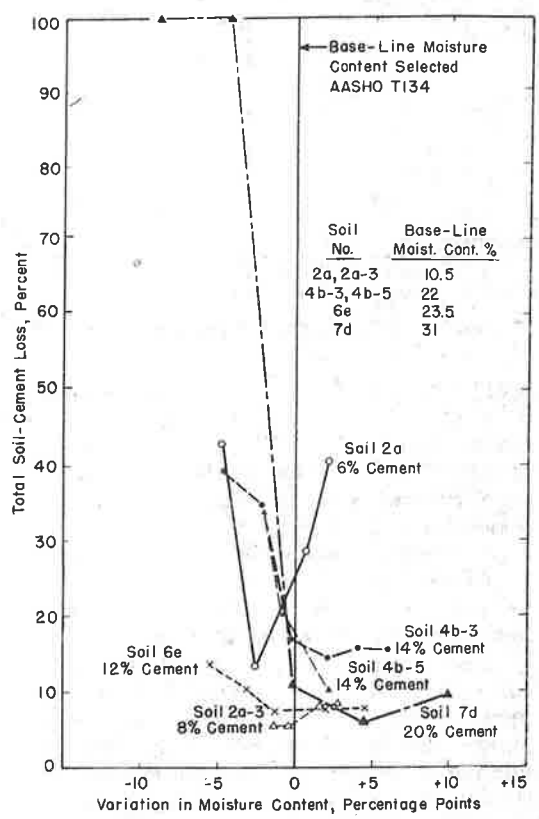

Figure 6. Effect of moisture content on soil-cement loss from freeze-thaw test.

on soil-cement mixtures made of sandy Soils 2a and 2a-3 was not the same as that found for the silty and clayey soils. In this case, moisture contents slightly on the dry side of base-line moisture content were favorable, suggesting that sand mixtures may follow to some degree the water-cement-ratio relationships for concrete.

The compressive-strength data for the various soil-cement mixtures are shown in Figure 7. Here it is seen that specimens

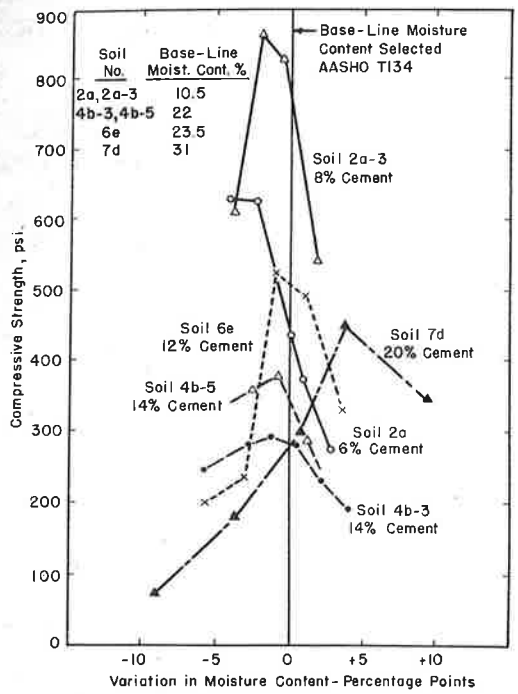

Figure 7. Effect of moisture content on 28-day compressive strength.

molded at the base-line moisture content, or slightly below, except for Soil 7d, have maximum strength. The data for mixtures of Soil 7d indicate that the base-line moisture content selected for this soil was about 5 percentage points below the moisture content which produced maximum effectiveness from the cement.

Based upon the wet-dry, freeze-thaw, and compressive-strength data combined, it appears that the best moisture content for Soil 7d soil-cement mixtures would be about 36 percent, or 5 percentage points above the selected base-line moisture content of 31 percent. As previously mentioned, the so-called optimum moisture content (that producing maximum effectiveness from the cement) for soil-cement mixtures having irregular moisture-density curves can be selected best after conducting special tests, such as these in Series 2.

It is to be noted that the newly selected optimum moisture content for mixture of Soil 7d (36 percent) is practically equal to the plastic limit (35 percent) of the soil, as indicated by the numerical difference between the P. I. and L. L. data in Table 1. It is of interest also to note that the plastic limit of Soil 6e (23 percent) is practically equal to the base-line optimum moisture of 23.5 percent, which was selected for Soil 6e soil-cement mixtures. Other tests on soils having irregular moisture-density curves confirm this generality.

The wet-dry, freeze-thaw, and compressive strength data, when considered together, indicate that for maximum effectiveness from the cement, sand mixtures should be compacted at optimum moisture content or slightly drier, whereas silty and clayey mixtures should be compacted at moisture contents 1 or 2 percentage points above optimum moisture.

Special Series 1 and 2

The test data for Series 1 and 2 give rise to questions as to the relative performance of soil-cement mixtures compacted to much-higher densities than those obtained in Series 1. In following the procedure of Series 1, i.e., molding specimens at different densities at the selected base-line moisture contents, the greatest density that was obtained was only about 5 pcf. above the selected base-line density. This is because the base-line water content plus air fills most of the voids in the mixture and thus limits the density.

If greater densities than these are desired, the moisture content must be decreased and a greater compactive effort used. The AASHO Modified method provides for this. In this method the standard 4-inch-diameter mold and the 2-inch-diameter rammer are used, but the material is placed in five layers, rather than in three as in the AASHO standard method, and each layer is compacted with 25 blows of a 10-lb. rammer falling 18 inches, rather than with a 5.5-lb. rammer falling 12 inches. This method produces a maximum density higher than AASHO base-line density at an optimum moisture content lower than AASHO base-line optimum moisture content.

Soils used in these tests to determine the value of high densities included sandy Soil 2a-4, silty Soil 4d, and clay Soil 6e-4. The cement contents used were those that would commonly be used with these soils in pavement base construction.

As shown by Figure 8, the maximum densities of the soil-cement mixtures compacted by the AASHO Modified procedure were considerably greater than the maximum densities obtained with the standard method. For sandy Soil 2a-4 the AASHO Modified density was 7.5 pcf. higher, and for the silty and clayey soils, approximately 13 pcf. higher. The optimum moisture contents were correspondingly lower with the AASHO Modified procedure, being about 2 percentage points lower for the sand mix and approximately 5 percentage points lower for the silt and clay mixtures.

Data in Table 2 indicate the relative quality of mixture produced using basic molding data obtained with the two methods. In this table, data are presented for specimens compacted at AASHO standard maximum density and AASHO standard optimum moisture content (A); AASHO Modified maximum density and AASHO Modified optimum moisture content (B); and AASHO standard maximum density and AASHO Modified optimum moisture content (C). The data obtained show that compressive strengths obtained using System B were considerably greater than those obtained using System A. This we might expect, as according to Series 1 the high densities are beneficial. Apparently at these higher densities less water is required in the mixture to effectively utilize the cement, and the acceptable moisture content is thus lower for the densities achieved by System B than for the lower densities of Series 2. As there is little difference between the wet-dry and freeze-thaw data for specimens compacted by Systems A or B and as the compressive strengths are much higher using System B, it appears that the soil-cement mixture compacted by System B is of the higher quality.

It is important to note that the density indicated by the AASHO Modified method as maximum for the silty and the clayey material is so great that it is difficult to obtain in construction practice. Methods of compaction which will produce this density are not generally available, and the density most likely to be obtained in construction is about that indicated as maximum by the ASTM method.

It is apparent that if only this latter density were obtained with a mixture compacted at the relatively low AASHO Modified optimum moisture content, the resulting quality of the mixture would be impaired. This is indicated in Table 2 by the compressive-strength data for the mixtures compacted using System C. For example, for the mixture using Soil 4d, the 28-day

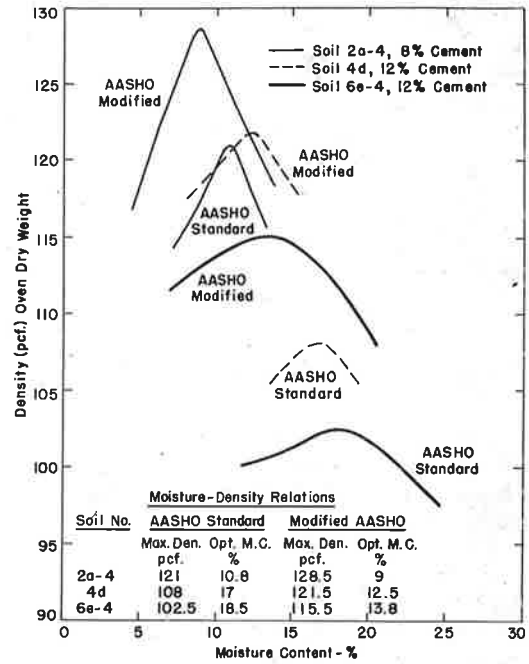

Figure 8. Moisture-density relations of soil-cement mixtures, Special Series 1 and 2.

compressive-strength test for System C shows only 293 psi., as compared with 1,202 psi. for System B and 668 psi. for System A. System C also yielded inferior soil-cement mixtures with the clay Soil 6e-4. However, the sandy mixture compacted using System C appears to be satisfactory.

These data correlate well with the data in Series 1 and 2, where it was shown that for AASHO standard density the molding moisture content of the silty and clayey soil-cement mixtures must be equal to or slightly greater than the base-line AASHO standard optimum moisture content but for sandy soils a somewhat lower moisture content was satisfactory.

It appears, therefore, that if densi-

TABLE 2
COMPRESSIVE STRENGTHS AND WET-DRY AND FREEZE-THAW LOSSES OF SOIL-CEMENT COMPACTED TO AASHO STANDARD AND AASHO MODIFIED MAXIMUM DENSITIES AND OPTIMUM MOISTURE CONTENTS

Compaction System[a]	Density, pcf	Moisture Content, %	Compressive Strength, psi			Wet-Dry Loss, %		Freeze-Thaw Loss, %	
			Age in Days			No. of Test Cycles			
			2	7	28	12	24	12	24
Soil 2a-4, 8% Cement by Volume									
A	121	10.8	265	665	800	3	5	5	7
B	128.5	9	435	732	1303	3	4	5	5
C	121	9	263	632	769				
Soil 4d, 12 % Cement by Volume									
A	108	17	352	596	668	3	7	3	6
B	121.5	12.5	787	933	1202	3	27	3	6
C	108	12.5	229	277	293				
Soil 6e-4, 12 % Cement By Volume									
A	102.5	18.5	203	417	486	31	86	9	35
B	115.5	13.8	326	427	709	28	97	5	6
C	102.5	13.8	70	138	149				

[a]A - AASHO Standard maximum density, AASHO Standard optimum moisture content
B - AASHO Modified maximum density, AASHO Modified optimum moisture content
C - AASHO Standard maximum density, AASHO Modified optimum moisture content

ties as great as those obtained by the AASHO Modified compaction procedure could be assured, in combination with their respective optimum moisture contents, soil-cement mixtures of superior quality would be produced. However, as these densities are not readily attained in practice, it usually is desirable to construct a soil-cement mixture near the AASHO standard optimum moisture content and to obtain as high a density as possible, preferably equal to AASHO standard density or greater. This procedure will provide sufficient water in the mixture to effectively utilize the cement at the particular density obtained.

Series 3: Effect of Prolonged Mixing

Soil-cement pavement bases are frequently constructed using mixed-in-place procedures in which the soil is pulverized in place, cement is added, and the dry mix is completed; water is then added and the damp mix is started. All of the required water is not added at one time, and several passes of the water equipment and of the mixing equipment may be necessary, with the result that the damp mixing may continue for 2 hours or more (8). Field experience has shown that mixtures of high quality may be produced in this way. A laboratory study of the effect of this prolonged damp-mixing period was undertaken in the next series.

With the thought of simulating field conditions, soil-cement was damp mixed for periods of 2, 4, and 6 hours in the laboratory and then molded into test specimens. During the mixing period, water was added to the dry mix in equal increments at approximately 20-minute intervals. After each addition of water, the mixture was mixed by stirring for about 2 minutes. The water added in each increment was proportioned so that at the end of the specified time the mixture was at optimum moisture content. The optimum moisture content increases as the length of mixing time increases, so preliminary tests were made first to determine the altered optimum moisture content of the mixtures.

Under unusual field conditions, mixture that is damp may remain undisturbed for long periods without the intermittent mixing previously described. To obtain information on the effect of such treatment, test specimens were molded of mixtures that had been brought to optimum moisture content and had then been left in the loose condition undisturbed (without intermittent mixing) for periods of 2, 4, and 6 hours. Water lost by evaporation was replaced just prior to molding the specimens.

Wet-dry and freeze-thaw specimens were molded using the standard AASHO compaction method, and compressive-test specimens were molded at the same density and moisture content. Soils used in these tests were sandy Soils 2a-2 and 2a-4, silty Soils 4b-3 and 4b-5, and clay Soils 6e-2 and 6e-4. The cement contents used were those which commonly would be used with these soils in pavement base construction.

The AASHO optimum moisture contents and maximum densities of the various soil-cement mixtures subjected to intermittent mixing are shown in Figure 9. These data show that the optimum moisture content increased and the maximum density decreased as the length of mixing time increased. These effects suggest that a loose, damp mixture, probably through base exchange, develops a new structure and texture as it ages during the prolonged mixing periods. That this change starts soon after the soil, cement, and water are mixed is evidenced by data which show that the resistance to penetration of a small piston forced into a freshly compacted soil-cement specimen is nearly always greater than the penetration resistance offered by the compacted raw soil at the same moisture content.

As a result of 4 to 6 hours of intermittent mixing, the optimum moisture for the sand soil-cement mixtures increased 0.6 percentage point; that for the silt soil-cement mixtures increased about 1.3 percentage points; and that for the clay soil-cement increased 1 to 2 percentage points. The corresponding decreases in density ranged from 2 pcf. for the sand and silt mixtures to about 0.5 pcf. for the clay mixtures.

Experience has shown that corresponding differences in optimum moisture content and maximum density may be considerably more in the field during mixed-in-place construction. Thus, the data presented here, plus field experience, emphasize the necessity in field construction of obtaining moisture-density relations of soil-cement mixtures near the end of the moist-mixing period, just before compaction begins. These field optimum moistures and field maximum densities should then be used as the criteria for controlling the compaction of the mixtures, rather than laboratory or field tests made before the damp mixing has been completed. This is particularly important for mixtures made of silty and clayey soils, since it is imperative that they be compacted at

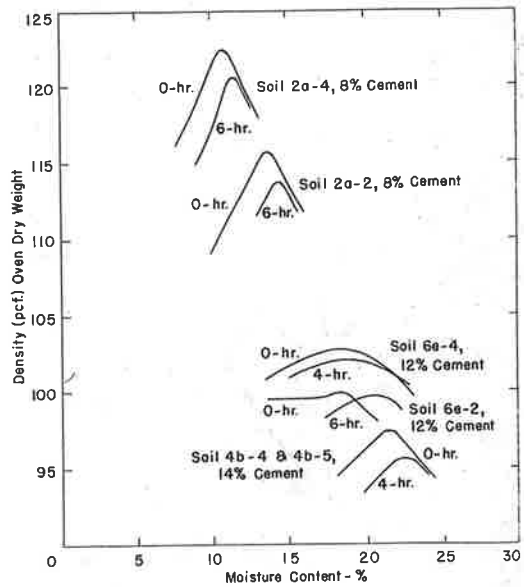

Figure 9. Moisture-density relations of soil-cement mixtures used in Series 3.

moisture-contents at or slightly greater than the new optimum.

Wet-dry and freeze-thaw test data for these soil-cement specimens, plotted in Figures 10, 11, and 12, show that the soil-cement losses increased as the length of the damp-mixing period increased. This was most pronounced when the mixtures were not intermittently mixed during the period. For instance, for Soil 4b-4 (Figure 11) the losses after two hours were 13 percent for the mixture that was intermittently mixed but 40 percent for that which was undisturbed during the standing period. The data indicate that the least possible time should be consumed in damp mixing prior to compaction and that intermittent damp mixing of short duration,

which is now common in soil-cement construction, is not seriously detrimental.

The compressive strength data are shown in Figures 13, 14 and 15. Figure 13 shows that the compressive strength for Soil 2a-2 decreased with the time of mixing, but for Soil 2a-4 it increased. (A similar observation will be noted in other test data involving prolonged mixing reported in Table 7.) Soil-cement mixtures made with Soil 2a-4 were stronger than those made with Soil 2a-2; although, as shown by Table 1, these two soils had practically the same gradation. However, Soil 2a-2 contained considerably more organic matter, and thus its reaction with cement was less effective than the reaction of Soil 2a-4. The data in Figures 14 and 15 for mix made of silty Soil 4b and clayey Soil 6e show that the strengths decreased with time of mixing. As in the case of the wet-dry and freeze-thaw tests, prolonged intermittent mixing was less harmful than an undisturbed delay.

Additional data showing the effect of prolonged mixing are presented in Series 5, Table 7; and in Series 8, Figures 20 and 21.

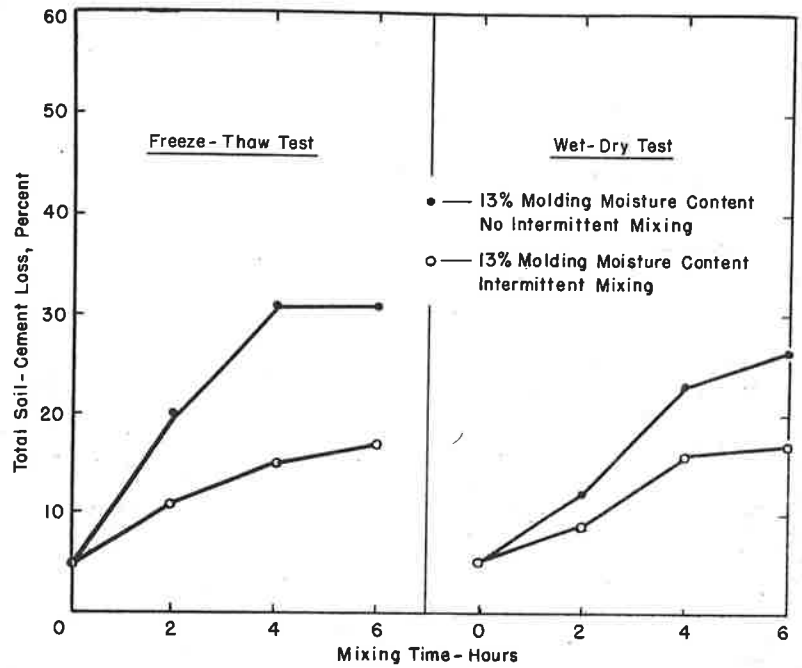

Figure 10. Effect of length of mixing time upon soil-cement losses: Soil 2a-2 plus 8 percent cement.

Series 4: Effect of Degree of Pulverization

Specifications for the construction of soil-cement base courses frequently require that 80 percent of the soil (exclusive of gravel, stone, etc.) be pulverized to pass the No. 4 sieve. Test Series 4 is an investigation of the effect of clay lumps in soil-cement, directed particularly toward the question of whether the quality of the mixture is adversely affected if less than 80 percent of the clay soil is pulverized.

Wet-dry and freeze-thaw soil-cement specimens were molded using Soils 4b-6 and 7h, each containing 0 percent, 20 percent, and 40 percent of lumps retained on a No. 4 sieve but passing a 1-inch sieve. The molding data for the specimens are given in Tables 3 and 4. In one set of specimens (A), air-dry clay lumps were added to the minus-No. -4 mixture which was at AASHO optimum moisture content. Specimens were molded immediately.

In the second set (B), air-dry clay lumps were added to the minus-No. -4 mixture, which was also air-dry. Water was then added to the total mix to bring it to optimum moisture content.

Thus, in Set A the clay lumps had less opportunity to absorb moisture during the mixing period than in Set B. In the latter case, some of the clay lumps were unintentionally pulverized during mixing. Immediately prior to molding specimens,

TABLE 3
MOLDING DATA FOR SOIL 4b-6, PLUS 14% CEMENT BY VOLUME
AASHO OPTIMUM MOISTURE CONTENT 19.8%, MAXIMUM DENSITY 102.5 PCF.
(SPECIMENS MOLDED ONLY FOR FREEZE-THAW TEST)

Set No.	Data on Clay Lumps			Moisture Content of Specimen, %		Density of Specimen, pcf.	Loss Due to 12 cyc. F-T, %
	% Included	Moisture Content, % When Added to Mix	Moisture Content, % After Mixing	Minus No. 4 Mix	Total Mixture		
	0	—	—	19.9	19.9	102.5	2
A	20	3 to 4	4 to 5	19.8	16.4	103	8
	40	3 to 4	4 to 5	19.8	13.2	100	62
B	20	3 to 4	13 to 18[a]	—	20.1	101	6
	40	3 to 4	13 to 19[b]	—	19.7	101	8

[a] 14% clay lumps (unpluverized soil retained on No. 4 sieve) after damp mix completed.
[b] 22% clay lumps (unpulverized soil retained on No. 4 sieve) after damp mix completed.

TABLE 4
MOLDING DATA FOR SOIL 7h, PLUS 12% CEMENT BY VOLUME
AASHO OPTIMUM MOISTURE CONTENT 16.8%, MAXIMUM DENSITY 108.4 PCF.
(SPECIMENS MOLDED FOR WET-DRY AND FREEZE-THAW TESTS)

Set No.	Data on Clay Lumps			Moisture Content of Specimen, %		Density of Specimen, pcf.	Loss Due to 12 Cycles, %	
	% Included	Moisture Content, % When Added to Mix	Moisture Content, % After Mixing	Minus No. 4 Mix	Total Mixture		W-D	F-T
	0	—	—	17.2	17.2	109	3	3
A	20	2	2	17	14.2	111	33	32
	40	2	2	17	11	109	100	100
B	20	2	9 to 13[a]	—	17.5	109.5	5	4
	40	2	11 to 16[b]	—	18	109.5	10	6

[a] 20% clay lumps (unpulverized soils retained on No. 4 sieve) after damp mix completed.
[b] 30% clay lumps (unpulverized soils retained on No. 4 sieve) after damp mix completed.

moisture content tests were made of the clay lumps and of the soil-cement mixtures.

As would be expected, the data in Tables 3 and 4 show that the clay lumps in Set A had gained little moisture by the time they were compacted into the test specimens, but the clay lumps in Set B had gained considerable moisture. The importance of this moisture factor is seen in the freeze-thaw and wet-dry test data, also presented in Tables 3 and 4. Here it will be noted that specimens of Set A had less resistance to alternate freezing and thawing and wetting and drying than Set B, and in some cases complete failure occurred by disruption of the specimens as the dry clay lumps absorbed water and swelled during the curing and testing periods. When the clay lumps were damp (Set B) and thus in a swelled condition at the time of inclusion in the test specimens, the unpulverized soil had little harmful effect.

These data show that the inclusion of damp clay lumps is not particularly harmful and may be permitted in soil-cement construction in accordance with properly written specifications. The inclusion of

dry clay lumps, however, is harmful and should not be permitted. To eliminate the possibility of dry clay lumps, clayey soils, when necessary, can be pre-wetted a short time prior to construction.

Series 5: Effect of Air-Entraining Cement

In Series 5 a study was conducted to determine the comparative performance of mixtures made with air-entraining and non-air-entraining cements. Both cements

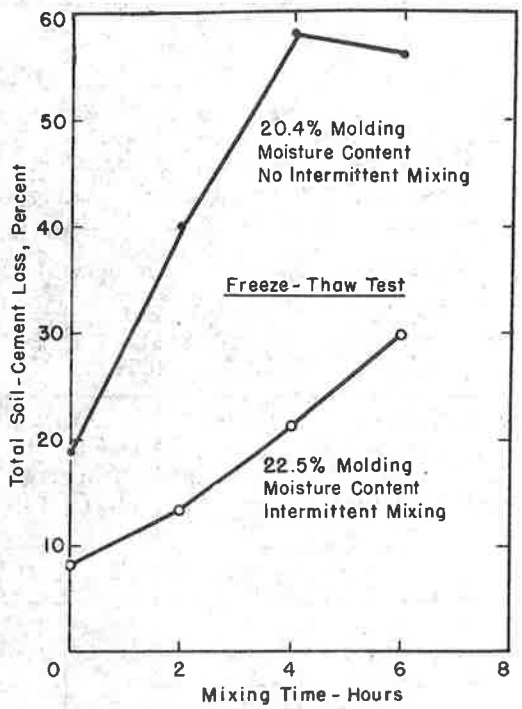

Figure 11. Effect of length of mixing time upon soil-cement losses: Soil 4b-4 plus 14 percent cement.

were from the same mill, but one (Type IA) was with vinsol resin interground. Three soils were tested with each of the cements: Soil 2a-4 plus 8 percent of cement, Soil 4b-5 plus 14 percent of cement, and Soil 6e-4 plus 12 percent of cement. Test data were obtained for mixtures that were intermittently mixed for periods of 0, 2, 4, and 6 hours. For the sake of brevity, only the data for the 0-hour and 4-hour soil-cements are presented.

Moisture-density data, presented in Table 5, were obtained for the various mixtures using the standard AASHO method. The maximum densities and optimum moisture contents for each group were practically the same regardless of the type of

TABLE 6
WET-DRY AND FREEZE-THAW TEST RESULTS FOR SOIL-CEMENTS CONTAINING TYPE I AND TYPE IA CEMENT

Soil No.	Approx. Cement Cont. by Vol., %	Type Cement	Wet-Dry Loss, % Mixing Time 0-hr	Wet-Dry Loss, % Mixing Time 4-hr	Freeze-Thaw Loss, % Mixing Time 0-hr	Freeze-Thaw Loss, % Mixing Time 4-hr
2a-4	8	I	5	10	8	16
		IA	4	10	6	13
4b-5	14	I	Tests not made		11	28
		IA			7	17
6e-4	12	I	17(8)[a]	26(18)	3	7
		IA	30(16)	25(16)	5	9

[a] Figures in () are soil-cement losses for specimens molded at a moisture content 4 percentage points wetter than ASTM indicated optimum moisture content.

cement, and the maximum densities generally decreased and the optimum moisture contents increased as the length of mixing time increased, which was also observed previously in Series 3.

Data from wet-dry and freeze-thaw tests are given in Table 6. Here it will be noted that there is relatively little difference in test data for the two cements; if there is any small advantage, it is in favor of Type IA.

Compressive strength results are given in Table 7. These data show only minor differences between the strengths obtained with Type I and Type IA cements.

Although these limited tests show little difference in the performance of mixtures made with Type I and Type IA cements, unusual effects have occasionally been noted in the laboratory with different soils and different cements. On this basis, it appears advisable to conduct the laboratory tests with the same type of cement that will be used in construction.

Series 6: Effect of Cement Content

The tests in Series 6 were made to investigate the effect of cement content on compressive strength and wet-dry and

TABLE 7
COMPRESSIVE STRENGTHS OF SOIL-CEMENTS CONTAINING TYPE I AND TYPE IA CEMENTS

Soil No.	Approx. Cement Cont. by Vol., %	Type Cement	Compressive Strengths, psi. Mixing Time, Hours: Zero, Age, Days 7	Zero 28	Zero 180	Four 7	Four 28	Four 180
2a-4	8	I	554	734	818	730	774	747
		IA	651	765	850	750	675	745
4b-5	14	I	358	440	503	325	429	486
		IA	322	411	516	314	401	489
6e-4	12	I	463	516	633	487	607	663
		IA	393	495	434	463	604	565

freeze-thaw resistance of soil-cement.

Moisture-density relations were established for mixtures of Soils 2a-6, 4d, and 7h with cement contents of approximately 8, 12, 16, 22, and 28 percent. From these curves, shown in part in Figure 16, the optimum moisture content and maximum density were obtained by interpolation and extrapolation for molding wet-dry, freeze-thaw, and compressive-strength specimens containing 6 to 34 percent of cement, as indicated in the tables and charts.

In this series, the wet-dry and freeze-thaw specimens were tested through 96 cycles. The data in Tables 8, 9, and 10 show that mixtures containing relatively high cement contents had great resistance to alternate wetting and drying and freezing and thawing. After 96 cycles many of the test specimens had practically no loss of material.

Soil-cement mixtures made of sand Soil 2a-6 were particularly resistant to wetting and drying and freezing and thawing, and as shown in Table 8, even the 8-percent-cement specimens gave fair performance for 96 cycles. All specimens containing 12 percent or more of cement were excellent, showing only a small loss after 96 cycles of test.

The data in Table 9 show that mixtures made of silty Soil 4d improved in quality as the cement content increased to 30 percent. Specimens containing 18 to 22 percent or more of cement showed good performance in the freeze-thaw and wet-dry tests for the full 96 cycles. In the wet-dry test several specimens split at the compaction planes (specimens were molded in three layers) and then cracked vertically into pieces which were hard and durable. Pieces less than ¾ inch in size were discarded and included in the material loss. The significance of this cracking has not been established; however, field performance of mixtures that crack

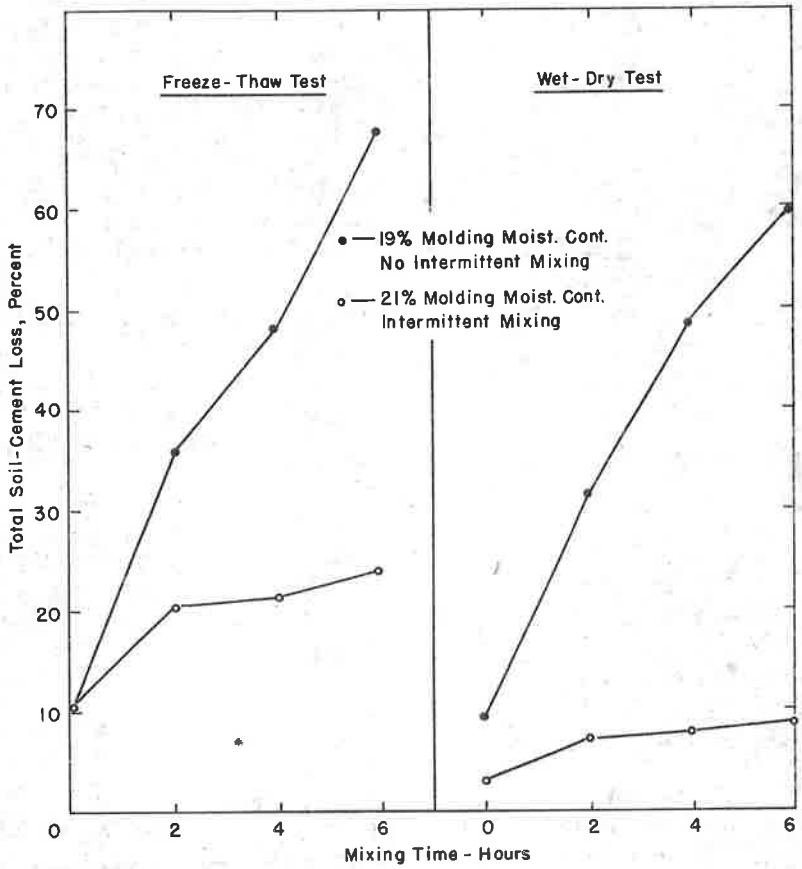

Figure 12. Effect of length of mixing time upon soil-cement losses: Soil 6e-2 plus 12 percent cement.

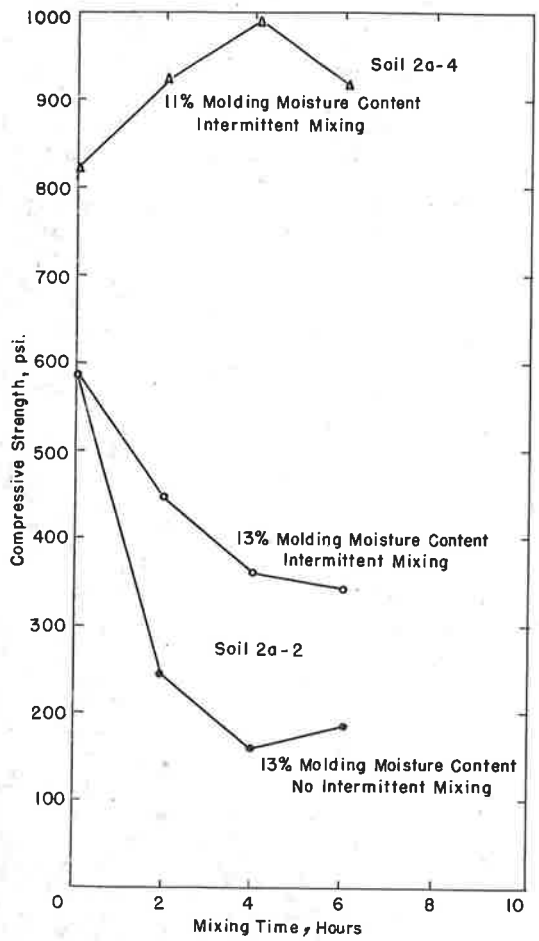

Figure 13. Effect of length of mixing time upon 28-day compressive strength: Soil 2a plus 8 percent cement.

in the laboratory wet-dry test has been satisfactory.

The data in Table 10 show that mixtures made of Soil 7h improved in quality as the cement increased up to 30 percent. Specimens containing 18 percent cement or more were good up to the 84th cycles. With this soil there was a sharp increase in quality as the cement content increased from 14 percent to 18 percent, particularly in the freeze-thaw test. As in the case of wet-dry specimens made of Soil 4d, Soil 7h specimens cracked in the wet-dry test but to a lesser extent.

The compressive-strength data for the various mixes are shown in Figures 17, 18, and 19. As might be expected, the specimens containing sandy Soil 2a-6 were considerably stronger than those containing silty Soil 4d, which were stronger than specimens containing clayey Soil 7h.

TABLE 8
Soil 2a-6
SOIL-CEMENT LOSSES % OF ORIGINAL WEIGHT

No. of Cycles	Wet-Dry Test								Freeze-Thaw Test							
	Cement Content By Vol., %															
	8	10	12	14	18	22	26	30	8	10	12	14	18	22	26	30
12	6	4	2	2	1	0	0	0	12	5	2	1	0	0	0	0
24	10	6	3	2	1	1	0	0	19	8	4	2	1	0	0	0
36	14	7	3	2	1	1	1	1	25	10	5	3	1	1	0	0
48	18	9	4	3	1	1	1	1	30	13	7	4	1	1	0	0
60	21	11	5	3	1	1	1	1	37	16	9	5	2	1	0	0
72	24	12	6	4	2	1	1	1	42	17	10	6	2	1	0	0
84	27	13	6	4	2	1	1	1	46	19	11	6	2	1	0	0
96	28	14	6	4	2	1	1	1	51	21	12	7	3	2	1	0

Soil 2a-6 showed a rather consistent increase in strength at all ages as the cement content increased from 6 percent to 30 percent. The other two soils showed a similar relationship to age 120 days, with some inconsistency in strength gain from 120 to 365 days. Maximum strengths obtained were 4,700 psi. for Soil 2a-6, 3,100 psi. for 4d, and 2,300 psi. for 7h.

Series 7: Effect of High-Early-Strength (Type III) Cement

Compressive strength tests were made to study the effect of Type III cement in soil-cement mixtures. Specimens of sandy Soil 2a-6 and silty Soil 4d, each with 6, 10, and 14 percent of cement, were molded at AASHO optimum moisture content and

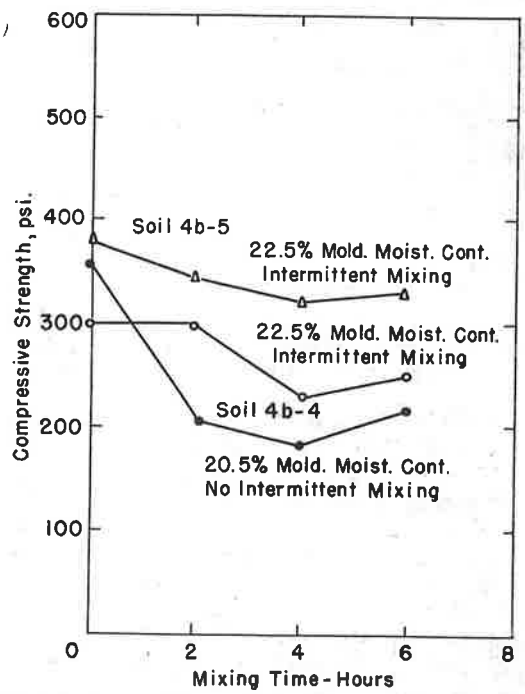

Figure 14. Effect of length of mixing time upon 28-day compressivd strength: Soil 4b plus 14 percent cement.

TABLE 9
Soil 4d
SOIL-CEMENT LOSSES % OF ORIGINAL WEIGHT

No. of Cycles	Wet-Dry Test								Freeze-Thaw Test							
	Cement Content by Vol., %															
	8	10	12	14	18	22	26	30	8	10	12	14	18	22	26	30
12	7	5	4	2	2	1	1	1	21	7	3	2	2	2	1	1
24	29	25	21	9	4	2	1	1	58	24	6	4	2	2	1	1
36	53	43	33	27	11	7	1	1	70	33	9	9	2	2	2	2
48	67	54	48	35	18	8	3	2	82	53	16	14	3	3	3	2
60	72	63	56	46	22	9	4	3	92	66	21	18	5	5	4	3
72	75	70	62	47	38	12	5	4	100	74	40	20	5	5	4	4
84	80	76	67	52	47	17	7	4	100	88	45	21	5	5	4	4
96	87	83	78	60	56	20	9	5	100	93	55	24	5	5	4	4

maximum density. To determine whether prolonged intermittent mixing would have an unusual effect on soil-cement mixtures containing Type III cement, one set of specimens was molded after a 4-hour mixing time. (The same procedures were used as in Series 3.) The moisture-density relations in Table 11 show that the optimum moisture content and the maximum density for the mixtures containing Type I or Type III cement are practically the same. As was established in Series 3, a prolonged mixing period of 4 hours resulted in a general decrease in maximum density and an increase in optimum moisture content.

Compressive strength data for specimens broken at ages of 1, 2, 3, 4, 6, 7,

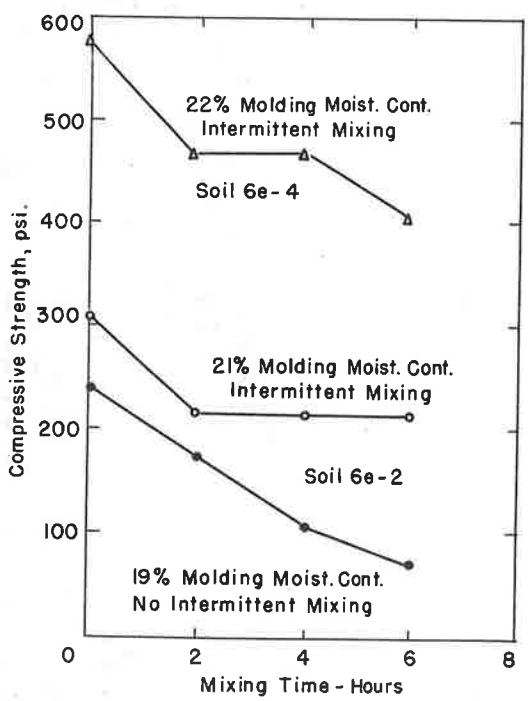

Figure 15. Effect of length of mixing time upon 28-day compressive strength: Soil 6e plus 12 percent cement.

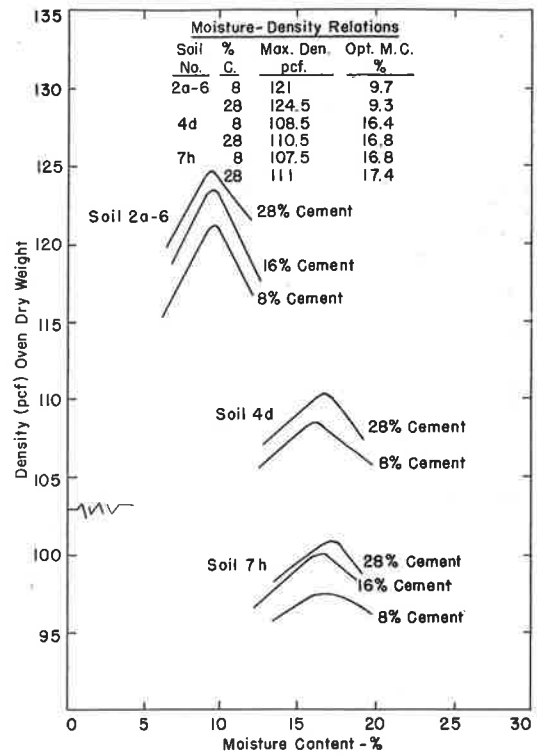

Figure 16. Moisture-density relations of soil-cement mixtures used in Series 6.

10, 14, 28, and 60 days are shown in Figures 20 and 21. For both soil types and both mixing procedures the early-age strengths were consistently greater for Type III than for Type I cement, and in nearly all cases the 60-day strengths were also greater for Type III.

The prolonged intermittent mixing was not seriously detrimental with either of the cement types, although it resulted in some loss of strength.

Series 8 and 9: Cement-Modified Soils

Most clayey soils are volumetrically unstable, for they shrink when dried and expand when wetted; furthermore, their strength characteristics are unusually sensitive to changes in moisture content. Stabilization of these soils is an important field, and portland cement in quantities less than required for regular soil-cement mixtures has been used to reduce the extent to which the soils shrink, swell, and lose strength. The material thus produced is referred to as cement-modified soil. This type of soil stabilization is

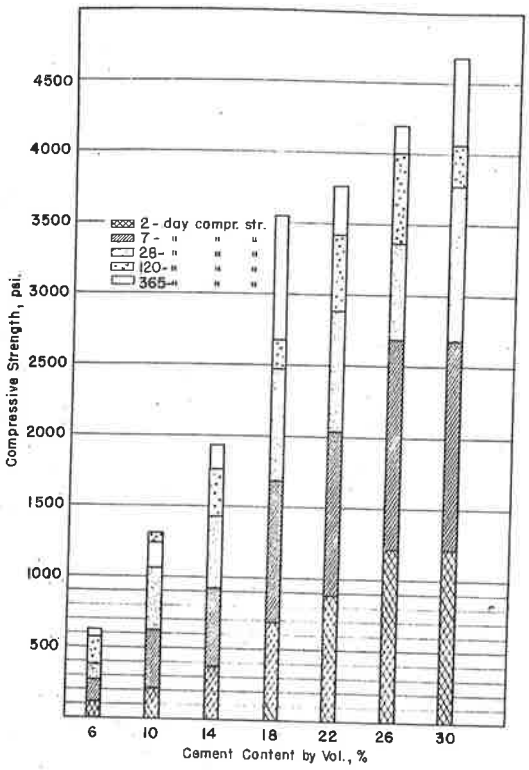

Figure 17. Effect of cement content and age on compressive strength: Soil 2a-6.

made possible through the surface-chemical effects of cement in reducing the water affinity and holding capacity of the clayey soil.

Cement modification may be applied also to granular materials which frequently in the natural state are poorly graded or contain so much clayey material that they become excessively plastic when wet. Of course these materials make excellent soil-cement mixtures with relatively low cement contents, but nevertheless there is considerable interest in modifying these materials rather than in definitely hardening them.

The optimum quantity of cement to modify a soil is not readily determined, as there are no standardized tests for evaluating the effect of the cement nor are there criteria for selecting the optimum cement content. The tests of Series 8 and 9 investigated the effect of cement on liquid limit, plastic limit, shrinkage limit, and gradation. A high plasticity index (liquid limit minus plastic limit) is normally associated with active clayey soils, whereas less-active clays, silts, or sandy soils have a lower index. Low shrinkage limits

TABLE 10
Soil 7h
SOIL-CEMENT LOSSES % OF ORIGINAL WEIGHT

No. of Cycles	Wet-Dry Test								Freeze-Thaw Test							
	Cement Content by Vol., %															
	8	10	12	14	18	22	26	30	8	10	12	14	18	22	26	30
12	9	7	3	2	1	1	1	1	10	6	3	3	2	1	1	1
24	24	18	10	4	1	1	1	1	19	18	4	4	2	1	1	1
36	40	33	16	9	2	1	1	1	36	26	7	7	3	2	1	1
48	61	45	27	18	8	2	1	1	61	41	9	8	3	2	2	2
60	72	48	39	24	11	6	1	1	84	86	41	10	4	3	2	2
72	78	49	43	31	15	7	1	1	100	100	64	25	4	3	2	2
84	80	52	45	33	19	9	3	1	100	100	83	43	4	3	2	2
96	92	56	46	35	24	11	5	1	100	100	97	52	34	27	3	3

are associated with soils that show high shrinkage, and vice versa. Thus by determining these soil constants for cement-modified soils, some measure of the effectiveness of the cement in modifying the undesirable plasticity characteristics of the soil may be obtained. With some soils, bearing-ratio tests were made to evaluate further the effect of the cement.

Series 8: Cement-Modified Fine-Grain Soils

In this series three cement-modified clayey soils were studied to determine the influence of various cement contents in altering the properties of the soils. Samples to determine test constants and grain size were prepared by compacting, at optimum moisture content, sufficient soil and cement mixture to fill a third of a standard 4-by-4.6-inch specimen mold.

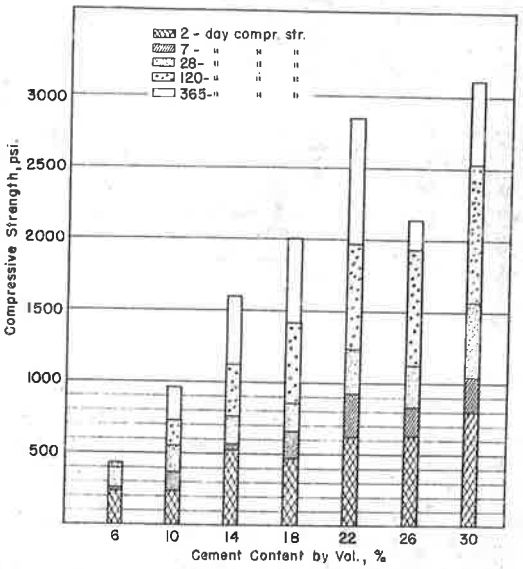

Figure 18. Effect of cement content and age on compressive strength: Soil 4d.

TABLE 11
MAXIMUM DENSITY AND OPTIMUM MOISTURE CONTENTS FOR SOIL-CEMENTS OF SOILS 2a-6 AND 4d

Soil No.	Soil 2a-6 with approx. 10% cement				Soil 4d with approx. 14% cement			
Cement	Type I		Type III		Type I		Type III	
Damp Mixing time, hr	0	4	0	4	0	4	0	4
Maximum density, pcf	122	119.5	122	119.5	107	107.5	106	105.5
Optimum moisture, %	9.7	11.0	9.7	11.0	17.8	18.3	17.8	18.2

These specimens were permitted to hydrate at 100 percent relative humidity for seven days; then part of the material was pulverized to pass a No. 10 sieve for a hydrometer analysis, and part was pulverized to pass a No. 40 sieve for determining test constants.

In one case, to see if repeated freezing and thawing affected the permanence of the cement influence, a set of specimens was subjected to 60 cycles of alternate freezing and thawing (following AASHO T 136). The materials were then pulverized to pass the sieves noted above.

The data in Tables 12 and 13 show that cement effectively reduces the plasticity index and increases the shrinkage limit of clayey soils. The small differences between the test constants before and after 60 cycles of freezing and thawing indicate that the effectiveness of the cement is not readily destroyed. The gradation analysis of the cement-modified soils shows that the percentage of clay-size particles is reduced by the cement action.

TABLE 12
TEST CONSTANTS AND GRADATION OF CEMENT-MODIFIED SOIL
Soil 6g, Clay Soil from Texas

% Cement by Volume	0	2	4	6	8	10
% Cement by Weight	0	2.16	4.37	6.61	8.90	11.24
Liquid Limit	54	55	52	50	48	47
Plastic Limit	21	21	24	31	33	35
Plasticity Index	33	34	28	19	15	12
Shrinkage Limit	18	23	26	29	31	33
Coarse Sand, % (2.0-0.25mm.)	1	4	6	18	23	35
Fine Sand, % (0.25-0.05mm.)	11	7	25	24	26	27
Silt, % (0.05-0.005mm.)	40	37	33	29	31	24
Clay (less than 0.005mm.)	48	46	36	29	20	14

Specimens compacted to approximately 92 pcf. at 26 percent water, and hydrated 7 days, then pulverized for test constants and grain size.

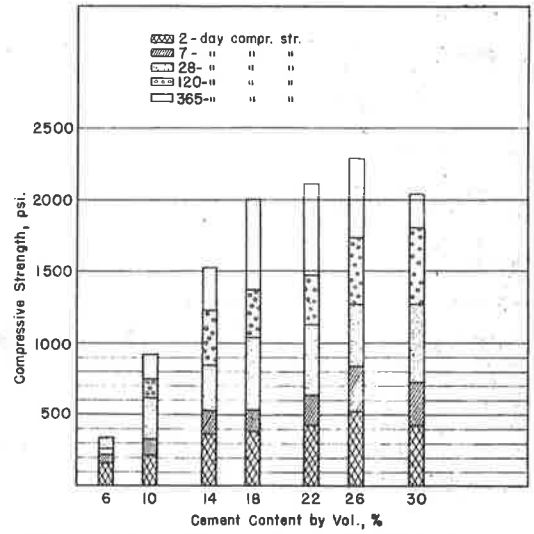

Figure 19. Effect of cement content and age on compressive strength: Soil 7h.

Additional data showing the effect of cement in modifying a silty clay loam soil are given in Table 14. In this case a bearing-ratio test was used as an aid in measuring the beneficial effect of the cement.

This test is the same as the California Bearing Ratio (CBR) test[3], but has been designated simply as a bearing-ratio test because at the high bearing values of some of the treated soils the ratio does not have quite the same significance as the CBR. The test is made by forcing a piston having an end area of 3 sq. inches into the top surface of a specimen confined in a steel mold 6 inches in diameter and 4.6 inches high. The cement-modified soil is compacted in the mold in three layers with the same compactive effort used for compacting soil-cement mixtures according to AASHO standard T 134. This requires 56 blows of the 5.5-lb. rammer on each of the three layers. In these tests, the soil and cement mixtures were hydrated in the molds for seven days at 100 percent relative humidity and then immersed in water for four days before testing. The load in pounds per square inch to force the piston into the specimen to a penetration of 0.1

[3] The California Bearing Ratio Test, reported by O. J. Porter (9) and by W. H. Jervis and Joseph B. Eustis (10), is based on the observation that a force of 1,000 psi. is required to push a 1.95-inch-diameter piston into a crusher-run, high-quality base-course material to a depth of 0.1 inch. The relative strength or California Bearing Ratio of other base course materials is obtained by determining the penetration resistance in pounds per square inch at 0.1 inch and by dividing this unit load by 1,000 and multiplying by 100 to obtain a percentage value. Thus a material having a penetration resistance of 500 psi. has a CBR of 50.

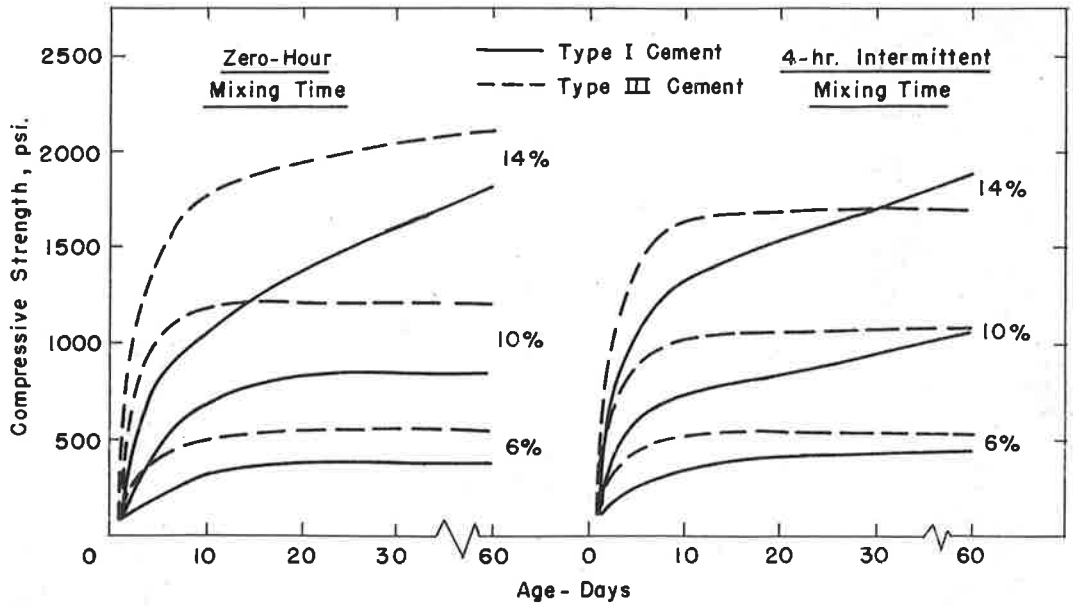

Figure 20. Comparison of compressive strengths obtained with normal (Type 1) cement and high-early-strength (Type 3) cement: Soil 2a-6.

inch, divided by 10, is referred to as the comparative-bearing ratio.

The data in Table 14 indicate that the addition of cement (up to 9 percent) to this fine-grain soil changed its plasticity characteristics by reducing the P.I. from 14 to 0 and greatly increased its strength as indicated by an increase in bearing-ratio values from 2 to 138.

Series 9: Cement-Modified Granular Soils

Relatively small quantities of cement added to granular soils not naturally suitable for base construction will increase their all-round stability and strength. Series 9 is concerned with this field of cement stabilization.

From the data previously discussed on cement-modified fine-grain soils, it appeared that the bearing-ratio test was fairly effective in showing the beneficial influence of the addition of cement to plastic soils which soften when they become wet. Thus this test was used in studying the effect of additions of relatively small quantities of cement to substandard granular materials. In addition, tests on the specimens at different ages and after various cycles of alternate freezing and thawing were made with the soniscope, a device (11) which measures the velocity with which shock pulses travel through the material. Normally, the velocity increases as the strength of the material increases and decreases if deterioration occurs due to frost action or some other cause.

Three granular soils, containing various percentages of silt and clay as listed in Table 15, were used in these tests. Soil 2b was a pit-run sand and gravel containing little silt and clay and might be considered a fairly good base material, except that it was poorly graded in the sand sizes;

TABLE 13
TEST CONSTANTS AND GRADATION OF CEMENT-MODIFIED SOIL
Soil 6e-5, Clay Soil from Illinois

% Cement by Volume	0		2		4		6		8		10	
% Cement by Weight	0		1.93		3.92		5.95		8.04		10.18	
Tests made after . . .	7 dy	60 cy	7 dy	60 cy	7 dy	60 cy	7 dy	60 cy	7 dy	60 cy	7 dy	60 cy
Liquid Limit	49	53	48	49	45	47	45	45	43	45	45	46
Plastic Limit	18	27	23	29	25	34	31	32	30	35	35	36
Plasticity Index	31	26	25	20	20	13	14	13	13	10	10	10
Shrinkage Limit	18	16	20	20	27	24	26	27	30	28	31	37
Coarse Sand, % (2.0-0.25mm.)	1	1	2	2	7	5	21	14	29	18	39	23
Fine Sand, % (0.25-0.05mm.)	6	5	10	5	22	12	27	19	24	19	21	17
Silt, % (0.05-0.005mm.)	59	52	52	51	55	51	40	50	40	42	34	39
Clay, % (less than 0.005mm.)	34	42	36	42	16	32	12	17	7	21	6	21

Specimens compacted to approximately 100 pcf. at 21 percent water and hydrated 7 days; one set pulverized; another set subjected to 60 cycles of alternate freezing and thawing, and then pulverized for test constants and grain size.

Soils 2c and 2d were gravelly plastic soils, fairly good base materials except that they contained considerable plastic clay (particularly Soil 2d) and were subject to softening when they became wet.

In a first group of tests, relatively low percentages of cement were added to Soils 2c and 2d, and test constants were determined for the modified materials after a hydration period of 2 days. The data presented in Table 15 show that the addition of cement greatly reduced the plasticity of the soils. Tests of this type were not made on Soil 2b, since it was nonplastic in its natural state.

TABLE 14
TEST CONSTANTS[a] AND BEARING RATIOS[b] OF CEMENT-MODIFIED SOIL
Soil 4e

% Cement by Volume % Cement by Weight	0 0	3 2.96	6 5.97	9 9.02
Liquid Limit	38	36	34	34
Plastic Limit	24	29	33	N.P.[c]
Plasticity Index	14	7	1	N.P.
Shrinkage Limit	20	21	26	29
Coarse Sand, % (2.0-0.25mm.)	1	1	4	6
Fine Sand, % (0.25-0.05mm.)	15	15	26	28
Silt, % (0.05-0.005mm.)	57	84[d]	70[d]	66[d]
Clay, % (less than 0.005mm.)	27			
Bearing Ratio	2	42	66	138
Bearing Ratio Specimens: Moisture Content, %	16	16	16	16
Density, pcf	98	95	96	99

[a] Test constants and grain size studies made on cement-modified soils hydrated seven days, then pulverized.
[b] Bearing ratio tests made after seven days hydration and four days immersion in water.
[c] Not plastic
[d] Silt and Clay combined

More important, however, than the reduction in plasticity of the soils, is the effect of the cement in increasing their strength. This was investigated by the bearing-ratio test on specimens containing various percentages of cement. Moisture-density tests were made using both the 4-inch-diameter mold (according to AASHO T 134 except that the material retained on a No. 4 sieve was included in the sample) and the 6-inch-diameter mold using equivalent compactive effort. Data obtained with both molds are given in Table 16. Specimens 6 inches in diameter and 4.6 inches high for the bearing-ratio test were molded of mixtures of each of the three soils containing 1½, 3, 4½, 6, and 10 percent of cement by weight. These same specimens were used for soniscope tests. In addition, standard AASHO specimens (4 inches in diameter) were molded for the AASHO wet-dry and freeze-thaw tests.

The specimens for the bearing-ratio

TABLE 15
TEST CONSTANTS AND GRADATION OF GRANULAR SOILS AND TEST CONSTANTS OF CEMENT-MODIFIED SOILS

Soil No.	2b	2c					2d				
% Cem. by Vol. % Cem. by Wt.	0	0	1.9 1.5	3.9 3	5.8 4.5	7.7 6	0	1.9 1.5	3.9 3	5.5 4.5	7.3 6
Liquid Limit	N.P.[a]	23	30	29	29	29	28	34	34	32	33
Plastic Limit	N.P.	13	22	22	24	28	13	25	28	29	32
Plasticity Index	N.P.	10	8	7	5	1	15	9	6	3	1
Plus No. 4 Gravel	25	20					15				
Coarse Sand, % (No. 4-0.25mm.)	67	54					43				
Fine Sand, % (0.25-0.05mm.)	6	7					8				
Silt, % (0.05-0.005mm.)	1	11					16				
Clay, % (less than 0.005)	1	8					18				

[a] Not Plastic

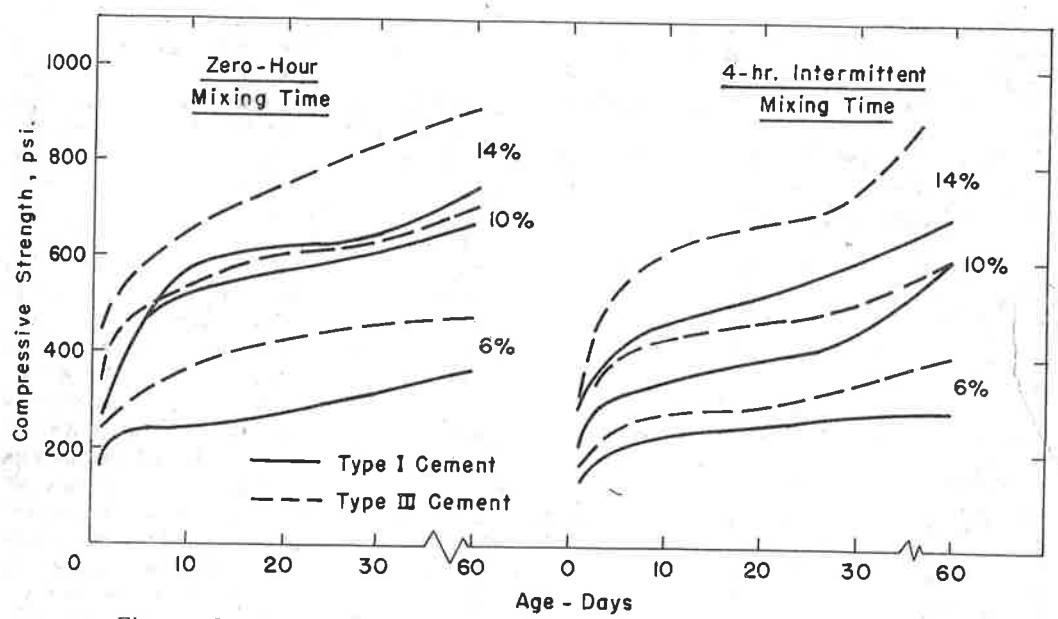

Figure 21. Comparison of compressive strengths obtained with normal (Type 1) cement and high-early-strength (Type 3) cement: Soil 4d.

and soniscope tests were retained in the molds and placed in the moist room. Several specimens of each cement content were molded so that they could be tested after various ages in the moist room and also after various cycles of alternate freezing and thawing. Thus, the tests permitted a study of the effect of cement content and time of curing on the bearing ratio and pulse velocity and, also, a study of the deteriorating effects of freezing and thawing. The bearing-ratio and soniscope specimens for alternate freezing and thawing were cured 21 days in the moist room before the test was started. The freeze-thaw cycle consisted of a period of 16 hours in the freezer at -20 F., followed by a period of 8 hours in the moist room at 73 F. During the test, the specimens were placed on their sides.

TABLE 16
MOISTURE-DENSITY RELATIONSHIPS

Soil No.	4-in. Diam. Mold						6-in. Diam. Mold					
	Cement Content by Weight, %											
	0		3		6		0		3		6	
	D[a]	O[b]	D	O	D	O	D	O	D	O	D	O
2b	133	9.5	132	10	132	10	133	8.5	133	9	134	8.5
2c	130	10	128	10.5	127	10.5	132	9.5	131	10	131	10
2d	126	11	123	12	122	12.5	127	10.5	126	11	124	11.5

[a] D = Maximum Density, pcf.
[b] O = Optimum Moisture Content, %

The cement contents used in this series

TABLE 17
BEARING RATIOS AT DIFFERENT AGES AND AFTER FREEZING AND THAWING
Soil 2b

% Cement by Wt.	As Molded Unsoaked	After Moist Room Cure, Days					After F-T, Cycles		
		7	21	37	87	161	12	48	100
0	36	38	40	41	51		17		
1 1/2	32	164	265	299	336	493	72	24	
3	67	471	578	702	741	806	435	464	463
4 1/2	50	595	788	809	1029	1108	752	743	755
6	40	788	993	1098	1186	1633	963	941	1091
10					1930	4270		1565	1780

overlap those required to produce soil-cement mix according to the criteria accepted for use with AASHO methods T 135 and T 136, the wet-dry test and the freeze-thaw test.

Based upon these tests, the following minimum cement quantities are required with the soils to produce "soil-cement": Soil 2b, 3 percent by weight (4.2 percent by volume); Soil 2c, 4.5 percent by weight (5.8 percent by volume); and Soil 2d, 6 percent by weight (7.3 percent by volume). These cement factors may be kept in mind to differentiate between so-called cement-modified soil and soil-cement.

The bearing-ratio and pulse-velocity data are presented in Tables 17 to 22. Included are the bearing-ratio values for specimens after periods of 7, 21, 37, 87, and 161 days in the moist room and after 12, 48, and 100 cycles of alternate freezeing and thawing. The moist room specimens at ages 37, 87, and 161 days are the same age as the freeze-thaw specimens after 12, 48, and 100 cycles of test.

Soniscope (pulse-velocity) values were obtained for specimens after curing for periods up to 87 days in the moist room and after as many as 48 cycles of freezing and thawing. Some of the specimens with low cement contents deteriorated fairly rapidly, and soniscope readings could not be made during the freeze-thaw test; in several cases the 100-cycle bearing-ratio tests could not be made.

Table 17 gives the bearing-ratio data for Soil 2b. Here it will be seen that the cement-treated soil mixtures, even with relatively low cement contents, had very high values. For instance, the mixture containing 3 percent of cement had a bearing ratio of 471 at age 7 days, and 806 at 161 days. Other mixtures had ratios considerably over 1,000. In making some of these tests, the loading piston was forced into the specimen to a depth of only 0.05 or 0.075 inch. Values in this high range have little significance, other than as indicators of relative hardness and resistance to penetration. Freezing and thawing reduced the bearing ratios for the mixture containing 1½ percent of cement; but mixtures containing 3 percent or more of cement showed no deterioration during the freeze-thaw test, although their rate of strength gain was less than that of specimens continously moist cured.

TABLE 18
PULSE VELOCITIES AT DIFFERENT AGES AND AFTER FREEZING AND THAWING
Soil 2b

% Cement by Wt.	Velocity Through Specimen-100 ft/sec									
	After Moist Room Cure, Days						After F-T, Cycles			
	7	21	37	53	71	87	12	24	36	48
1 1/2	65	73	77	79	83	82				
3	82	91	98	100	102	100	87	89	89	88
4 1/2	96	105	115	115	120	118	104	104	105	104
6	107	116	120	124	125	125	113	116	114	113
10	119	127	129	130	136	135	123	128	129	128

The soniscope data for Soil 2b are presented in Table 18. The pulse velocities did not decrease significantly during the freeze-thaw test, again showing good resistance to deterioration. As might be expected, the pulse velocities for soil-cement mixtures of Soil 2b increased with increased cement content and with time of moist curing. Velocities of more than 10,000 ft. per sec. were common.

Bearing-ratio and soniscope data for Soil 2c are presented in Tables 19 and 20. This soil required higher cement contents than Soil 2b to achieve the same degree of hardness as indicated by bearing-ratio

TABLE 19
BEARING RATIOS AT DIFFERENT AGES AND AFTER FREEZING AND THAWING
Soil 2c

% Cement by Wt.	As Molded Unsoaked	After Moist Room Cure, Days					After F-T, Cycles		
		7	21	37	87	161	12	48	100
0	11	5	3	6	5		3	2	
1 1/2	10	148	230	233	245	378	67	18	
3	15	255	302	316	414	727	131	34	
4 1/2	15	326	387	453	564	901	323	293	358
6	14	459	518	579	742	1048	418	499	507
10					1317	1361		935	829

TABLE 20
PULSE VELOCITIES AT DIFFERENT AGES AND AFTER FREEZING AND THAWING
Soil 2c

% Cement by Wt.	Velocity Through Specimen - 100 ft/sec									
	After Moist Room Cure, Days						After F-T, Cycles			
	7	21	37	53	71	87	12	24	36	48
1 1/2	69	76	85	86	89	86				
3	78	84	90	92	98	96	55			
4 1/2	85	88	97	98	102	102	74	80	82	82
6	87	93	100	102	104	105	87	87	91	91
10	97	101	105	107	111	110	98	97	102	103

and soniscope tests. The data show, however, that cement quantities of 4½ percent by weight or more produced soil-cement mixtures that had good resistance to freezing and thawing. For instance, the 4½-percent mixture showed a bearing-ratio of 323 after 12 cycles of test and 358 after 100 cycles, and pulse velocities for this same mixture were 7,400 ft. per sec. after 12 cycles, and 8,200 ft. per sec. after 48 cycles.

Corresponding data for soil 2d are shown in Tables 21 and 22. This soil required more cement than Soil 2c to resist deterioration in the freeze-thaw test. A cement content of 6 percent by weight produced a mixture having good bearing ratios for continuous moist curing, but this same mixture in the freeze-thaw test showed a loss both in bearing ratio and in soniscope velocity. The soil-cement mixture with 10 percent of cement went through 100 cycles of test without apparent deterioration as indicated by bearing-ratio and soniscope tests.

The test data show that relatively small quantities of cement notably increased the overall strength characteristics and resistance to softening from freeze-thaw action of the three substandard granular base materials. Although much value was obtained from cement contents that might be said to produce cement-modified soil, considerably more value was obtained from the slightly greater cement contents required to produce soil-cement mixtures. Both the bearing-ratio and the soniscope tests appeared to be effective in measuring the relative deteriorating effects of alternate freezing and thawing.

SUMMARY AND CONCLUSIONS

The data presented in this report are intended to be helpful to engineers in developing an understanding of many of the physical properties of soil-cement mixtures. In some instances, more mixtures have been tested under each series than were reported in this paper. The data from the other tests corroborate the data presented here. Nevertheless, it is possible that the performance of some may not follow the patterns established here, because of different chemical and physical properties of the soils involved. The comments which follow summarize the information developed from these tests.

TABLE 21
BEARING RATIOS AT DIFFERENT AGES AND AFTER FREEZING AND THAWING
Soil 2d

% Cement by Wt.	As Molded Unsoaked	After Moist Room Cure, Days					After F-T, Cycles		
		7	21	37	87	161	12	48	100
0	10	7	7	5	6		2	2	
1 1/2	18	94	109	129	128	140	17	7	
3	19	171	240	268	320	396	28	15	
4 1/2	19	226	295	299	355	584	93	31	
6	19	280	367	388	438	738	198	31	
10					709	1144		499	517

TABLE 22
PULSE VELOCITIES AT DIFFERENT AGES AND AFTER FREEZING AND THAWING
Soil 2d

% Cement by Wt.	Velocity Through Specimen - 100 ft/sec									
	After Moist Room Cure, Days						After F-T, Cycles			
	7	21	37	53	71	87	12	24	36	48
1 1/2	66	67	68	68	68	69				
3	77	79	80	80	82	85				
4 1/2	79	81	81	83	88	88	55			
6	82	82	81	84	88	89	70	67	27	
10	89	95	91	96	98	99	85	89	96	94

Series 1 and 2: Moisture and Density

The moisture content of a soil-cement mixture and the density to which the material is compacted have a great influence upon the quality of the product after cement hydration.

For general soil-cement-paving construction, the most-effective moisture content is approximately equal to or slightly above the optimum moisture content indicated by AASHO method T 134; moisture contents below the optimum may produce silty and clayey mixtures of inferior quality. The quality improves as the density increases; thus, mixtures at proper moisture content should be compacted to the highest practical density, at least equal to that obtained by AASHO method T 134.

For special soil-cement construction where very-heavy compactive effort is available, the quality of the mixture may be improved by lowering the moisture content and greatly increasing the density. However, to take advantage of this, special laboratory tests are necessary to establish moisture and density control limits, and careful checks must be made in the field to insure that these control limits are closely maintained.

Series 3: Prolonged Mixing Periods

Prolonged periods of damp mixing impaired somewhat the quality of the mixture. However, with most soils, mixing periods as long as 4 hours were not seriously harmful, provided the mixture was intermittently mixed several times an hour and provided the moisture content at time of compaction was at or slightly above the optimum prevailing at that time. The optimum moisture content generally increases as the length of mixing time increases; therefore, moisture-density tests are necessary toward the end of the damp-mixing period to determine the new optimum prevailing at that time.

Series 4: Clay Balls in the Mix

The quality of silty and clayey soil-cement mixtures was highest when 100 percent of the soil (exclusive of gravel, stones, etc.) was pulverized to pass a No. 4 sieve. However, the quality was not seriously affected by the presence of as much as 30 percent of unpulverized soil, provided the lumps of soil were damp at the time the soil-cement mixture (at optimum moisture content or slightly above) was compacted. If the soil lumps were dry at the time they were compacted in the soil-cement, the quality of the material was seriously impaired.

Series 5: Air-Entraining Cement

Soil-cement mixtures containing air-entraining (Type IA) cement behaved approximately the same as those containing Type I cement. Moisture-density relations, compressive strengths, and wet-dry and freeze-thaw test results were sufficiently similar to show that the cements may be used interchangeably in soil-cement construction.

Series 6: High Cement Contents

The compressive strength and resistance to wetting and drying and freezing and thawing increased as the cement content was increased. Good quality mix was obtained with cement contents generally in the range of 8 percent to 14 percent (depending upon the soil). However, mixtures having unusually high compressive strength (2,000 to 4,000 psi.) and excellent resistance to alternate freezing and thawing and wetting and drying were obtained with relatively high cement contents of, say, 22 percent to 30 percent, by volume.

Series 7: High-Early-Strength Cement

High-early-strength (Type III) cement hardened soil-cement mix at a faster rate than Type I cement. Prolonged mixing periods of several hours did not seriously impair the quality of mix containing Type III cement. Thus, for special construction where high early strength is required, Type III cement may be used.

Series 8: Cement-Modified Fine Grain Soils

The addition of cement in quantities less than those required to produce hardened soil-cement mix reduced the plasticity of clayey soils, thus reducing their tendency to shrink and swell excessively.

Series 9: Cement-Modified Granular Soils versus Granular Soil-Cement

The addition of relatively small quantities of cement to substandard granular

materials reduced their plasticity and increased their strength. The addition of slightly greater quantities of cement (producing soil-cement) materially increased strength above those of the cement-modified soils and resulted in materials having considerable resistance to deterioration from alternate freezing and thawing. In this study, bearing-ratio and soniscope tests were effective in measuring the progressive deterioration of specimens in the freezing-and-thawing test.

Acknowledgment

The data reported were accumulated at the Portland Cement Association Laboratories over a period of more than 15 years. Consequently, the author is indebted to a number of engineers who assisted in conducting the test. Much of the work was done by E. G. Robbins and M. S. Abrams. Miles D. Catton, now assistant to the vice president for research and development, was in administrative charge of most of the research and development work on soil-cement mix. The paper was reviewed by Douglas McHenry, director of development, whose comments are gratefully acknowledged.

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