RESEARCH ON THE PHYSICAL RELATIONS OF SOIL AND SOIL-CEMENT MIXTURES

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SYNOPSIS

The report presents the results of soil and soil-cement tests on 329 soils from 37 States which were performed in the Portland Cement Association soil-cement laboratory during the past five years. Included are the usual routine tests on soils and moisture-density, wet-dry, freeze-thaw and compressive strength determinations on soil-cement mixtures

These tests show the predominate physical relations of soil and soil-cement mixtures. A grouping of soils according to the U S P R A classification shows, in general, that soils in the A-2 and A-3 groups will require 6, 8, or 10 per cent cement by volume for satisfactory results, the A-4 and A-5 groups will require 8, 10, or 12 per cent cement by volume and the A-6 and A-7 groups will require 10, 12, or 14 per cent cement by volume for satisfactory results These same data show the generality that cement requirements increase with silt and clay content Data on hydrogen ion concentration (pH) are included showing that a soil may be acid, neutral, or alkaline and yet it will respond satisfactorily to hardening with cement The study of organic contents of soils shows this factor to be most diverse and it, therefore, has a variable influence on soil-cement mixtures ranging from no perceptible influence to a major influence.

The development of scientific control methods are also discussed for use on soils having irregular type moisture-density curves as well as those having parabolic type moisture-density curves.

The report points out that such factors as grain size, gradation, silt and clay content, density, optimum moisture, water holding capacity, surface area, organic content, void-cement ratio, hydrogen ion concentration, compressive strength, etc., contribute to an analysis of soil and soil-cement relations but they are so diverse and interrelated in character and influence that none of them have a constant, major, predominating influence. Study of these test results together with correlated field experiences builds up an understanding of soil-cement as a structural material having its own characteristics which are definite, consistent, and reproducible. All these facts together show that some factor or influence of a chemical or physico-chemical nature, such as the mineral composition of the soil grain and its adsorbed ions, may play a predominate part in evaluating soil and soil-cement relations and research on these factors holds promise of contributing valuable information on these relations.

The investigation of soils and soil-cement mixtures was undertaken by the Development Department of the Portland Cement Association in 1935. The primary objective of this work was to determine whether scientific control methods could be evolved and applied to a combination of soil and cement to produce a hard, durable structural material for light traffic roads. A secondary objective of equal importance from a practical standpoint was to determine whether such a structural material could be produced in the field with available road building equipment at a reasonable cost. The same research covered the influence of cement in changing the characteristics of soils, such as water-holding capacity and density.

The results of this early work, setting forth scientific control methods which were evolved, as well as practical and economical field construction methods, have appeared in previous Proceedings of the Highway Research Board.[1]

[1] Miles D. Catton, "Basic Principles of Soil-Cement Mixtures and Exploratory Laboratory Results," *Proceedings*, Highway Research Board, Vol 17, Part II (1937).

Miles D Catton, "Laboratory Investigation

This report includes

1. Test results on some of the heavy clay soils not hardened successfully in the exploratory research started in 1935.
2. Summary and brief interpretation of all the exploratory test data in the light of present knowledge.
3. Physical Relations of Soils and Soil-Cement Mixtures. Summary and interpretation of test results on soils received from field projects.
4. Interpretation of some of the major physical and physico-chemical relations of soil and soil-cement.

the U. S. Public Roads Administration (U.S.B.P.R.). The exploratory work indicated, however, that laboratory procedures could be evolved for hardening them with cement and the following brief summary of the successful outcome of these tests will complete the record on the soils included in the exploratory research. Two additional research soils were retested.

In the exploratory research work, these heavy clays were tested with relatively low cement contents. However, the exploratory test results indicated a general trend that cement requirements for adequate hardening would increase with the clay content of the soil.

TABLE 1

HEAVY CLAY SOILS—EXPLORATORY RESEARCH

Laboratory Sample No.	Soil Group U S P R.A. Classification	Source	Description
6b	A-7-6	Fairfax Co , Va	Clay subsoil
6c	A-6	Guadalupe Co , Tex.	Clay subsoil
7c	A-7-6	Pike Co , Mo	Clay subsoil
7d	A-7	Hinds Co , Miss.	Clay subsoil
7e	A-7	Hinds Co , Miss.	Clay (Sharkey) subsoil
8a	A-8	Minnesota	Peaty muck (silt loam) topsoil
6d*	A-6	San Joaquin Co., Calif.	Clay (adobe) topsoil
7b*	A-6-7	Michigan	Clay subsoil

* Retested.

TEST RESULTS ON HEAVY CLAY SOILS

In the report on soil-cement exploratory laboratory results,[1] six heavy clay soils, (see Table 1), did not show satisfactory hardness with the cement contents, moisture contents, and densities investigated. The physical test constants and grain size of these soils are given in Table 2 At the time these heavy clay soils were selected, they were among the most unfavorable subgrade soils yet identified and tested by

Also, it was found in later work that some soil-cement mixtures produced moisture-density curves with two peaks or humps near each other and extended testing established the peak of the curve at the higher moisture content, the second peak, as the "optimum" for these slightly irregular curves. These soils were tested further by the simple method of increasing cement contents until satisfactory results were obtained.

More important, from a research standpoint, was the fact that the moisture-density curves for some of the heavy clays did not show a peak or optimum for judging the moisture content and

of Soil-Cement Mixtures for Subgrade Treatment in Kansas," *Proceedings*, Highway Research Board, Vol. 17, Part II (1937)

Miles D Catton, "Soil-Cement Mixtures for Road," *Proceedings*, Highway Research Board, Vol 18, Part II, p. 314 (1938).

density required to produce most satisfactory results. Hence, it was necessary to conduct research to determine moisture and density control factors for soils not producing parabolic type curves with the moisture-density test. Such a research project was set up and followed with tests on the research soils in question.

Shortly after the exploratory research previously reported was completed, which set forth scientific control methods,[2] a series of compressive tests was included in routine testing of soil-cement mixtures. The compressive test together with other research results indicated that the compressive strength of a particular soil-cement mixture would vary with density and moisture content and might serve as a test method for determining approximate values for density and moisture control. It should be emphasized that in this series of tests the moisture and density used for a particular test specimen corresponded to some one point on the moisture-density curve for that particular soil-cement mixture. The practical, probable limitations of handling soils at a moisture content much above the plastic limit on field construction were also recognized.

TABLE 2

PHYSICAL TEST CONSTANTS AND GRAIN SIZE[a] HEAVY CLAY SOILS—EXPLORATORY RESEARCH

Laboratory Sample No.	6b	6c	7c	7d	7e	8a	6d	7b
Liquid Limit (L L.)	62	61	60	118	67	170	48	44
Plastic Limit (P.L)	29	23	27	35	22		20	24
Plasticity Index (P.I)	33	38	33	83	45	0	28	20
Shrinkage Limit (S L)	13	10	14	14	12	66	10	18
Shrinkage Ratio (S R)	1 9	2 1	1 9	1 9	1 9	0 8	2 0	1 8
Centrifuge Moisture Equivalent (C M E)	40	39	39	98[c]	58[c]	92	31	52[c]
Field Moisture Equivalent (F.M E)	39	34	34	50	32	244	28	23
Sand, above 0 05 mm	23	10	11	14	32	10	14	5
Silt, 0 05–0 005 mm.	35	43	43	18	16	80	48	19
Clay, 0.005—0 mm.	42	47	46	68	52	10	38	76
Colloids, below 0 001 mm [b]	24	20	29	[d]	28	7	18	32
Specific Gravity	2 815	2 720	2 711	2 761	2 721	2 077	2 696	2 727

[a] Tests conducted by Division of Tests, Public Roads Administration
[b] Also included in clay fraction
[c] Water logged
[d] Flocculated

Strength Tests of Soil-Cement Mixtures Having Parabolic Type Moisture-Density Curves

Soils having parabolic type moisture-density curves were selected for initial investigation of compressive strength "patterns". Soil-cement specimens 2 in high and 2 in. in diameter were molded in a special apparatus (see Fig 1), which permitted compaction from both ends of the specimen to give very close density control. In the lighter soils a very uniform density was obtained

[2] These test procedures have been approved by the American Society for Testing Materials and carry the A S T.M Designations· D558-40T, D559-40T, and D560-40T

throughout but on the clay soils there was some decrease in density in the center of the specimen, showing the difficulty of obtaining uniform density by straight, confined compressive forces on even these small specimens and in spite of compacting from both ends of the specimen.

Theoretical quantities of soil, cement, and moisture required to produce a specific density and moisture content, selected from a point on the soil-cement moisture-density curve, were computed

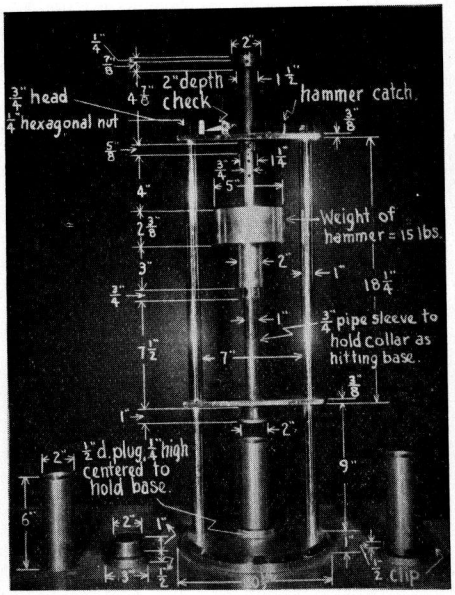

Figure 1. Apparatus for molding two-inch compressive strength specimens of soil-cement.

for a 2-in. specimen of required density. Cement contents by volume of 6 per cent and 10 per cent were generally used. Occasionally, cement contents of 14 per cent and 18 per cent were selected when higher cement contents were needed to adequately harden the soil. These materials were then combined, placed in the mold, and compacted to produce the 2-in. specimen which then had the required characteristics. Specimens were molded in pairs for compressive strength tests at ages of 2, 7, and 28 days.

After molding, they were stored in an atmosphere of high humidity at room temperature until they attained the required age. On the day of test, the 2-in. strength specimens involved were removed from storage and submerged in water for 1 hr. before testing. A previous research project had proved that unless the specimens were saturated before testing compression results included a variable clay cohesion factor. The soaking procedure eliminated this factor to a considerable extent so that the compressive strength remaining was a direct criterion of the influence of cement in producing compressive strength.

In addition to molding strength specimens representing various points on the moisture-density curves, usual wet-dry and freeze-thaw specimens were molded representing the same points. Results of these tests are given on Figures 2 and 3.

In Figure 2, illustrating test results on a silty clay loam, it will be noted that the compressive strength results, when plotted, give a parabolic type curve. The maximum strength is obtained at a moisture content slightly below that giving maximum density in the moisture-density test. Also, it will be noted that best combined results in the wet-dry test and freeze-thaw tests are obtained at a moisture content slightly above that giving maximum density in the moisture-density test. Note that the wet-dry test is not critical for this soil.

In Figure 3, illustrating test results on a clay, it will be noted that the compressive strength results also give a parabolic type curve. The maximum strength is obtained at a moisture content equal to that giving maximum density in the moisture-density test. Also, it will be noted that best combined results in the wet-dry and freeze-thaw tests are obtained at a moisture content slightly above that giving maximum density in the moisture-density tests. Note that the wet-dry test is most critical in this

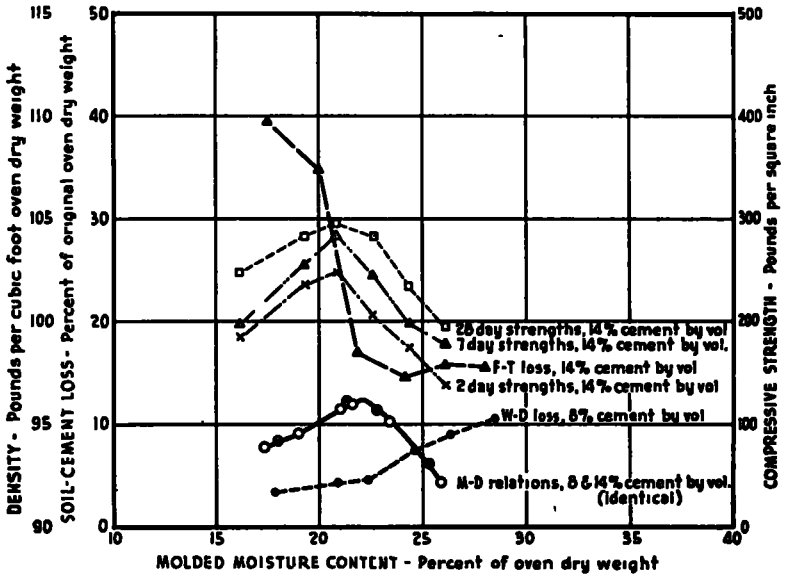

Figure 2. Relation of moisture-density (M-D) relations (A.S.T.M. Designation: D558-40T), wetting and drying (W-D) and freezing and thawing (F-T) tests (A.S.T.M. Designations: D 559-40T & D 560-40T) and compressive strengths. Soil no. 4b-3, Illinois silty clay loam U. S. P. R. A. soil group A-4. Density of test specimens corresponds to density as shown on moisture-density curve for same moisture content.

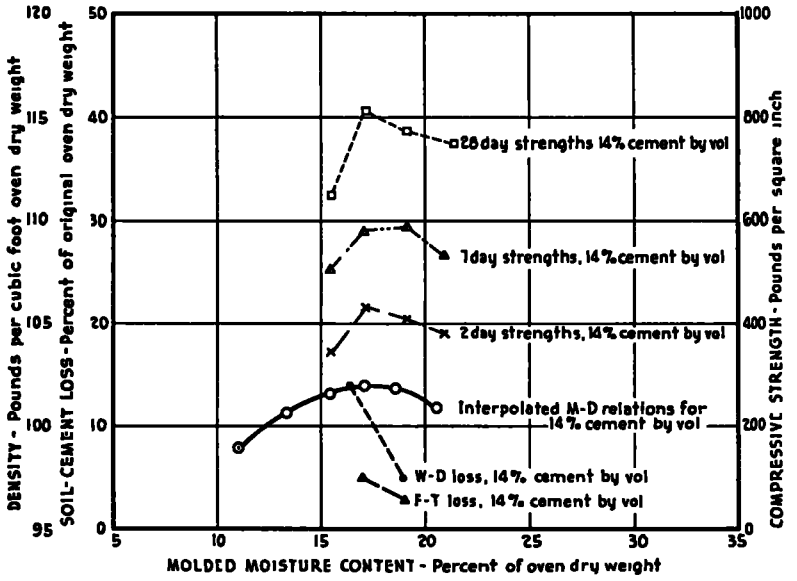

Figure 3. Relation of moisture-density (M-D) relations (A.S.T.M. Designation: D 558-40T) wetting and drying (W-D) and freezing and thawing (F-T) tests (A.S.T.M. Designations: D 559-40T & D 560-40T) and compressive strengths. Soil no. 7c, Missouri clay subsoil. U. S. P. R. A. soil group A-7-6. Density of test specimens corresponds to density as shown on moisture-density curve for same moisture content.

case although soil-cement losses are about equal at the moisture contents producing satisfactory control.

These data are most important in that they show that there is reasonable agreement in the optimum moistures for maximum density, maximum compressive strength, and also for maximum hardness and durability as shown by the wet-dry and freeze-thaw tests. Other research data on these relations give comparable results. Thus, the optimum moisture for maximum compressive strength and optimum for maximum density are in close agreement. Also, the average of optimum moisture for wet-dry results and freeze-thaw results is in close agreement with the optimum moisture for maximum density.

Another important point on moisture control on *heavy silts and clay soils* is shown in Figures 2 and 3, and verified in other research work which merits particular comment although it will not be covered in detail in this report. This point is that with heavy silts and clay soils having parabolic type moisture-density curves, hardness and durability equal to or slightly greater than that obtained with moisture at the optimum moisture content can be obtained with moisture contents slightly above the optimum moisture content producing maximum density and maximum compressive strength. The moisture range involved and the increase in hardness and durability vary with each soil. The same research on these soils shows that compressive strengths decrease rapidly and soil losses in the wet-dry and freeze-thaw tests increase rapidly at moisture contents below the optimum Thus, for practical field control the safe moisture to use in building soil-cement in heavy silts and clays is the optimum or slightly above, even though some density and compressive strength may be sacrificed. The sacrifice of some compressive strength is not critical since the lower strength obtained is adequate for this type of construction.

Other research completed and being prepared for publication shows the influences of density variables. While these tests are primarily of interest at this time from a laboratory research standpoint, they show that decreases in density below "maximum density" produce substantial decreases in compressive strengths and durability. Also, that small increases in density above "maximum density" produce somewhat better results but require large increases in compaction forces.

Tests of Soil-Cement Mixtures Not Having Parabolic Type Moisture-Density Curves

After having established the fact that the optimum moisture for maximum compressive strength was also near the optimum for hardness and durability, the exploratory research heavy clay soils having irregular moisture density curves, previously mentioned, were tested. Optimum moisture was determined by compressive strength tests and these followed by usual wet-dry and freeze-thaw tests. Then cement contents were increased, using moisture contents embracing the peak of the strength-moisture content curve, until satisfactory results were obtained. It should be noted that experienced soil laboratory engineers are required for proper handling of these heavy clays. Figures 4 and 5 are representative of the results of these tests.

The data for irregular moisture-density curves, in Figures 4 and 5, show that adequate hardness and durability are obtained at moisture contents slightly above the moisture contents giving maximum compressive strengths. This substantiates the same point for regular moisture-density curves.

Results

Table 3 gives the major results of the tests on the heavy clays. Note the very

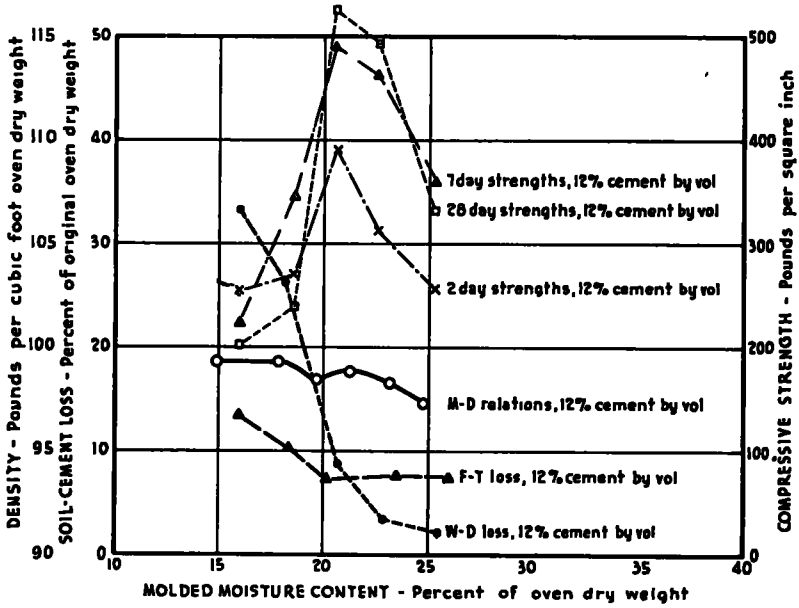

Figure 4. Relation of moisture-density (M-D) relations (A.S.T.M. Designation: D 558-40T) wetting and drying (W-D) and freezing and thawing (F-T) tests (A.S.T.M. Designations: D 559-40T and D 560-40T) and compressive strengths. Soil no. 6e, Illinois clay U. S. P. R. A. soil group A-6. Density of test specimens corresponds to density as shown on moisture-density curve for same moisture content.

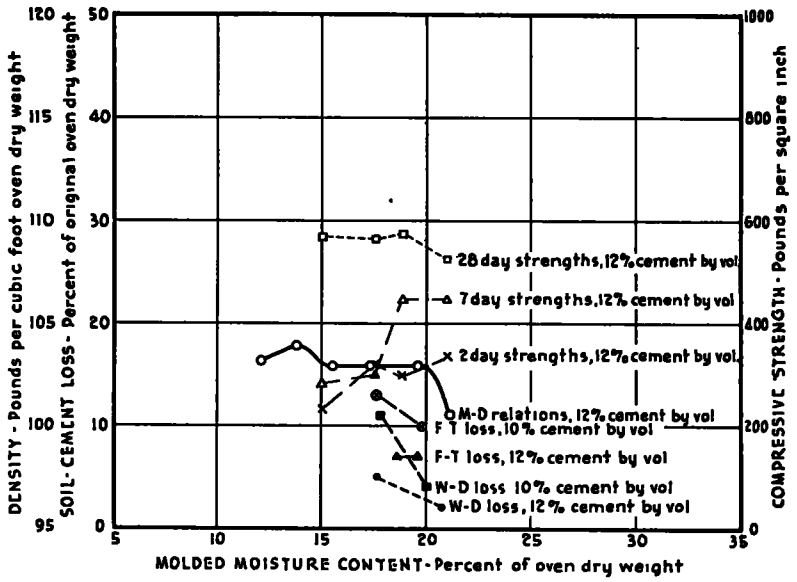

Figure 5. Relation of moisture-density (M-D) relations (A.S.T.M. Designation: D 558-40T), wetting and drying (W-D) and freezing and thawing (F-T) tests (A.S.T.M. Designations: D 559-40T and D 560-40T) and compressive strengths. Soil no. 7b, Michigan clay subsoil U. S. P. R. A. soil group A-6-7. Density of test specimens corresponds to density as shown on moisture-density curve for same moisture content.

wide range in cement contents required. Also note the variations in the physical test constants and grain size test results shown in Table 2. For example. soil 6b contains only 42 per cent clay and requires 30 per cent cement by volume, yet soil 7b containing 76 per cent clay requires only 12 per cent cement by volume. In addition, results are given for soil 8a which is a peaty soil having very low density and very high organic content. The successful hardening of this soil is most significant in analyzing many aspects of soil-cement mixtures, although the hardened mixture itself would probably not be suitable for roadways.

Figure 6 shows the wet-dry test specimens and Figure 7 shows the freeze-thaw specimens at the conclusion of testing.

TABLE 3

CONTROL FACTORS FOR ADEQUATE HARDNESS, HEAVY CLAY SOILS—EXPLORATORY RESEARCH RESULTS

Lab. Soil No.	6b	6c	7c	7d	7e	8a	6d	7b
Type of Moisture Density Curve[a]	R	I	R	I	I	R	I	I
Cement for Adequate Hardness, % by Vol.	30	20	14	20	28	32	24	12
Moisture Content of Soil-Cement Mixtures, %, Oven Dry Wt	25	27	19	39	39	57	24	19
Density of Soil-Cement Mixtures, lb /cu.ft.	95	96	101	81	80	55	96	103

[a] Regular moisture density curve designated "R". Irregular moisture density curve designated "I".

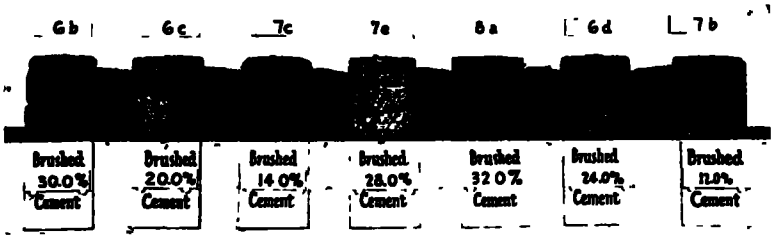

Figure 6. Condition After 12 Cycles of Alternate Wetting and Drying

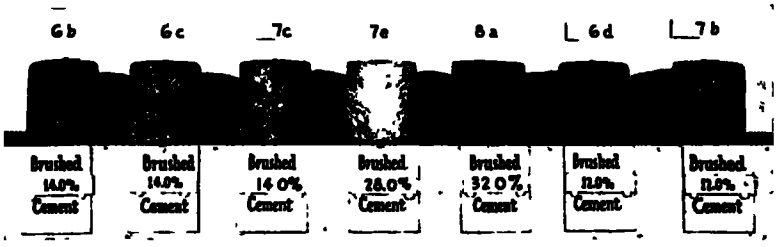

Figure 7. Condition After 12 Cycles of Alternate Freezing and Thawing

SUMMARY OF EXPLORATORY RESEARCH DATA

Time has shown that a further, brief discussion of all the exploratory research data would be helpful. For example, although for research purposes the exploratory tests included cement contents

of 2, 4, and 6 per cent by weight—quite low cement contents—these cement contents did not generally produce satisfactory hardness and durability. As will be shown by subsequent data in this report, cement contents of 8, 10, 12, and 14 per cent *by volume*, more commonly produce satisfactory results Although these points are brought out in the exploratory report in question, the low cement contents were in some instances understood as indicating cement contents producing satisfactory hardness and durability.

Also, the need of controlling cement contents on an apparent *volume* basis should again be emphasized. Ninety-four pounds of cement is considered as 1 cu. ft. This basis for control permits easy, rapid, and accurate comparisons to be made between all tests and all field projects. It prevents confusion in thinking and in analysis of test data. Further, it permits field operations to be controlled with a minimum of control data and a minimum of calculation.

The results of the early tests were placed in various "Treatment Groups" depending upon degree of hardness and upon resistance to freezing and thawing tests and wetting and drying tests. In the early work such general groupings were made of available data to evaluate the influence of physical tests, such as liquid limit, per cent solids, etc., on cement contents required for adequate hardness and durability. The wide range in these factors was noted at that time. Each "Treatment Group" was based essentially on the range of cement contents required to produce the same relative hardness and resistance to the freeze-thaw and wet-dry tests. For example, "Treatment Group I" could be designated to cover soils which can be satisfactorily hardened with cement contents of 4, 6, and 8 per cent by volume. "Treatment Group II" could designate soils satisfactorily hardened with cement contents of 10 and 12 per cent by volume, etc. This system will be used later in this report to summarize test results on the 329 soils included in this report and to show again the wide range of physical relations which prevail for soils responding to similar cement contents.

Thus, this series of exploratory research tests establishes scientific control methods for soils having not only parabolic type moisture-density curves but also for those having irregular curves. By following these procedures it is possible to determine the required cement and moisture contents and densities for producing a hard, durable structural material. When these data are established, the next step is to determine practicability of field construction and costs. It is known, for example, that some very heavy clay soils would be very expensive to pulverize with present equipment and would require such high cement contents that they are impractical to use. Fortunately for practical field work, these heavy clays are limited in extent of occurrence and, therefore, many engineers will not be called upon to perform the more extended tests required for their evaluation. The data submitted in this report also show that high liquid limits, clay content, etc, do not necessarily indicate soils requiring extended testing or high cement contents. These data reinforce the general conclusion that the only reliable method of learning soil-cement characteristics is by actual test.

PHYSICAL RELATIONS OF SOILS AND SOIL-CEMENT MIXTURES

The test procedures developed to investigate soil-cement mixtures, as stated in earlier reports, were evolved after a thorough study of the literature on soil physics, mechanics, and chemistry, and years of laboratory and field experience with concrete. Many possible methods of test for possible control were analyzed and weighed. Further, control methods

for concrete mixtures were subjected to the same critical analysis. Such items as the physical test constants of soils, their surface area, their compacted density and related factors illustrate some of the soil variables. Such items as structural strength, water-cement ratio and cement-space relations and related factors illustrate some of the concrete variables. It is, therefore, clear that the soil-cement test procedures were evolved after recognizing the fact that there might exist some physical characteristic of soil, concrete, or soil-cement which would evaluate soil-cement more rapidly and accurately. Recognition was given these possibilities by establishing a soil and soil-cement testing routine in the Portland Cement Association soil-cement laboratory which would give test data for analyzing each control factor that could be anticipated. These test routines were followed on all soils tested in connection with proposed soil-cement field construction projects.

The testing routines established covered the following:

On Soils:
- Physical test constants (A.S.T.M. Procedures)
- Grain size (A.S.T.M. Procedures)
- Organic content (Colorimetric method)
- pH, hydrogen ion concentration (Electrometric method)
- Moisture-density relations (A.A.S.H.O. Procedures)
- Specific gravity (A.A.S.H.O. Procedures)
- Soil Classification
  - U.S P.R.A. method
  - U. S. Bureau of Chemistry and Soils (when identified in field)
- Textural Classification
  - U.S.P.R A. method (based on U.S. B.C. & S. method)

On Soil-Cement:
- Moisture-density relations (Now A.S.T.M. Procedure)
- Wet-dry test (Now A.S.T.M. Procedure)
- Freeze-thaw test (Now A.S.T.M. Procedure)
- Compressive strength tests

The data obtained from these tests also permitted calculating additional factors of interest including:

Surface area of soils and soil-cement mixtures

Void-cement ratios of soil-cement mixtures

The test data permit all of these variable to be studied separately, collectively, and in any desired combination.

Since this work was started, the Portland Cement Association soil-cement laboratory has received (to November 1, 1940) over 1,500 samples of soil (about 100,000 lb.) from all parts of the continent and from other parts of the Western Hemisphere. Complete tests were not run on all these samples since many were similar and others required only preliminary testing or visual examination to answer questions involved for the soil at the time. There remain available for critical study at this time 329 soils to show some of the more important physical relations of soil and soil-cement. The soils in this group were not hand-picked except to eliminate from this study those having incomplete test data and those having more than 15 per cent gravel or crushed stone retained on a No. 4 sieve. Thus, all reliable data which apply to soil proper were included and studied. Additional studies will be made of the soils having appreciable quantities of gravel or crushed stone retained on a No. 4 sieve.

The 329 soils included in this study represent a very wide, representative and excellent range of soils as found in the United States. This is clearly shown graphically in Figure 8, where they have been plotted on a triaxial textural chart. Also, they cover a wide geographical range, shown in Figure 9.

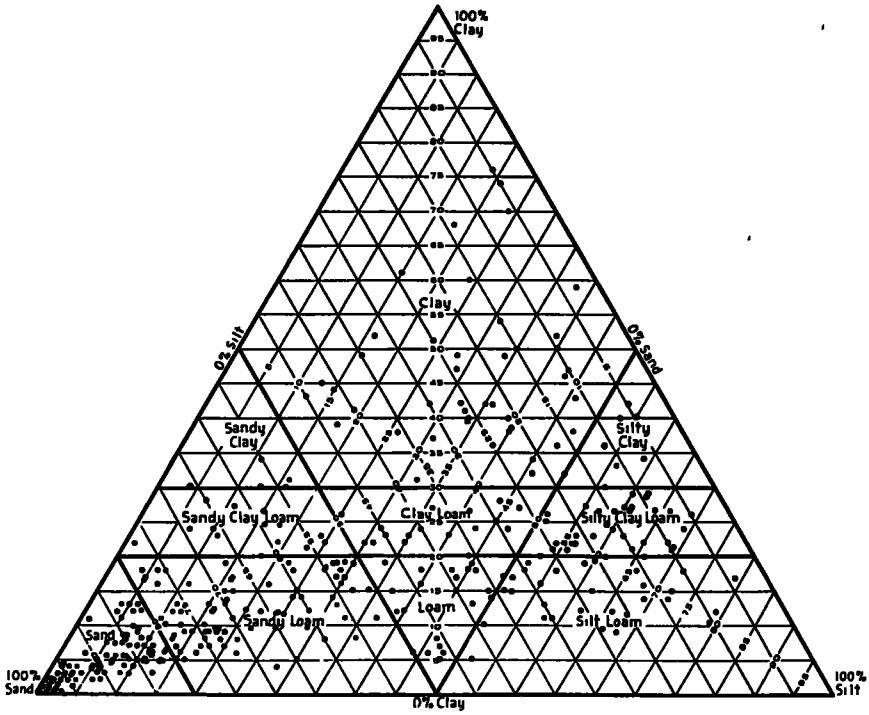

Figure 8. Gradation of soils from 37 states included in soil-cement study. 329 soils from field projects. 17 exploratory research soils also plotted

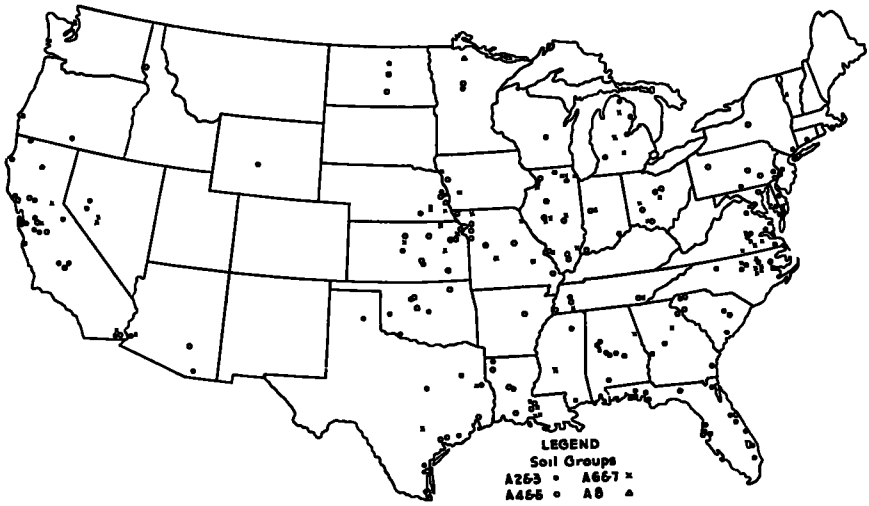

Figure 9. Geographic location of soils from 37 states included in soil-cement study. 329 soils from field projects. 17 exploratory research soils also plotted

With this large number of soils and corresponding soil-cement mixtures available for study representing a full range of soils from all parts of the country, it is possible to make reliable comparisons of many important factors. The primary purpose of this study is to determine the more important physical relations of soil and compacted soil-cement. These relations can then be used to further define compacted soil-cement mixtures.

Method of Analysis

In the following studies the primary basis of comparison is the cement content by volume required to produce compacted soil-cement mixtures which will withstand the standard wet-dry test and standard freeze-thaw test with small weight losses. This represents a durable, structural material. The following technical factors, based on an extended laboratory testing program, on field experience and the outdoor exposure of hundreds of tested specimens (see Fig. 10) have been set up for the present study as criteria of cement contents required to produce specimens of satisfactory hardness, durability, and serviceability:

Figure 10. Wet-dry and freeze-thaw soil-cement specimens are stored outdoors at Elmhurst, Ill., after 12 cycles of laboratory testing.

1. Losses during 12 cycles of either the wet-dry test or freeze-thaw test (A.S.T.M. Designations: D559-40T and D560-40T) shall conform to the following standards:

U.S.P.R.A. soil classifications A-2[3] and A-3, not over 14%

U.S.P.R.A. soil classifications A-4 and A-5, not over 10%

U.S.P.R.A. soil classifications A-6 and A-7, not over 7%

2. Maximum volume at any time during either wet-dry test or freeze-thaw test shall not exceed volume at time of molding by more than 2 per cent.

3. Maximum moisture content at any time during either wet-dry test or freeze-thaw test shall not exceed that quantity which will completely fill the voids of the specimen at time of molding.

4. Compressive strengths of 2-in. soil-cement test specimens shall increase with age and with increases in cement content in the ranges of cement content producing results meeting requirements 1, 2, and 3.

5. Mixtures of soil and extraneous materials such as cinders, mine waste, etc., and soils containing more than 15% gravel or crushed stone retained on the No. 4 sieve will not be included in this study but constitute a separate study.

6. Soil-cement test results which meet the above criteria 1 to 4, inclusive, are grouped according to cement contents by volume of even integers, such as 6%, 8%, 10%, 12%, 14% and 16%, to permit easy comparison of hard, durable compacted soil-cement mixtures having similar characteristics.

These criteria for judging cement contents producing satisfactory results should not be considered as irrevocable recommendations but rather as criteria found to be satisfactory with present knowledge as well as, for a matter of record, the criteria used in this study.

In considering these criteria, it is necessary to emphasize the general soil loss and strength "patterns" of soil-cement, which show that in testing it is generally unnecessary to investigate cement contents by volume in smaller ranges than 2 per cent, such as 8 to 10 per cent, 10 to 12 per cent, etc. Study of hundreds of soil loss "patterns" shows that a change of cement contents by less than 2 per cent by volume does not materially change soil losses when these losses are within the range of satisfactory control.

Consideration of field construction factors also shows that ranges of cement content by 2 per cent by volume are also adequate. In general, for a 6-in.

[3] In testing some 1,500 samples, none have fully met classification requirements for A-1 soils.

compacted roadway a cement content of 2 per cent by volume costs five cents with cement at $2 25 per bbl. A commonly used 10 per cent cement content, 0.45 bag per sq.yd. of 6-in. compacted depth, gives a cost of about 25 cents per sq.yd. for materials. It is not wise or true economy to jeopardize field success by attempting to control cement contents within too narrow limits. The practice of the Portland Cement Association in laboratory and field has been to vary cement contents by increments by volume of 2 per cent and in all cases on field work to specify the cement content which gives low soil losses.

brought out clearly first by a simple tabulation of U.S P.R.A. soil groups and cement contents for suitable hardness and durability, see Figure 11. This shows immediately that there is a rather wide range of cement contents required to satisfactorily harden the range of soils in each soil group Also that certain cement contents predominate in each group.

A total of 141 soils are A-2 soils. The A-2-4, A-2-6, and A-2-7 soils are also included in the A-2 group in all studies. One hundred and eleven soils, 79 per cent, give satisfactory results with cement contents by volume of 6, 8,

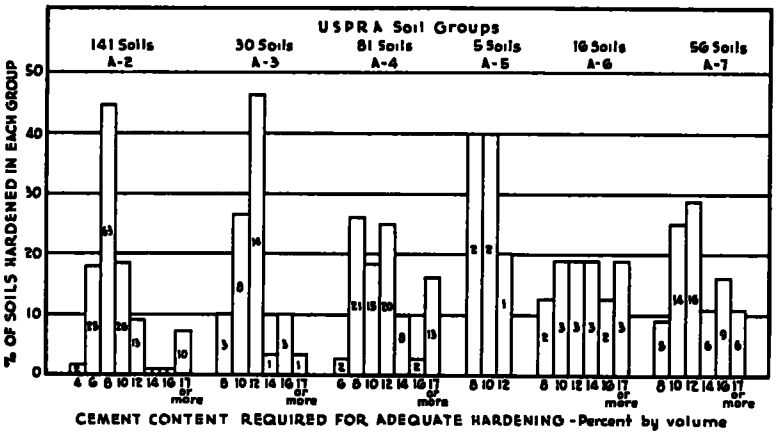

Figure 11. U. S. P. R. A. Soil Groups and Cement Contents for Adequate Hardening

The studies to follow use the cement content required to produce satisfactory hardness and durability for comparisons with the variables studied, such as compressive strength, density, and others listed under testing routines. Charts are drawn on the same basis. Thus, dozens of analyses have been made and more than five years' work is involved in this study. However, in studying all these data it is equally clear that any of the factors analyzed can logically be said also to be the basis of comparison.

Cement Content Producing Adequate Hardness vs. Soil Group

The general physical relations of soils and compacted soil-cement mixtures are

or 10 per cent. Thus, the study shows that when an A-2 soil is encountered for use, the wet-dry test and freeze-thaw test should be conducted first on cement contents of these ranges. The data also show that 63 soils, 45 per cent, gave satisfactory results with 8 per cent cement by volume and indicate the generality that 8 per cent cement will be satisfactory on about half the A-2 soils.

The grouping brings out further that soils do exist which will give satisfactory results with 4 per cent cement and also that some A-2 soils may possess characteristics which require quite high cement contents for satisfactory hardening

In the A-3 group, 30 soils are available for study; 22 soils, 73 per cent, require

10 or 12 per cent cement. The lowest cement content is 8 per cent and the highest is 16 per cent. A-3 soils would be tested first with cement contents by volume of 8, 10 and 12 per cent.

There are 81 A-4 soils available for study; 56 soils, 69 per cent, require 8, 10, or 12 per cent cement, and these cement contents by volume should be investigated first in this group.

There is a definite trend for cement contents to increase with increases in silt and clay content. The A-2 and A-3 soils fall generally into the 6, 8, and 10 per cent cement content groups. The A-4 and A-5 soils fall generally into the 8, 10, and 12 per cent cement content groups and the A-6 and A-7 soils fall generally into the 10, 12, and 14 per cent cement content groups. This is shown further by noting the minimum cement contents producing satisfactory results in each soil group. A minimum of 4 per cent is found in the A-2 group. Six per cent cement is a minimum for A-4 soils and 8 per cent is the minimum for the A-7 group.

It is also apparent that there is a general overlapping of cement content requirements in the various soil groups.

However, these data do not show one general characteristic of all soil groups that is most important. In a particular locality or small area, each soil group will have its own particular answer which will in general fall in a much narrower cement range As pointed out by L. D. Hicks, Assistant Engineer of Materials and Tests, North Carolina State Highway Commission, in last year's Proceedings,[4] a specific soil horizon of a specific soil series, as identified by the U. S Bureau of Chemistry and Soils, Department of Agriculture, will probably have a constant cement requirement Until these answers for soils in a particular locality are known, the cement contents most likely to give successful results are indicated by this broader study of 329 soils from 37 states.

It should also be emphasized that tests on hundreds of other soils reinforce this general conclusion. The procedure followed in the Portland Cement Association soil-cement laboratory is to compare a soil for test with similar soils already tested from the same area and use this comparison for preliminary bench marks. In cases where soil series and soil horizon are identified, the comparisons can be easy, rapid and accurate.

This plotting of cement requirements with soil group establishes what has been called a test "pattern" This terminology is adopted to indicate generally similar conditions and conclusions and also to differentiate from an exact relation or answer. Various "patterns" will be developed and discussed.

The study of soil group and cement content was selected for discussion first because it brings out directly the fact that there are no simple relations between the physical characteristics of soils and soil-cement. It shows that certain trends are evident, but they are not susceptible to use in a simple formula or statement which will give a positive soil-cement answer for a particular untested soil. Obviously, as the engineer's personal experience broadens, he can more accurately estimate cement needs for soils of his acquaintance. However, as the data indicate, the number of soils falling outside a cement range of even four percentage points, such as 8, 10, and 12 per cent, are great enough (averaging 27 per cent) to require specific testing to obtain a dependable, economical answer. The data also show why it is necessary to test three different cement contents to establish reliable control factors with the first series of tests.

[4] L D Hicks, "Sampling, Soil Classification and Cement Requirement—North Carolina," *Proceedings*, Highway Research Board, Vol 19, page 521

Value of Hydrogen Ion (pH) Determinations

When this work was started pH determinations were made on each soil investigated. These data were needed to throw some light on the general characteristics of soils and their reaction with cement and to answer definitely such questions as:

Must a soil have a pH of less than 7, be acid, to react properly with cement in compacted soil-cement mixtures?

Must a soil have a pH of more than 7, be alkaline, to react properly with cement in compacted soil-cement mixtures?

Does the hydrogen ion concentration (pH) of a soil directly influence the quantities of cement required for satisfactory results?

The pH value of soils in this study has been compared with the following soil characteristics:

1. Liquid Limit
2. Plasticity Index
3. Shrinkage Limit
4. Maximum Density
5. Optimum Moisture
6. Organic Content (Colorimetric Method)

They were also compared with the following soil-cement characteristics:

1. Cement Content for Adequate Hardness
2. Compressive Strength
3. Cement-Voids Ratio
4. Maximum-Density
5. Optimum Moisture

From a soil-cement standpoint, the most important relations in this study should be indicated by plotting the pH value of the soil with the cement content required for the compacted soil-cement mixture. These relations are shown in Figure 12. It becomes evident immediately that successful results were obtained with soils whose pH ranged from 4 to over 10. Further, this same range prevails in general for each cement content answer. Therefore, the questions of influence of soil acidity and alkalinity are answered definitely. A soil

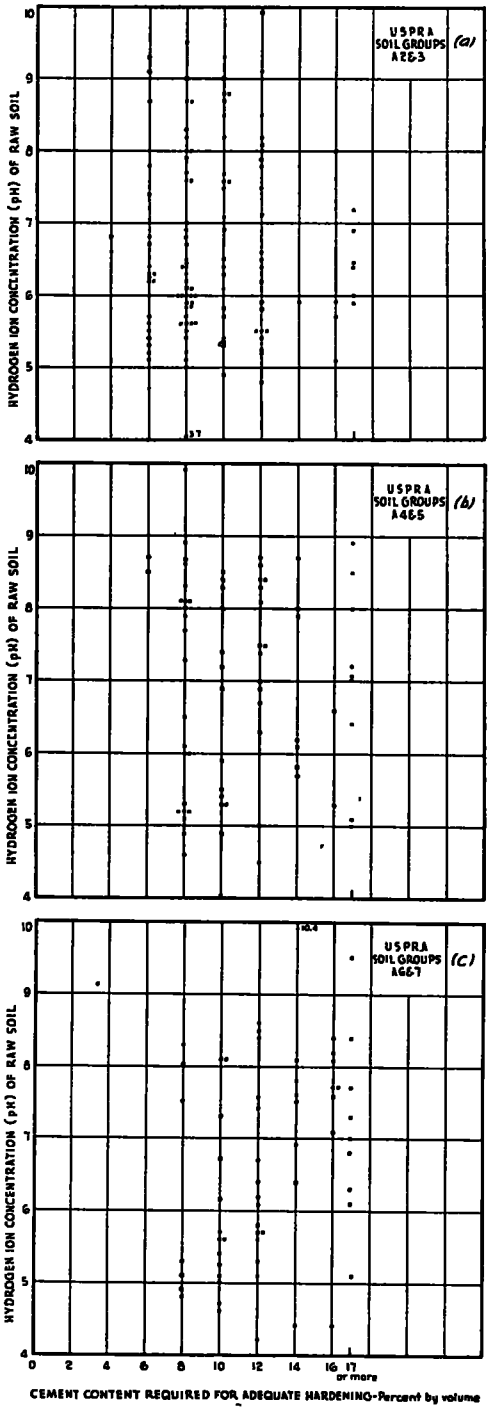

Figure 12. Relation of cement contents required for adequately hardening soils to the raw soil hydrogen ion (pH) concentrations.

can be either acid, neutral or alkaline and will respond in equal degree to cement when the pH value is the only soil variable involved.

Plotting pH values with organic content as determined by the colorimetric method[5] further substantiates these facts. See Figure 13. It will be noted that with very low organic contents the pH values of the soils range from 4 to 10 and required cement contents vary through a wide range. This holds true until organic test results reach values of about 5,000 p.p.m. When the organic content exceeds 5,000 p.p m., the soils are acid. Care must be exercised to interpret this fact properly. It shows with two exceptions, for the soils in this study, that if the organic content is 5,000 p.p.m or over, the soil will also be acid. It does not show that if the soil is acid it will have a high organic content.

A further significant study was made by comparing pH of soils and the compressive strength, at 28 days, of soil-cement mixtures containing 10 per cent cement by volume. See Figure 14. Again it will be noted that the pH value of the soil is not a direct primary factor influencing the compressive strengths of soil-cement mixtures. It is clearly shown that the same strength can be obtained with soils having a wide variation in pH value from high acid to high alkaline

The other factors plotted and studied gave the same general answer. These factors will not be discussed or the results shown since they add nothing of significance to the study. However, the results become a matter of record.

All these studies show clearly that the pH value of a soil does not, by itself, indicate the manner in which a soil will respond to cement treatment. There-

[5] The colorimetric test is discussed in detail under "Soil-Cement and Organic Relations" later in the report.

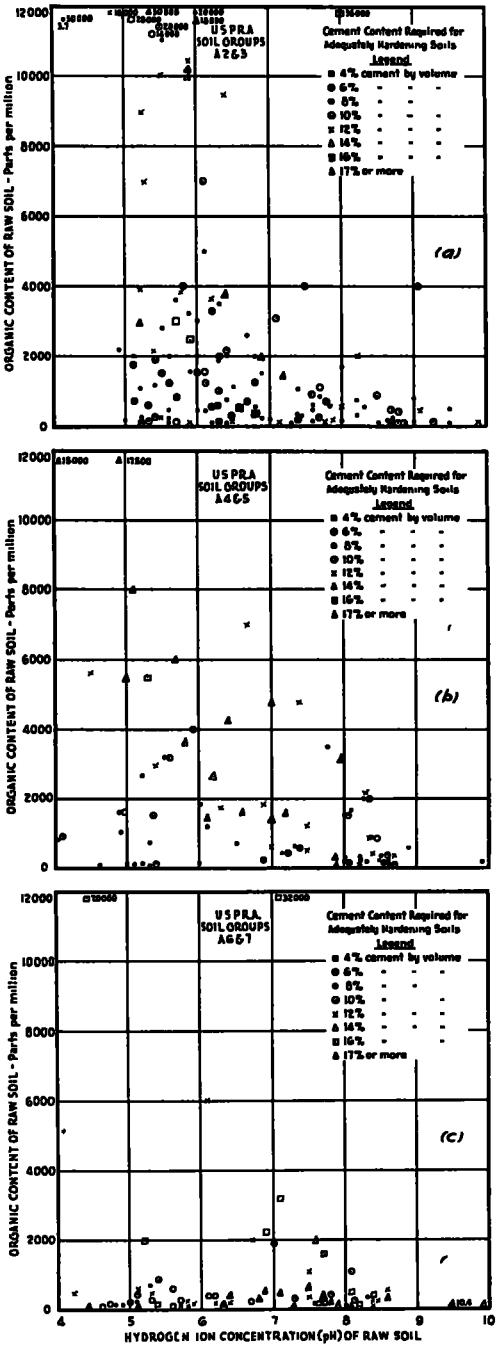

Figure 13. Relation of organic contents to hydrogen ion (pH) concentrations of raw soils.

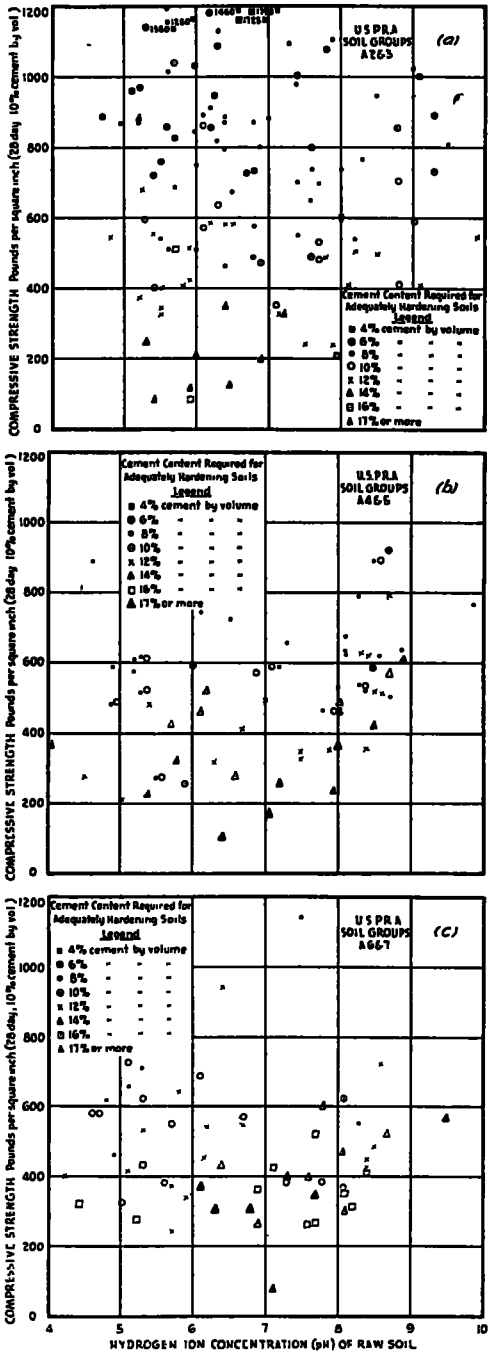

Figure 14. Relation of Compressive Strengths to Raw Soil Hydrogen Ion (pH) Concentrations

fore, on November 1, 1940, the pH determinations of soils were discontinued by the Portland Cement Association soil-cement laboratory except in connection with research problems. It is fully recognized that the pH value of a soil may be correlated with one or more other test factors to show some significant relation. This is illustrated by the pH organic relations of the soils in this study which show, with two exceptions, that when the organic content exceeds 5,000 p.p.m., the soils were acid. This does not necessarily mean that the organic content produces the acid condition, but it does show, for the soils studied, that the factors producing the organic content occur together with an acid soil condition. Such factors as water-holding capacity and grain size as well as the geographical location of the soils, which involve climate, weathering agencies, soil forming processes and geological origin of the soil, are all intertwined with the apparent high organic-acid relation. Further, a particular soil horizon at some specific geographical location may possess characteristics which can be interpreted relatively or directly in terms of pH values.

It should be repeated that the pH determinations were made to uncover any direct relation between the test and the general reaction of the soil hardening with cement These tests and data show that a soil may be acid, neutral or alkaline and will respond equally well to cement yet the test by itself is not significant in indicating cement requirements.

Soil-Cement and Organic Relations

For many, many years the concrete technician has recognized the fact that some concrete aggregates, particularly sands, may contain organic materials or compounds which prevent normal cement hydration and crystallization. Obviously, similar factors should be expected in soil-cement mixtures, par-

ticularly those using topsoils which would contain vegetation in various stages of decomposition. A study of organic tests made by the concrete technician and the agricultural engineer uncovered several "organic test" methods. It was necessary to study how these tests were conducted and what "organic" factors they would show, together with the dependability of each test method. A particularly useful research project on the subject was conducted by the U. S. Department of Agriculture[6] and another by the Portland Cement Association Research Laboratory.[7]

These studies of organic test methods[8] as well as studies of the chemistry of organic compounds in soils brought out the significant fact that the soil chemist was confronted with a multitude of variable factors which made it very difficult, if not impossible, to determine the chemical composition of organic compounds in soils. Also, that all test procedures had limited accuracy and dependability. The study also pointed up two technical organic factors which would not influence cement and cement hydration.

The first obvious factor was that undecomposed vegetation, such as roots and twigs, could not react with cement. This phase of organic content is illustrated by research soil 8a, a peaty muck with very low density and a high organic content, as shown by a combustion loss of 39 per cent and a colorimetric test result of 28,000 p p.m (2.8 per cent). Hence, any combustion organic test which includes these organic materials in the test result would not apply. Furthermore, the method also drives off other constituents not too easily evaluated.

The second obvious factor was that carbon compounds, such as coal, carbon, etc., and other water insoluble compounds which are derived from decomposed vegetation, would be inert and not react with cement. Again a combustion test would not be desirable.

Therefore, these two organic factors, undecomposed and decomposed vegetation, would not be of importance in indicating the reaction of cement with these organic materials. This analysis of primary influence, however, must not be confused with the influence such organic materials, roots, coal, etc., might have on the soil-cement mixture after cement hydration because of subsequent rotting, volume change, leaching due to capillary water, etc. The organic material, to be a direct influence, would need to be in the form of liquids absorbed or adsorbed by the soil grains.

The investigation of organic test methods led to the adoption of the colorimetric method as best applying to the problems of soil-cement mixtures. This procedure is based on the preparation of organic solutions of known content of tannic acid and sodium hydroxide and, by comparing the color of 3 per cent sodium hydroxide solutions after soil washing with the color of known tannic acid solutions, a relative organic content determined in parts per million. The colorimetric test procedure adopted for the soil-cement tests is essentially the same as "Standard Method of Test for Organic Impurities in Sand for Concrete", A S T.M. Designation: C40-33. This test method has definite limitations but for soils it presented the least short-

[6] "A Critical Laboratory Review of Methods of Determining Organic Matter and Carbonates in Soils," Technical Bulletin No 317, June, 1932, U S Department of Agriculture

[7] "Comparison of Standards for Colorimetric Test for Sand," *Proceedings*, A S T M, Vol. 34, Part I

[8] Organic Test Methods· Loss on Ignition; Modified Rather Method, Combustion Method, Calculation of Organic Matter from Quantity of Nitrogen Present; Hydrogen Peroxide Method, Colorimetric Method (Sodium Hydroxide)

comings. The procedure permits duplication of test results with reasonable accuracy but it is definitely recognized to indicate only the approximate quantities of organic material soluble in a 3 per cent solution of sodium hydroxide.

Studies were made to show the relations between organic content and the following soil factors.

1. Liquid Limit
2. Plasticity Index
3. Shrinkage Limit

The following soil-cement factors were studied:

1. Compressive Strength
2. Cement Content Required for Adequate Hardness
3. Maximum Density
4. Optimum Moisture

The comparison of organic content and physical test constants brings out the fact that the sands and silts (A-2, A-3, A-4, and A-5 soils) in this study may have high organic content with the clays generally having low organic content. A statistical study brought out the point that the soils containing less than 20 per cent sand had very low organic contents and the soils showing high organic test results contained over 50 per cent sand. This is typically illustrated in Figure 15 showing the organic content and liquid limit of soils

One of the most valuable organic soil-cement comparisons is brought out by studying the 28-day compressive strength data for specimens containing 10 per cent cement by volume, see Figure 16. These data show that there is a definite trend for compressive strengths to decrease as the organic content increases. Also, sufficient data are presented of soils having high organic contents and high strengths to show that the colorimetric test is not a direct index of either detrimental organic materials or the detrimental influence of organic materials. This is further substantiated by

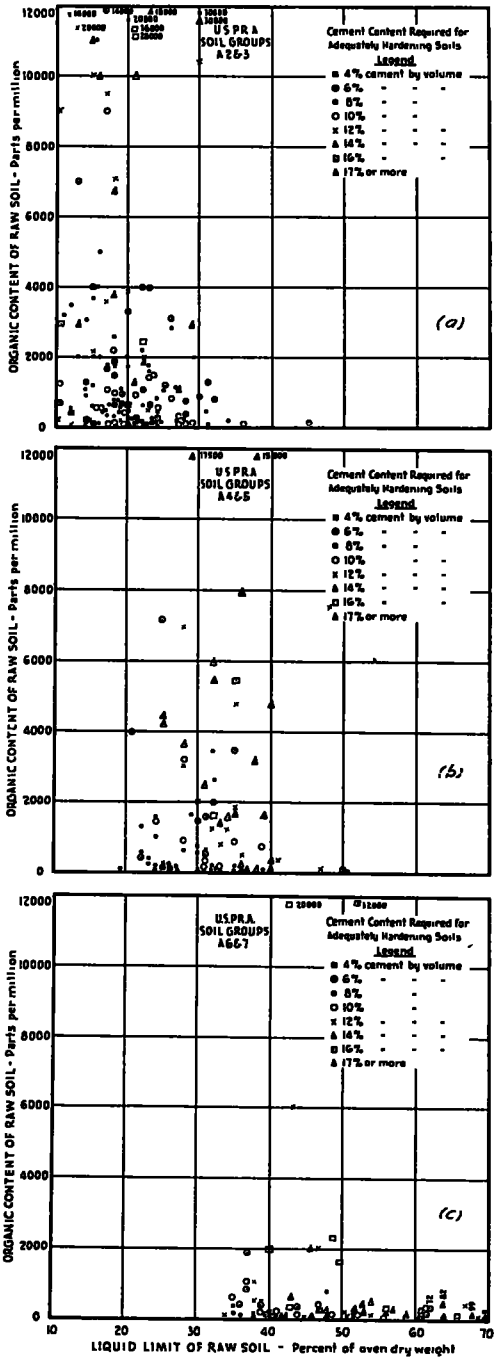

Figure 15. Relation of Organic Contents to Liquid Limits of Raw Soil

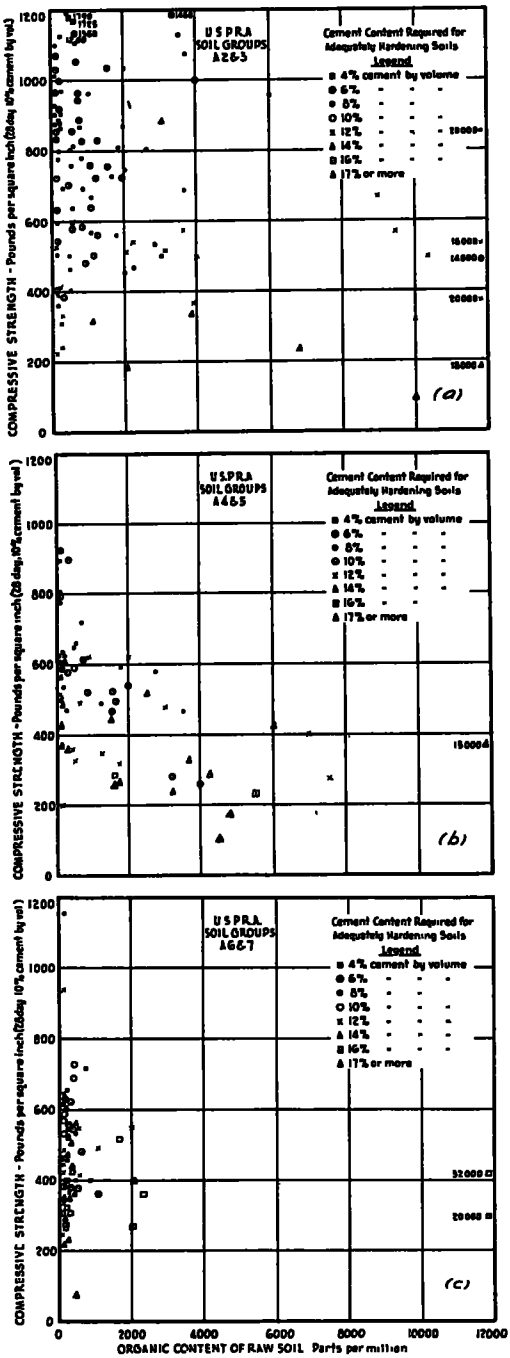

Figure 16. Relation of Organic Contents to Compressive Strengths

data on soils of low organic content which also have low strengths. The data are consistent in indicating that when the colorimetric test shows 2,000 p.p.m. or more, the contained organic material may influence the action of the cement as shown by reduced compressive strengths. A few soils have been tested which had organic test results of the order of 1,000 p.p.m. and which required very high cement contents for satisfactory hardening. In the absence of knowledge to permit more accurate explanation, this need of high cement content has been attributed to the particular organic material present. It is also recognized that there might be some base exchange factor on which test data are not available.

As shown by the colorimetric test, a more direct comparison of the influence of the organic content of soils on cement is obtained by comparing organic contents with cement contents required for satisfactory hardness and durability, see Figure 17. By studying a particular cement content plotted in Figure 17(a), A-2 and A-3 soils, it is seen that soils with quite high organic test results are associated with soils of very low organic content and yet these soils having wide ranges in organic content require the same cement content for adequate hardening. Thus, the soils having satisfactory results with 8 per cent cement have organic test results ranging from a trace to 30,000 p.p.m. These graphs are significant in reinforcing the conclusion made from the strength comparison that the colorimetric organic test does not necessarily disclose unfavorable cement reaction factors although high results in the colorimetric test may indicate that a detrimental cement factor is present.

In any case, the wet-dry and freeze-thaw tests will give the final dependable result. As pointed out in the Portland

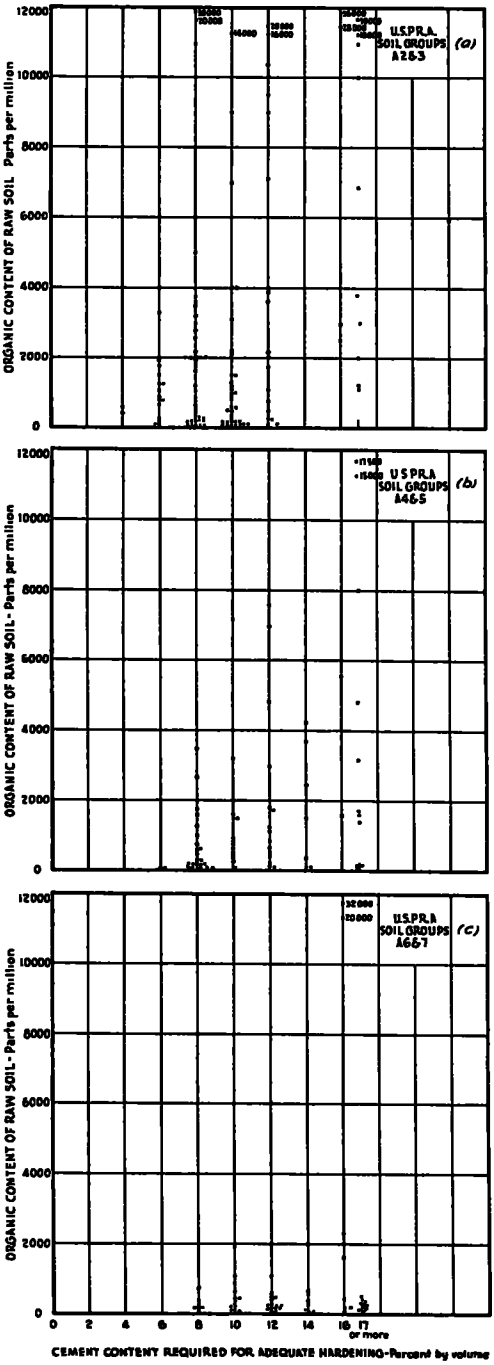

Figure 17. Relation of organic contents to cement contents required for adequately hardening soils.

Cement Association Research Laboratory work on the colorimetric test of sands for concrete, it is only an indication of the organic influence and when high organic contents are shown, the final decision rests on the results of strength tests of sand-cement briquettes according to recommended A.S.T.M. test procedure. When high organic test results are shown in soil-cement, and after compressive strength checks are made, one further step must be taken by making final checks with wet-dry and freeze-thaw tests. Laboratory and field experience substantiates this procedure.

The charts obtained in making the other organic comparisons in this study are not shown or discussed. They verify the foregoing trends.

Data are not included or discussed which deal with soils having coatings of material easily removed by superficial washing or rubbing. Neither are data included or discussed dealing with unfavorable reacting soils, often A-2 or A-3 soils, made favorable to cement by the simple addition of moderate amounts of another soil, usually of A-4, A-6 or A-7 soil. While gradation and density may be improved by the soil admixture, these factors do not appear to be of major significance in indicating the amount of cement to add for successfully hardening the resulting mixture. *This phenomenon of hardening influence resulting from the addition of other soils is most significant, however, in pointing up the probable predominate influence of the physico-chemical relations of soil and soil-cement.*

These data show that the colorimetric test for organic content indicates the general trend of the amount of detrimental organic materials which may be present. When the colorimetric test gives results in excess of 4,000 p.p.m., it is wise to consider testing specimens with cement contents in excess of those indicated by the soil group alone. Also, should the soils be black topsoils, "A"

horizon soils, tests should include cement contents two percentage points higher than would be the case otherwise. Testing of a soil should not be abandoned because it gives a high colorimetric organic test result. When time is available for considerable testing, the compressive strength "pattern" should be developed first to indicate probable cement content ranges and followed with a series of wet-dry and freeze-thaw tests on specimens containing cement contents in these ranges. If need be, these tests are followed with additional tests on specimens containing more cement.

Soil-Cement and Compressive Strength Relations

In order to obtain compressive strength data for study and analysis, 2-in. specimens are first molded with cement contents by volume of 6 and 10 per cent which are broken in compression at 2, 7 and 28 days. Specimens are stored at room temperature in an atmosphere of high humidity until the day of testing and are then broken after one hour soaking. Additional strength specimens containing 14 per cent, and occasionally 18 per cent, cement by volume are molded when soils are encountered requiring these higher cement contents for satisfactory results. Fixed cement contents by volume are selected since this would also give a fixed cement influence. There would be the same number of cement grains in every test specimen, thus giving a fixed bench mark for comparison. For the same reason, strength breaks are made at fixed ages

The influence of cement in producing compressive strengths in compacted soil-cement mixtures can be analyzed from two basic viewpoints. The cement influence will be made evident by increases in strengths with increases in age and by increases in strength with increases in cement content. Thus, the 6 per cent cement specimens should show increases in strength with age. The 10 per cent cement specimens should likewise show increases in strength with age and, in addition, at any fixed age, they should show greater strength than the 6 per cent specimens of the same age.

A study of hundreds of soil-cement specimens during test and the performance of soil-cement field projects shows that the chemical changes involved in cement hydration are similar in soil-cement and concrete. Further, since soil constitutes such a great part of the volume of compacted soil-cement mixtures, the major characteristics of soil play a predominate part in analyzing compacted soil-cement mixtures, particularly during the early stages of cement hydration

Thus, certain characteristics of compacted soil-cement mixtures are analyzed in terms of cement and cement hydration and others are analyzed in terms of soil and its characteristics. For example, as soil-cement construction extends into freezing weather, recognition must be given the fact that cement hydration and crystallization proceeds very slowly at temperatures near freezing and is halted by temperatures of 32°F. or lower. Hence, construction work must cease long enough before these low temperatures prevail to permit substantial cement hydration and crystallization which will then give the completed work strength to withstand repeated freezing and thawing.

Soil characteristics are used to analyze soil-cement immediately after construction and before cement begins to play its part At that time, for example, the mass will increase or decrease in volume in direct ratio with changes in moisture content. It is this fact which calls for a specification requiring placement of moist cover on completed work to prevent changes in moisture content and volume before the cement can hydrate to hold the mass together.

Therefore, soil-cement as a structural

material cannot be analyzed and thought of in terms of cement or of soil alone. Instead, the characteristics of soil-cement are learned by test and experience and not by direct composite comparison with some other structural material. Naturally, some soil-cement characteristics will be similar to soils, others similar to cement, and a few can be compared with concrete; but soil-cement, as a structural material, will have its own distinctive characteristics. Repeated experience in laboratory and field with many soils and soil-cement mixtures will result in an understanding or philosophy of soil-cement which will permit accurate analyzing of the functioning of the material in the laboratory and field.

Many of the present studies have been made primarily to uncover any basic relations between soil-cement and both soil tests and soil-cement tests which would permit such tests to be used as a basis for determining satisfactory cement requirements. Since compressive strengths are relatively easy to determine, they merit detail study. The following factors have been compared with compressive strength data:

1. Maximum Density
2. Optimum Moisture
3. Cement Content for Adequate Hardness
4. Hydrogen Ion Concentration (Previously discussed)
5. Organic Content (Previously discussed)

The 28-day compressive strengths of 2-in. specimens containing 10 per cent cement have been plotted with maximum density, see Figure 18. A study of these data show at once that there is a wide range in strength for any particular density. Also, there is a definite trend or "pattern" of strength increasing with density. The greatest strengths are obtained with the soils having the greatest density.

The range in strengths and densities

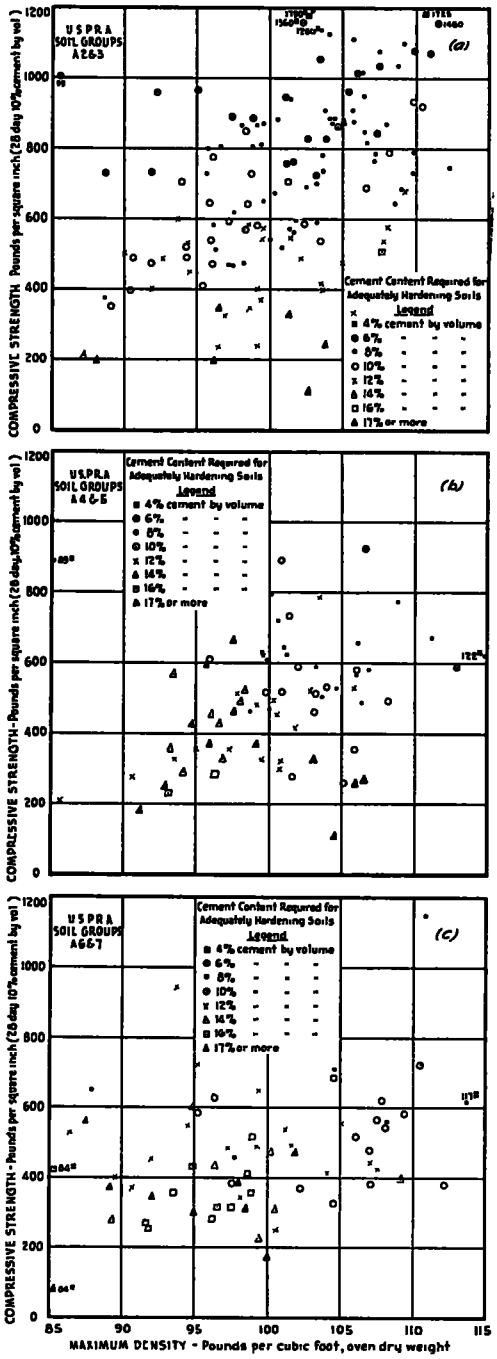

Figure 18. Relation of compressive strengths to the maximum densities of soil-cement mixtures.

can be brought out by selecting the soils requiring 10 per cent cement for satisfactory hardness and studying the densities and 28-day strengths of 10 per cent cement content specimens which are shown in Table 4.

It will be noted that the overlapping of densities and strengths is so great that there is no criterion for control on a density-strength relation basis. Further, the strength ranges are too great to establish a criterion for strength alone.

TABLE 4

Soil group	Maximum Density Range, lb. per cu ft.	10% Cement Content, 28-Day Compressive Strength Range, lb per sq in
A-2	105–125	350–920
A-3	106–113	475–645
A-4[c]	101–111[a]	465–610[b]
A-6 and A-7	95–112	330–725

[a] One density of 118 lb

[b] Other strengths of 260, 275, and 890 lb. per sq in

[c] No strengths for A-5 soils.

TABLE 5

Soil group	Average Maximum Density, lb per cu ft	10% Cement Content, Average 28-Day Compressive Strength, lb per sq in
A-2	115	630
A-3	110	568
A-4	108	521
A-6 and A-7	105	519

These data on densities and compressive strengths for soils requiring 10 per cent cement for adequate hardness bring out several interesting points. Since these soils require the same cement for satisfactory results, it is logical that they have about the same broad compressive strength ranges and do not possess the much greater strength ranges or differences possessed by the A-2, A-3, A-4, A-6 and A-7 groups as a whole, as shown in Figure 18. The same general trends are evident, however, as shown by Table 5 of average densities and average compressive strengths The A-2 densities and strengths are above those of A-4 soils, and those of A-4 soils are above A-6 and A-7 densities and compressive strengths.

Figure 19 shows optimum moisture-strength data. These data again show a wide range in strengths for the same optimum moisture with a strength "pattern" showing decreases in strength with increases in optimum moisture. These data can be analyzed from several viewpoints, including moisture content, but show no consistent, specific relations.

A further strength study has been included to show the relation between compressive strength and cement content required for satisfactory hardness and durability, see Figure 20. A wide range of strengths is obtained with each group of soils requiring the same cement content for satisfactory durability. The range in strength for any particular group of soils is too great to use as a criterion.

Again test "patterns" are obvious. Strengths decrease with clay and silt content as shown by Figure 20. Also, as the cement content for satisfactory hardness increases, the compressive strengths decrease.

The 10 per cent cement compressive strength "patterns" of soils also requiring 10 per cent cement for satisfactory hardness and durability shed further light on the compressive strength characteristics of compacted soil-cement. Figure 21 shows the 10 per cent cement compressive strength of these same soil-cement mixtures at 2, 7, and 28 days These curves show not only a wide range of compressive strengths at any particular age, but also a wide range in rate of strength gain. Further, there is similarity in strengths of each soil group at any particular age The curves show clearly that the strength at 2 days is not indicative of strengths at 7 or 28 days

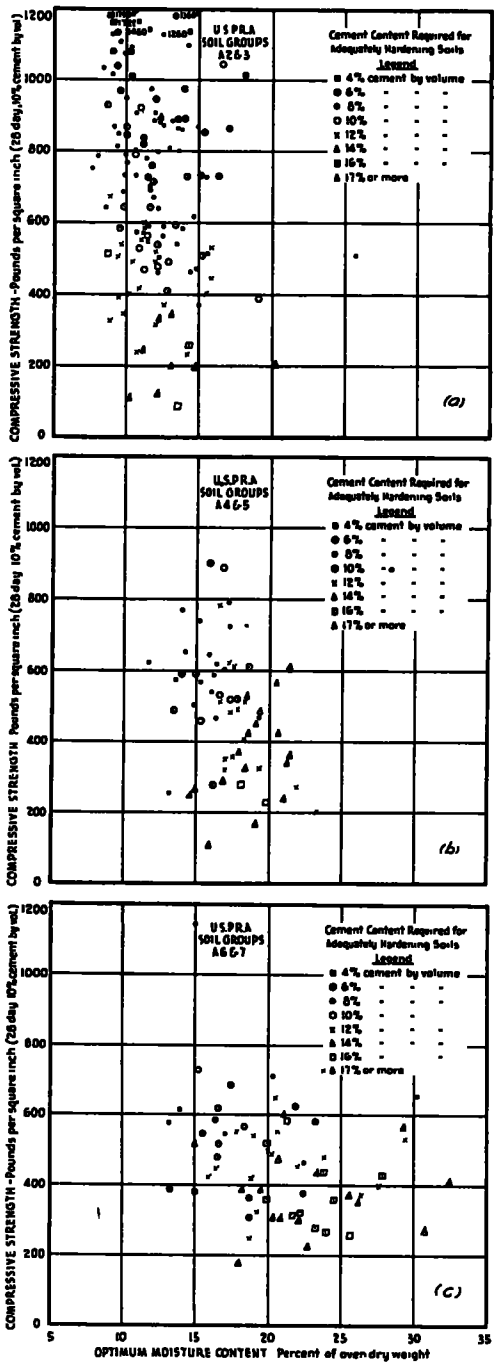

Figure 19. Relation of compressive strengths to the optimum moisture contents of soil-cement mixtures.

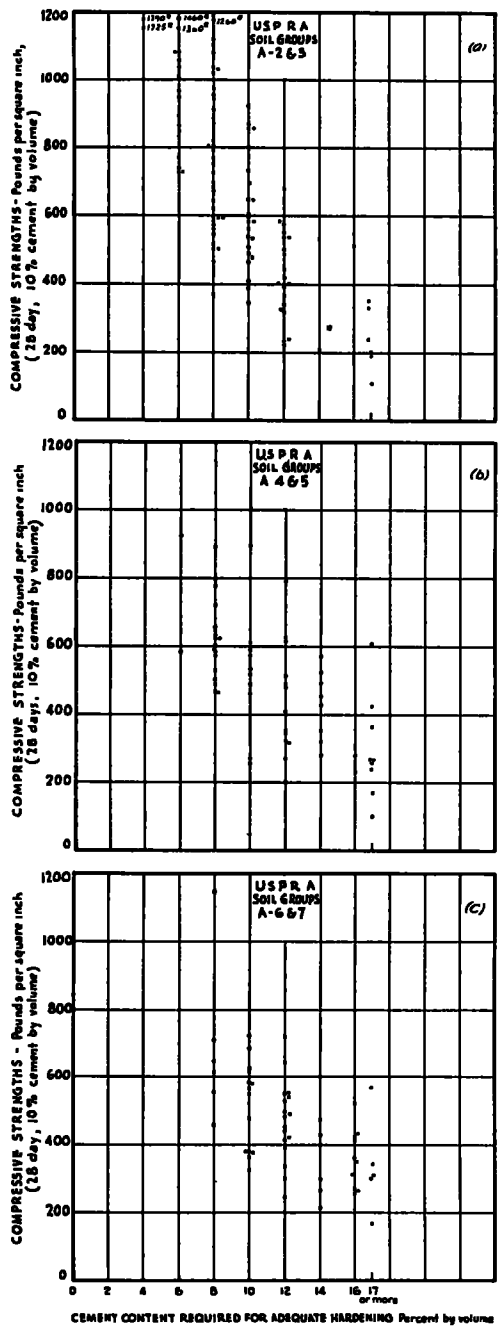

Figure 20. Relation of compressive strengths to cement contents required for adequately hardening soils.

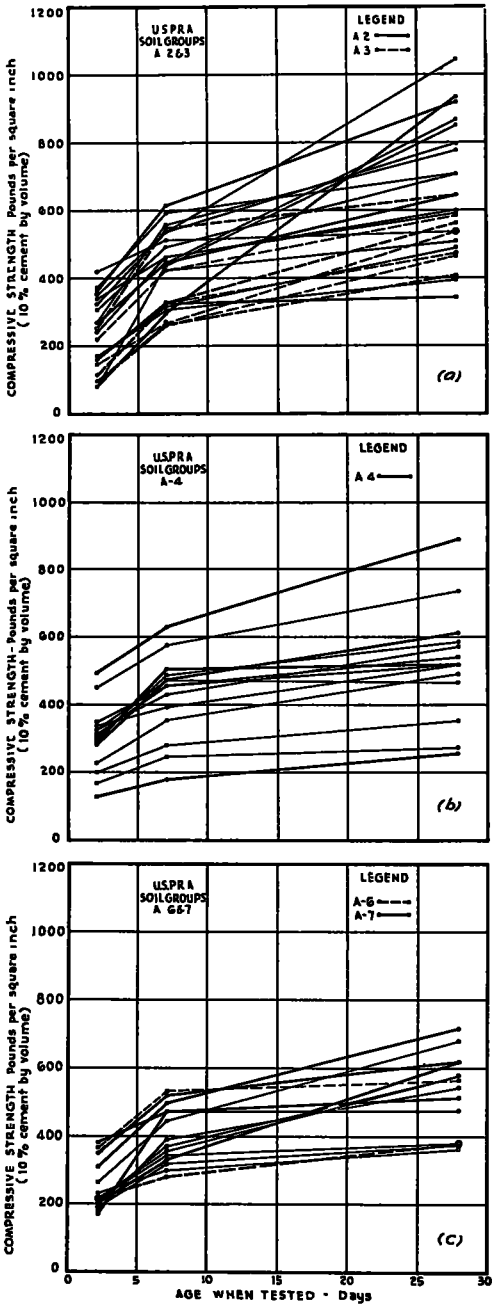

Figure 21. Two, seven and twenty eight day compressive strengths of soil-cement mixtures requiring 10 per cent cement for adequate hardness.

nor are the 7-day strengths indicative of 28-day strengths. The strength "patterns" at 2 and at 7 days are similar for the soil groups with a definite trend again shown of lower gain in 28-day strengths as the silt and clay content increases.

All strength data show that several factors are present in the soil itself which prevent a uniform reaction with cement in producing compressive strengths. The strength "patterns" show that grain size as reflected in density, optimum moisture, and soil group are contributing factors. As previously pointed out, organic content can also be a factor. Also water-holding capacity of raw soil as reflected in the physical test constants, liquid limit, plasticity index, etc., are contributing influences. All these factors can and do contribute a varying influence in each soil-cement mixture to produce wide variations in compressive strengths. However, for each individual soil these factors are fixed and *the resulting soil-cement mixture reacts the same in check tests to give uniform test results for each soil-cement mixture.* These factors will be discussed again later.

Soil-Cement and Adequate Hardness

The exploratory research test results and subsequent laboratory test results on soils used in field construction show clearly that a dependable, structural material of compacted soil-cement can be successfully produced by using control factors determined by the present A.S.T.M. procedures which include wet-dry tests and freeze-thaw tests These latter tests are sometimes termed "durability tests" since they simulate weathering conditions. However, the tests were evolved to produce destructive agencies which could not be withstood by soil alone but would be withstood by a structural material. The wet-dry test introduces very high shrinkage stresses

while the freeze-thaw test introduces very high expansive stresses. The significance of the shrinkage and expansive forces produced in the tests must not be overlooked. They mean more in analyzing soil-cement as a structural material than they do in terms of weathering, although they also prove the ability of compacted soil-cement to withstand weathering. Since a structural material must withstand shrinkage and expansion forces similar to those introduced by these tests, it is fundamentally important to conduct both wet-dry tests and freeze-thaw tests on compacted soil-cement specimens and obtain low weight losses to insure having a structural material.

The effectiveness of the wet-dry and freeze-thaw tests in evaluating soil-cement can now be studied in detail. Since considerable time is required for the tests, the Portland Cement Association and all others interested in soil-cement are on a constant search for more rapid test methods. The available test data have permitted specific studies to be made of several test factors which have been useful in evaluating soil or concrete. A great number of factors have been studied in addition to those presented so far in this report.

The wet-dry and freeze-thaw test results have been compared with the following soil factors

1. Liquid Limit
2. Plasticity Index
3. Surface Area of Soil

They have also been compared with the following soil-cement factors:

1. Maximum Density
2. Optimum Moisture
3. Compressive Strength
4. Cement-Voids Relations

The comparisons of liquid limit, plasticity index, and surface area of soil with cement content for satisfactory hardness and durability are given in Figures 22, 23 and 24. Because of previous dis-

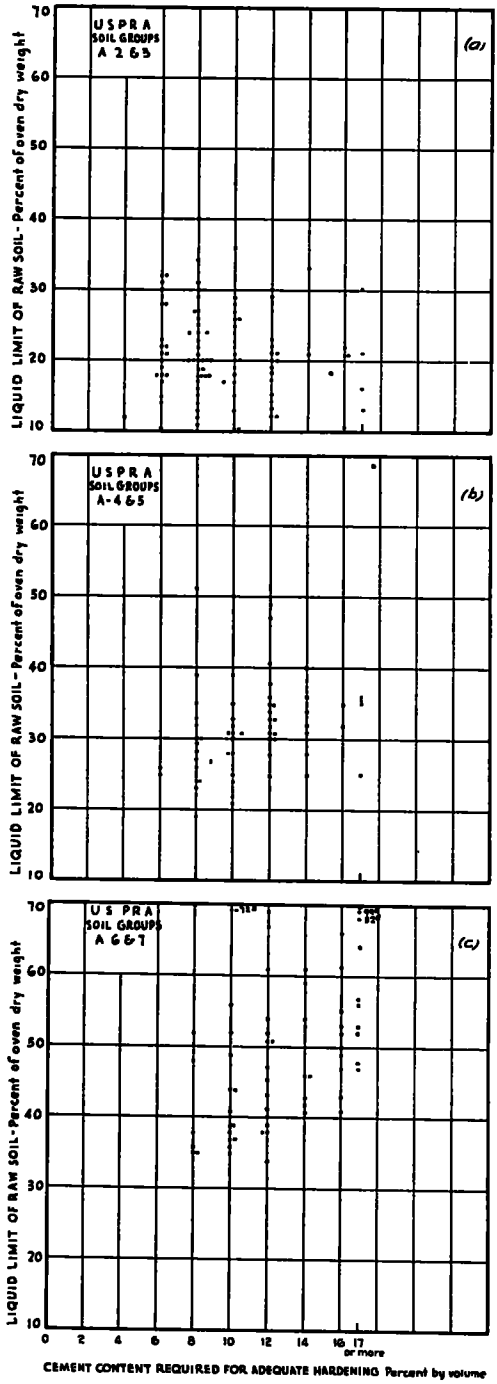

Figure 22. Relation of raw soil liquid limits to cement contents required for adequately hardening soils.

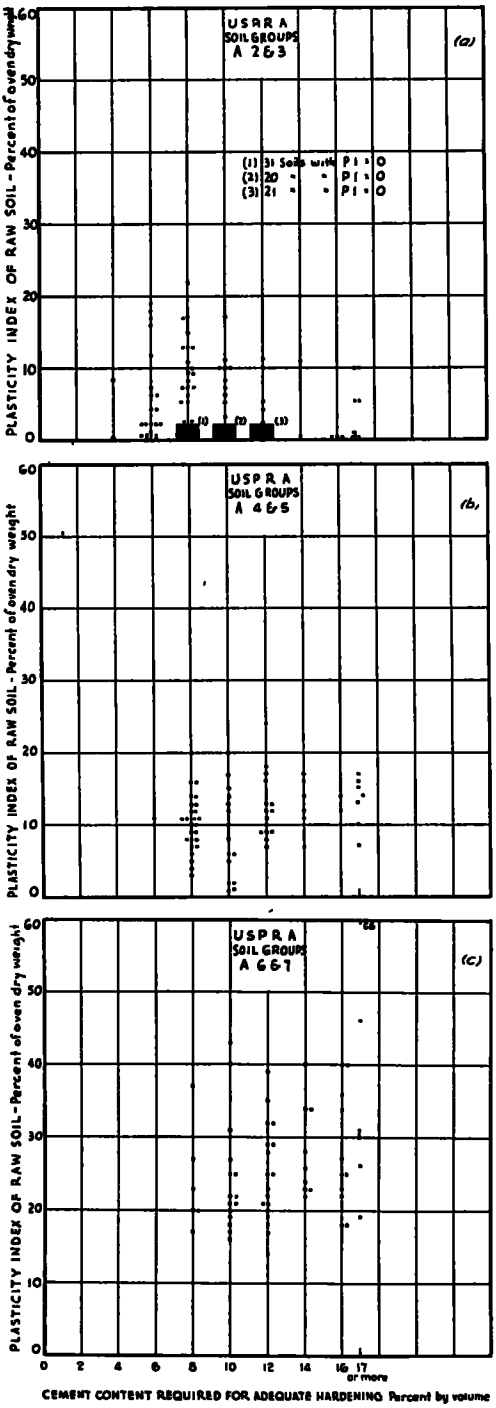

Figure 23. Relation of plasticity indices to cement contents required for adequately hardening soils.

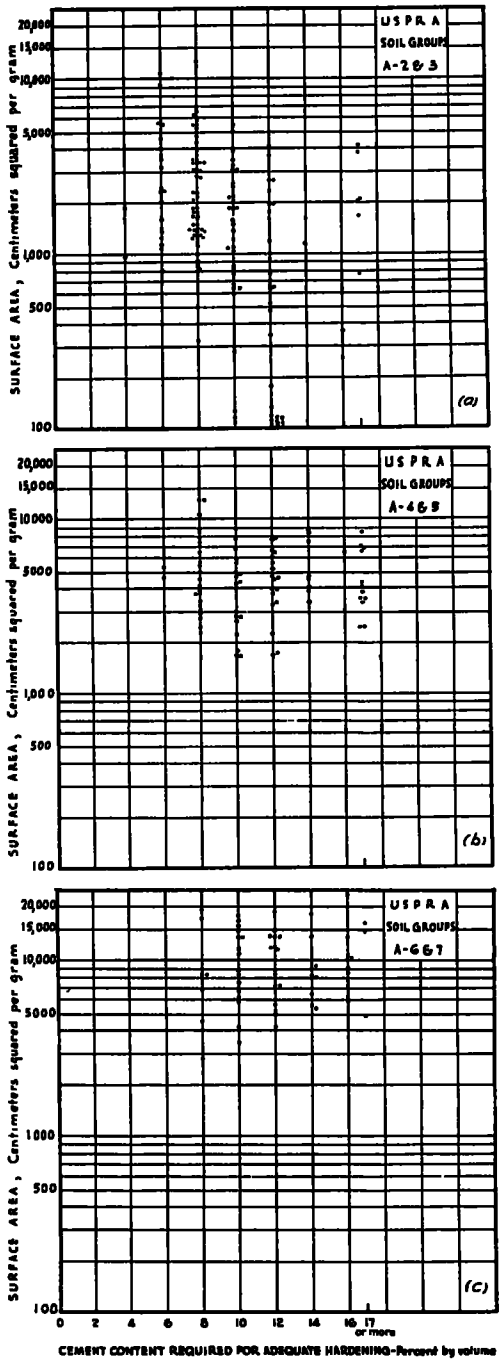

Figure 24. Relation of surface area to cement contents required for adequately hardening soils.

cussions, it can suffice to say that the liquid limit, plasticity index, or surface area cannot be used as criteria for control of soil-cement mixtures. The data again show trends or test "patterns" indicating that, in general, as the liquid limit, plasticity index, or surface area increases, the cement required to produce a structural material increases.

Considerable time and study was spent on working up the surface area data for soils. The grain size distribution of the soils was determined by the standard A.S.T.M. procedure involving the use of hydrometers and the application of Stokes Law. The soils engineer is familiar with the variations in results produced by procedure, dispersion agents, and methods. Also, that the shape of the soil grain, round, irregular, or disc shaped, is of importance. All these factors become of major inportance in computing surface area since surface areas increase very rapidly with decreases in grain size. The surface area of grains of the clay size, 0 005 mm. and below, is very great, yet the determination of clay content is the most inaccurate. However, the grain size test results are assumed to be relatively accurate. After studying surface areas as determined from a plotted grain size curve with those determined by assuming an average size for each constituent (such as 0 0275 mm. for silt) it was evident that small errors of test introduced larger errors than those introduced by taking an average size for each constituent, such as silt. Accordingly, this study is based on the latter more rapid method. The soils included in this study have very great ranges in surface area and, therefore, should surface area be an outstanding, predominate primary factor in evaluating soil-cement mixtures, this factor would become quite obvious. However, as the data show, soils may have widely different surface areas and yet respond to cement in a very similar manner. While surface area is recognized as a contributing factor, it cannot be used to predict or indicate cement requirements with the accuracy possible with a general factor such as is given by U.S.P R A. soil classification.

For purposes of record, it can be said that other soil test constants and grain size studies were made which added nothing further to the knowledge of soil-cement characteristics.

The soil-cement comparisons of maximum density, optimum moisture, compressive strengths, and cement-void relations with cement content for satisfactory hardness are given in Figures 25, 26, 20, and 27.

Detail discussion is again unnecessary as the same general test "patterns" are shown The range in maximum density, optimum moisture, compressive strength, and cement-void relations for any one cement content giving satisfactory results is too broad for use as a criterion of cement contents required. Again as the maximum density increases and optimum moisture decreases, cement content requirements decrease. The compressive strength data are also a repetition of previous test "patterns" showing a wide range of strengths for the various soils and the cement contents required for satisfactory hardness. None of the curves indicate practical or theoretical control methods as a strength criterion. In other words, cement requirements for satisfactory hardness can only be estimated within broad limits on the basis of maximum density, optimum moisture, or compressive strength results.

Considerable space could properly be devoted to a discussion of the cement-voids relation and cement content for satisfactory hardness. However, the charts themselves are self-explanatory in showing wide ranges in cement contents required to harden soil-cement mixtures with the same cement-voids

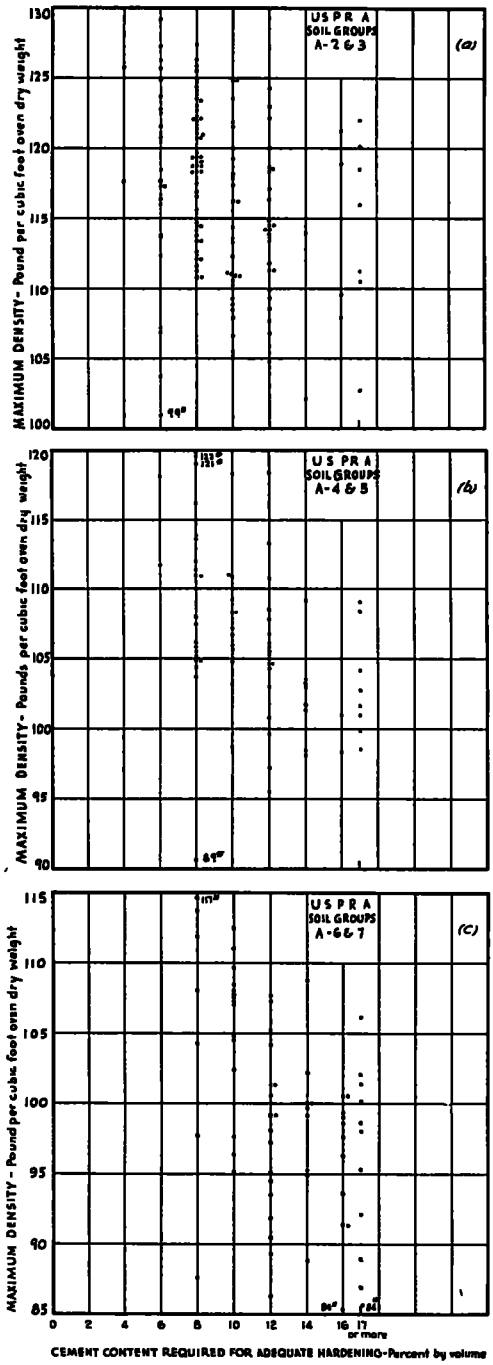

Figure 25. Relation of maximum densities of soil-cement mixtures to cement contents required for adequately hardening soils.

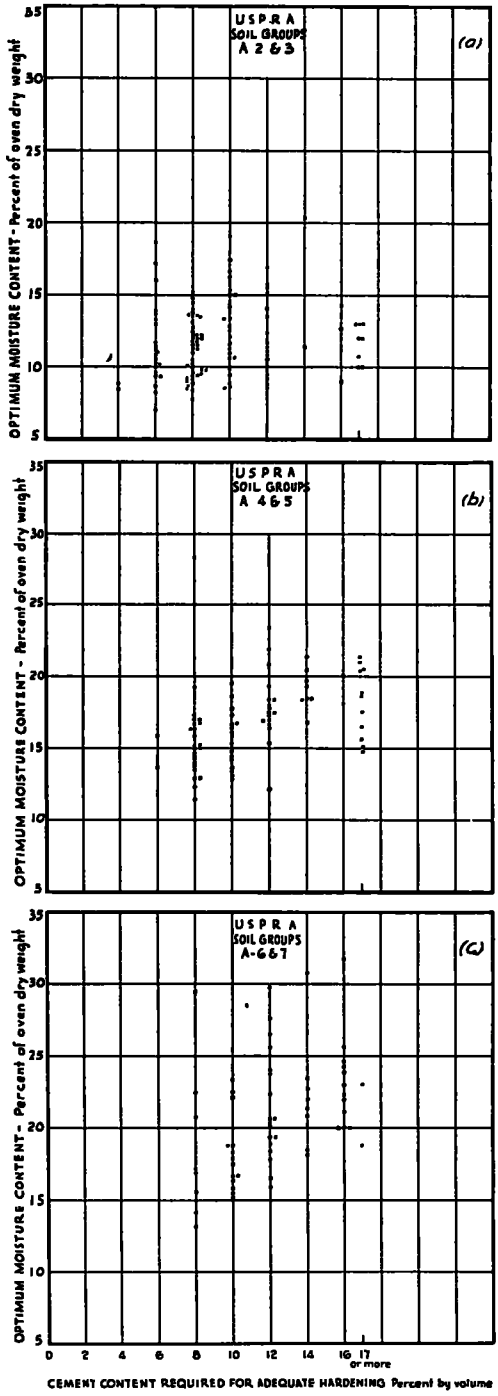

Figure 26. Relation of cement contents required for adequate hardening and optimum moisture contents of soil-cement mixtures.

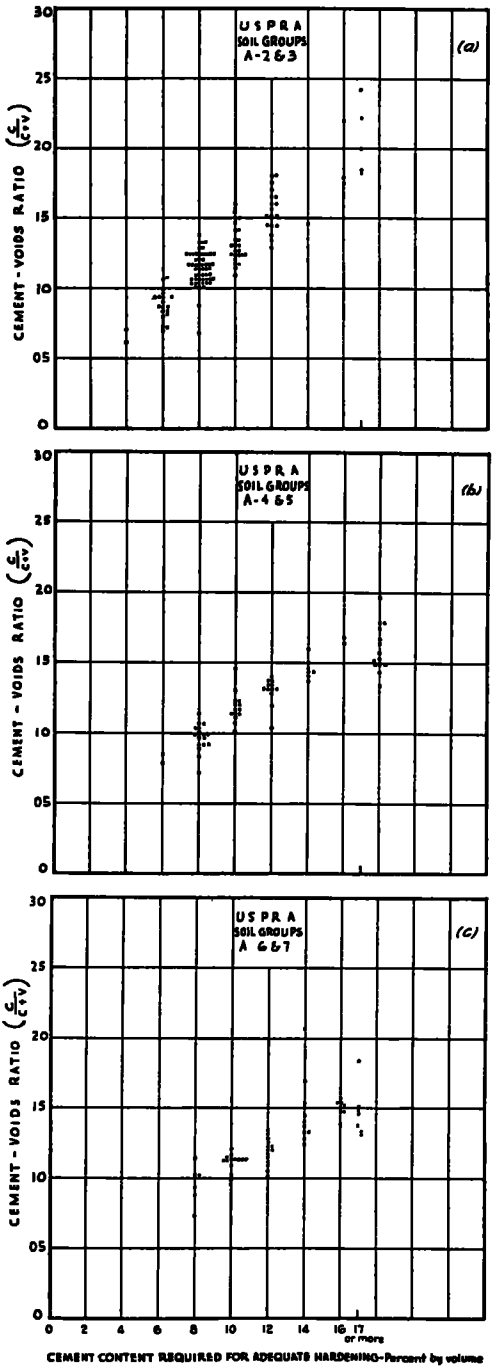

Figure 27. Relation of cement-voids ratio to cement contents required for adequately hardening soils.

ratio. In this study the same relation of cement to voids plus cement, the cement-voids (space) ratio under oven dry conditions, $\left(\frac{v}{c+v}\right)$, has been used as in concrete proportioning work for the past 20 years. The same relative results are shown by the simple relation of cement to voids $\left(\frac{c}{v}\right)$, except a greater range or variation is involved. A general test "pattern" is developed showing, as to be expected, an increase in cement content for satisfactory hardness as the cement-space ratio increases. Again, no workable cement-voids relations appear.

Treatment Groups

It is helpful in studying soil-cement mixtures to have a table showing the relations of various test results to cement contents required to produce adequate hardness and durability. Such a table was prepared in the exploratory laboratory research report and again referred to in this report Again, for purposes of study such a tabulation has been prepared for the soils included in this study. Results are given in Table 6. The characteristics of soils requiring 17 per cent cement by volume or more are not given since they are so diverse in many respects that they add little to the value of the tabulation.

Table 6 merits detail study by those desiring to know intimately the characteristics of compacted soil-cement mixtures. While it is a repetition of some of the data given on the various charts in the report, many comparisons can be made rapidly and easily. Further, many questions on the characteristics of compacted soil-cement mixtures can be answered by studying the data submitted. The table permits more rapid development of the philosophy of soil-cement mixtures and the factors which govern testing and construction.

terial. It has been pointed out repeatedly that the lower cement contents may change the soil characteristics[9,10] but as cement contents are increased, a condition is reached where the addition of more cement changes the material *from a different soil to a structural material.*

Study of soil-cement mixtures in the laboratory and field indicates that each cement grain picks up a varying number of soil grains (depending on the grain size of the soil) and as the cement hydrates and crystallizes, a new and larger soil grain or agglomeration is produced. As more and more cement is added, more soil grains lose their identity to become larger soil grains or agglomerations. The agglomeration of cement and soil grains is shown by the tests of soil-cement mixtures of low cement content.[9, 10] These agglomerations of cement grains and soil grains can also be thought of as links in a chain and when enough cement has been added to link all agglomerations together, with pockets of trapped soil, the mixture becomes a structural material rather than a soil.

All the test data also indicate that some factor is present in soil which does have a prevailing influence on the ability of cement to harden the compacted soil-cement. The fact that compressive strengths vary for soils of similar grain size and water-holding capacity, that cement requirements vary for soils having similar U.S P R.A. soil grouping, similar density, similar strengths, similar water-holding capacity, and other similarities gives substantial support to the hypothesis that there is some such factor, other than physical relations, which plays an important role in determining the influence of soil in compacted soil-cement relations.

Therefore, the chemical composition of the soil and, possibly, the nature of adsorbed ions are factors which must be tested, studied and evaluated. The laboratory work on this wide range of soils indicates that the red and yellow soils, high in iron and aluminum content and relatively low in silica content, usually respond readily to hardening with cement. In the absence of chemical composition, ionic or other chemical tests, these soils responding readily to hardening are thought and spoken of as soils which "like" cement or have a strong affinity for cement. In other words, some soils of relatively low density, high water-holding capacity, and even high colorimetric organic value may harden satisfactorily with as little as 8 per cent cement. These soils, obviously, have some predominate "liking" or affinity for cement which overcomes what are otherwise unfavorable physical factors. Further, as mentioned briefly under "Soil-Cement and Organic Relations", a soil not "liking" cement can be made to "like" cement by the simple use of a moderate amount of another soil.

This work points up the probability that the chemical research field in soil-cement has great possibilities for uncovering important soil-cement relations. While the Portland Cement Association soil-cement laboratory has made sporadic explorations in this chemical field since 1935, the large amount of testing required for construction work has prevented a systematic attack of the problem. Chemical research is very important, however, and plans have just been completed for establishing a fellowship at the University of Missouri Engineering School to explore this promising field. The fellowship will be carried out under the direction of

[9] Miles D Catton, "Laboratory Investigation of Soil-Cement Mixtures for Subgrade Treatment in Kansas," *Proceedings*, Highway Research Board, Vol 17, Part II.

[10] Carl R Reid, "Concrete Pavement Subgrade Design, Construction, Control," and E J Sampson and H G Henderson, "Dispersion of Soils and Soil-Cement Mixes," *Proceedings*, Highway Research Board, Vol 19.

Dr. Hans F. Winterkorn who has been a leader in applying soil chemistry to road problems

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