BASIC PRINCIPLES OF SOIL-CEMENT MIXTURES AND EXPLORATORY LABORATORY RESULTS

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In recent years increasing attention has been devoted to the improvement of secondary roads In this field there is an insistent demand for low-cost, stable, all-weather surfaces Aiming at this objective, some experimenting was done with soil-cement mixtures during the past 20 years In general, the results obtained were unsatisfactory However, enough information was developed by these sporadic efforts to indicate that an intensive and thorough investigation of soil-cement mixtures might uncover certain fundamentals which would lead to the development of this material for the construction of low first cost secondary roads

Of especial significance was the pioneer work of the South Carolina State Highway Department on soil-cement mixtures This work was initiated in 1932 at the suggestion of Dr Charles H Moorefield while State Highway Engineer While the results of this early work were far from perfect they were nevertheless most challenging

Accordingly in January 1935, Frank T Sheets*, Consulting Engineer and Director of Development of the Portland Cement Association and the writer began a thorough study of technical literature on soils, including soil physics, mechanics and chemistry This was supplemented by a review of the South Carolina work and some exploratory work of the U S Bureau of Public Roads

This general survey indicated that there were possibilities of combining soil and cement to produce a low-cost, all-weather road for use in the light traffic road field provided the relations of soil and cement could be evaluated and such work removed from a cut-and-try or hit-and-miss process

In the review of soil knowledge to date, the work of R R Proctor[1] of the Los Angeles, California, Water Board was found to be outstanding in that he brought national attention to the principle that a direct relation exists between the moisture content of a soil, the degree of compaction and the resulting density These principles were uncovered by the Materials and Research Division of the California State Highway Commission

In the work conducted by Proctor it was found that the compaction of soil in the field obtained by a sheepsfoot roller could be duplicated in the laboratory by packing three successive layers of soil about one and one-half inches thick in a cylinder with a five and one-half pound rammer Each layer is packed by 25 blows of the rammer dropping free through a distance of 12 in The moisture, compaction and density relations he used show that each soil has an optimum moisture content which will produce maximum density (stability) in a soil

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* Since September 1, 1937, President, Portland Cement Association

[1] "Fundamental Principles of Soil Compaction" by R R Proctor, Field Engineer, Bureau of Waterworks and Supply, Los Angeles, California *Engineering News-Record*, August 31, September 7, 21 and 28, 1933

when it is compacted according to the above specifications Also that any selected density for a given soil can be obtained repeatedly by duplicating the required moisture content and compacting procedure The Proctor Laboratory equipment is shown in Figure 1

In view of these relationships, it became evident that the adoption of this procedure might make it possible to prepare any desired number of identical specimens of soil-cement mixture, having a predetermined and most desired density If soil-cement mixtures followed the general moisture-density relations of raw soils, then the preparation of soil-cement specimens compacted to optimum moisture at maximum density would place the material in the most stable condition possible to obtain in the field Further, it was essential to determine the quantities of cement required to produce a soil-cement mixture which would be stable and durable when exposed to field conditions Therefore, the durability and stability of soil-cement mixtures would need to be determined by means of laboratory weathering tests

With the adoption of these concepts it was obvious that an exploratory investigation of soils and soil-cement mixtures should consist of

A A laboratory investigation to determine,
  1 Moisture-density relations of soil-cement mixtures at
    (a) Maximum density
    (b) Optimum moisture
  2 Cement content required in soil-cement mixtures, compacted at optimum moisture to maximum density, to produce satisfactory durability and stability
    (a) Based on repeated freezing and thawing
    (b) Based on repeated wetting and drying
  3 Relation of optimum moisture of soil-cement mixtures to moisture required to hydrate cement
B A field investigation to determine the practicability of applying laboratory findings

A laboratory research project was outlined for developing these exploratory data for a wide range of soils Arrangements were made for cooperation with the South Carolina State Highway Department in determining the needed laboratory data for a specific project and with the South Carolina Highway Department and the U S Bureau of Public Roads in the construction of a 1½-mile field project This project was built late in the fall of 1935 near Johnsonville, S C, under the supervision of the South Carolina State Highway Department and M D Catton after completion of a laboratory investigation of the soil which followed the procedures outlined in this report Results were obtained which proved that soil could be properly pulverized, cement and moisture contents controlled and uniform, specified density obtained with sheepsfoot rollers This work was reported by W H Mills, Jr, Testing Engineer, South Carolina State Highway Department, at the November, 1936 meeting of the Highway Research Board [2]

The laboratory research project of the Association has been under way since 1935 While all the exploratory work has not been completed, the work on all top soils and several common subsoils has been very stimulating and satisfactory and has progressed far enough to warrant a summary of results Work is still under way on several very bad subsoils of limited occurrence which were selected so that eventually the entire range of road soils would be studied

The following is a progress report on the work completed to date

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[2] *Proceedings*, Highway Research Board, Vol 16, p 322

LABORATORY INVESTIGATION

Purpose

The purpose of this project was to determine

1 Whether moisture-density relations of soils also hold for soil-cement mixtures

2 Whether moisture content at optimum was sufficient to hydrate the added cement

3 Whether cement hydration is a primary or secondary contribution to the stability and durability of soil-cement mixtures

4 The predominating physical-chemical relations of soils and cement

5 Whether all the results obtained in items 1 to 5 vary with soil types

6 Whether the stability and durability of soils commonly occurring in the United States can be improved appreciably by the addition of cement

The data secured in studying these questions should show the relative adaptability of portland cement to the treatment of the soils found throughout the United States under prevailing climatic conditions and indicate field construction requirements

TABLE 1

IDENTIFICATION OF SOILS TESTED

Laboratory Sample No	Soil Group, U S Bureau of Public Roads Classification	Source	Description
2a	A-2	South Carolina	Fine sandy loam top-soil
3a	A-3	San Joaquin Co , California	Fine sand top-soil
4a	A-4	Calloway Co , Missouri	Silty clay loam subsoil
5a	A-5	Minnesota	Clay subsoil
5c	A-5	Maryland	Micaceous sandy loam top-soil
5d	A-4	Latah Co , Idaho	Heavy silt loam top-soil
6a	A-6	Pike Co , Missouri	Clay subsoil
6b	A-7-6	Fairfax Co , Virginia	Clay subsoil
6c	A-6	Guadalupe Co , Texas	Clay subsoil
6d	A-6	San Joaquin Co , California	Clay (adobe) top-soil
7a	A-4	Franklin Co , Kansas	Light silty clay subsoil
7b	A-6-7	Michigan	Clay subsoil
7c	A-7-6	Pike Co , Missouri	Clay subsoil
7d	A-7	Hinds Co , Mississippi	Clay subsoil
7e	A-7	Hinds Co , Mississippi	Clay (Sharkey) subsoil
7f	A-7-4	Sangamon Co , Illinois	Light silty clay loam top-soil (Bates Road)
8a	A-8	Minnesota	Peaty muck (silt loam) top-soil

Outline of Laboratory Tests

Series 1 Selection of all representative soil types from various parts of the United States and the determination of their physical test constants and grain size The soils selected for testing are given in Table 1, together with their identification

Series 2 Determination of moisture-density relations of raw soils by varying the moisture content and using the Proctor method of compaction

Series 3. Determination of influence of various percentages of portland cement on moisture-density relations of soil-cement mixtures using the Proctor method of compaction Determinations of the resistance of the resulting specimens to the Proctor penetration apparatus were also made but have since been abandoned as no relations could be found between these penetration indices and desirable cement contents Further, no readings could be obtained after the specimens had hardened for a few hours

TABLE 2

Physical Test Constants and Grain Size of Soils

Lab Sample No	Optimum Moisture, Per Cent	Liquid Limit (L L)	Plastic Limit (P L)	Plastic Index (P I)	Shrinkage Limit (S L)	Shrinkage Ratio (S R)	Centrifuge Moisture Equivalent (C M E)	Field Moisture Equivalent (F M E)	Sand, Above 0 05 mm	Silt, 05- 005 mm	Clay, 005-000 mm	Colloids, Below 001 mm (1)	Specific Gravity
2a	10	19	17	2	15	1 8	10	18	77	1	22	15	2 662
3a	11	18	—	0	28	1 5	7	23	88	1	11	7	2 690
4a	16	30	23	7	20	1 7	28	25	7	69	24	10	2 683
5a	31	65	35	30	31	1 5	49	43	6	24	70	17	2 647
5c	17	36	33	3	30	1 5	19	35	61	23	16	10	2 732
5d	16	32	25	7	22	1 7	26	28	16	66	18	8	2 647
6a	20	58	22	36	13	1 9	34	28	23	28	49	32	2 680
6b	20	62	29	33	13	1 9	40	39	23	35	42	24	2 815
6c	22	61	23	38	10	2 1	39	34	10	43	47	20	2 720
6d	19	48	20	28	10	2 0	31	28	14	48	38	18	2 696
7a	17	35	21	14	16	1 8	25	21	14	56	30	13	2 635
7b	18	44	24	20	18	1 8	52*	23	5	19	76	32	2 727
7c	20	60	27	33	14	1 9	39	34	11	43	46	29	2 711
7d	28	118	35	83	14	1 9	98*	50	14	18	68	**	2 761
7e	22	67	22	45	12	1 9	58*	32	32	16	52	28	2 721
7f	21	46	29	17	20	1 7	31	29	20	60	20	10	2 590
8a	81	170	—	0	66	0 8	92	244	10	80	10	7	2 077

(1) Also included in clay fraction
* = water logged
** = flocculated

Series 4 Determination of influence of variable cement contents on the durability and stability of soil-cement mixtures by obtaining weight of material lost upon repeated cycles of wetting and drying of cylinders compacted to maximum density at optimum moisture

Series 5 Same as Series 4, using moisture changes, volume changes and weight of material lost in repeated cycles of freezing and thawing of cylinders as a criterion of the influence of added cement upon the durability and stability of soil-cement mixtures

The U S Bureau of Public Roads cooperated in this work by determining the physical test constants and grain size of the soils to be studied Hence all the data reported for Series 1 were obtained from that source Since the Bureau performed the tests of Series 1, the Association work could be focused on the tests which supplied the relationships between moisture content, compaction and density of soil and soil-cement mixtures.

The equipment for the laboratory work consisted of two sets of the Proctor soil testing equipment (metal cylinders, rammers, penetration disks), a small oven, scales and miscellaneous equipment.

A large oven was used for drying soil-cement cylinders tested in the wetting and drying series. A large refrigerator, capable of freezing specimens to −15° F. in about 20 hours, was used for freezing soil-cement cylinders.

TEST PROCEDURES

Physical Test Constants and Grain Size of Soils.

The physical test constants and grain size of the soils were determined according to the standard test procedures of the U. S. Bureau of Public Roads; results are given in Table 2.

All percentages of moisture and cement in the soil specimens given in this report are based on the oven dry weight of the soil unless stated otherwise.

Determination of Moisture-Density Relations Of Raw Soil Compacted by Proctor Method.

The moisture-density relations of a soil are determined after the soil has been air dried and pulverized to pass a No. 4 sieve. The moisture content of the air dry soil, expressed as a percentage of the weight of soil when oven dry, is then determined. A cylinder of air dry soil is then compacted by the Proctor method and weighed. From this weight determination and the known moisture content, the weight per cubic foot of compacted soil in the cylinder, when oven dry, is computed. Another cylinder is prepared by adding about two per cent moisture to the soil and compacting. The compacted cylinder is then weighed, a sample of the soil oven dried to determine its moisture content and the oven dry weight per cubic foot of compacted soil again computed.

This process is repeated until the moisture content of the soil is considerably above the plastic limit. The oven dry weight per cubic foot obtained by compaction is then plotted with the corresponding moisture content. This gives the moisture-density relations of the soil. Figure 17, shows the moisture-density relations of the Illinois Bates Road light silty clay loam top-soil, which is typical of many soils.

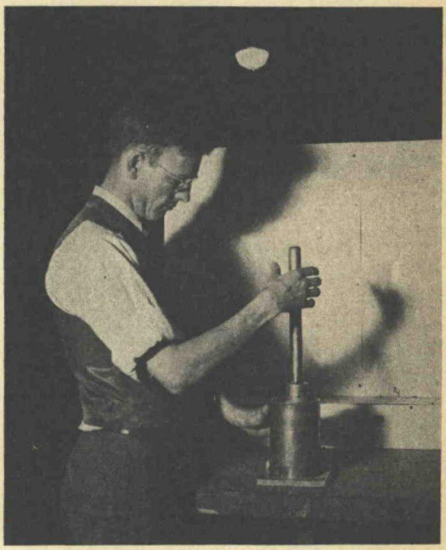

Figure 1. Proctor Compaction Apparatus

Determination of Moisture-Density Relations of Soil-Cement Mixtures Compacted by Proctor Method

Soil-cement mixtures were obtained by adding 2, 4, 6 and 10 per cent cement to the oven dry weight of the soil. The moisture-density relations of each soil-cement mixture were obtained by the methods described for raw soils.

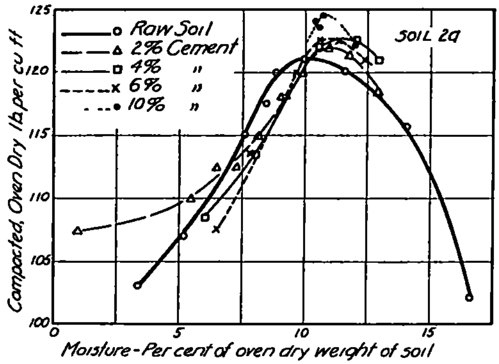

Figure 2. Moisture-Density. South Carolina fine sandy loam top-soil No. 2a, Soil Group A-2.

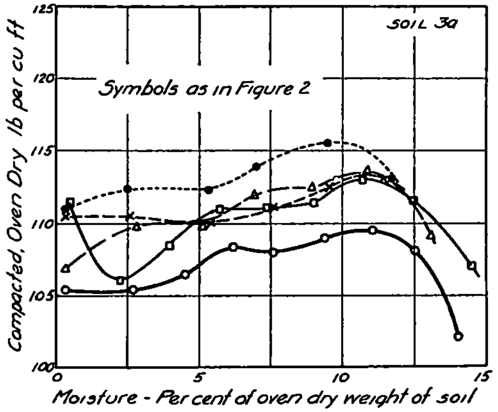

Figure 3. Moisture-Density. California fine sand top-soil, No. 3a, Soil Group A-3.

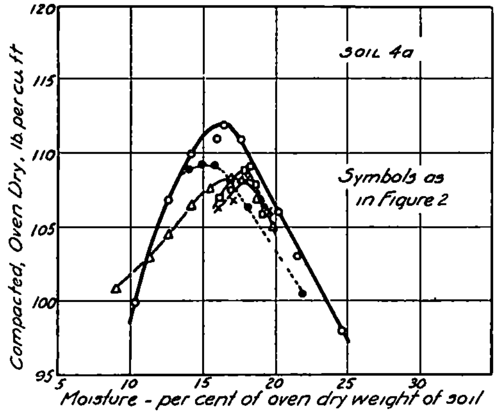

Figure 4. Moisture-Density. Missouri silty clay loam subsoil, No. 4a. Soil Group A-4.

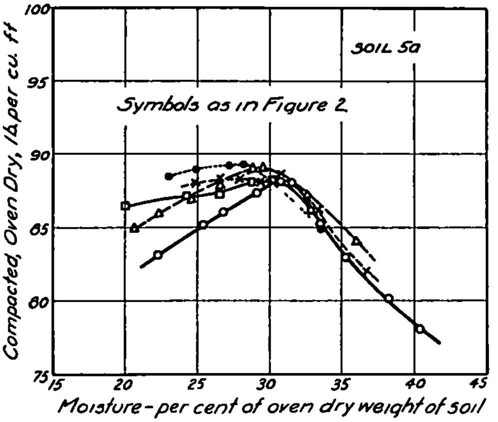

Figure 5. Moisture-Density. Minnesota clay subsoil, No. 5a, Soil Group A-5.

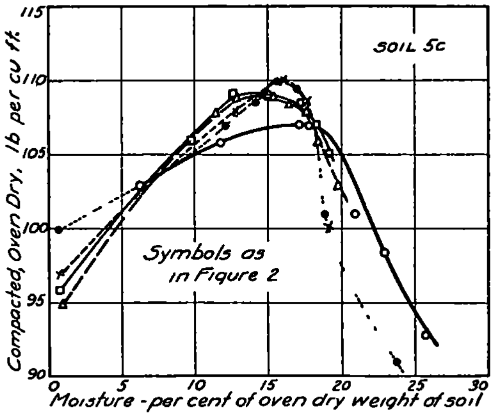

Figure 6 Moisture-Density Maryland micaceous sandy loam top-soil, No. 5c, Soil Group A-5.

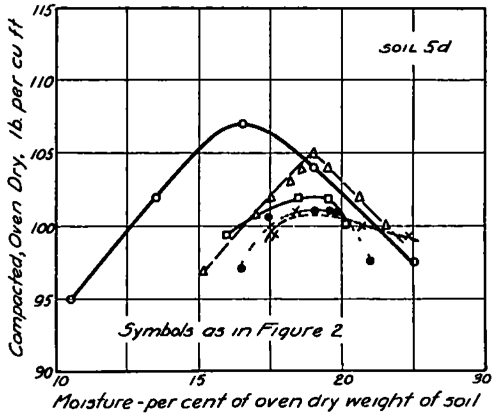

Figure 7. Moisture-Density. Idaho heavy silt loam top-soil, No. 5d, Soil Group A-4.

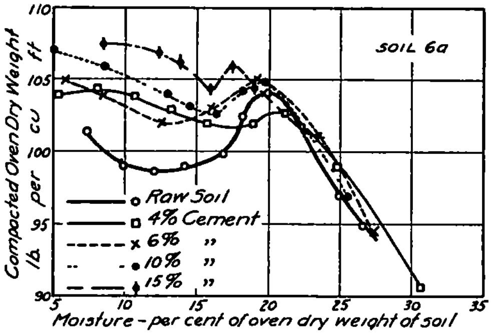

Figure 8 Moisture-Density Missouri clay subsoil, No 6a, Soil Group A-6.

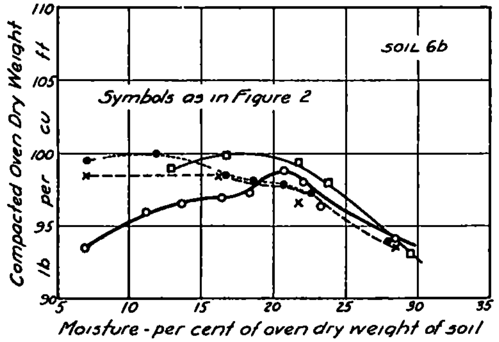

Figure 9. Moisture-Density. Virginia clay subsoil, No 6b, Soil Group A-7-6.

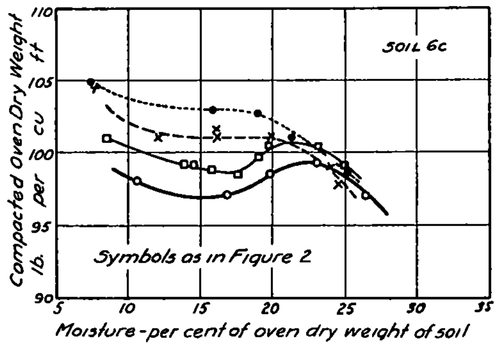

Figure 10. Moisture-Density Texas clay subsoil, No. 6c, Soil Group A-6.

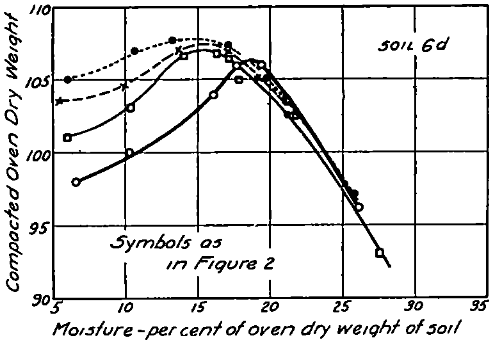

Figure 11. Moisture-Density. California clay (adobe) top-soil, No 6d, Soil Group A-6

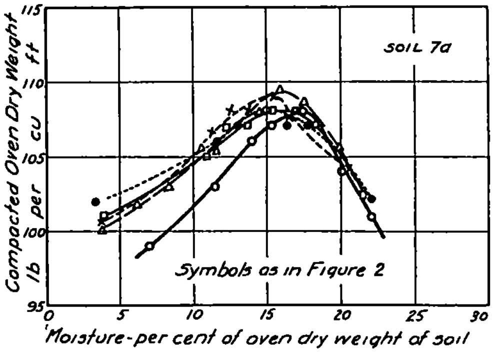

Figure 12. Moisture-Density. Kansas light silty clay subsoil, No. 7a, Soil Group A-4

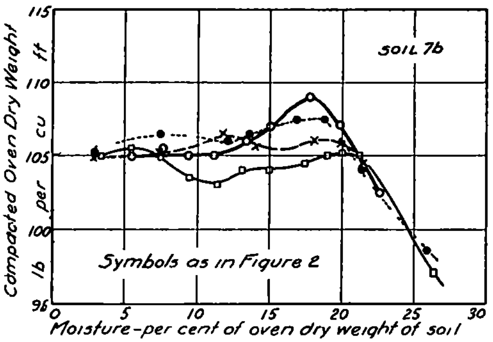

Figure 13 Moisture-Density Michigan clay subsoil, No 7b, Soil Group A-6-7.

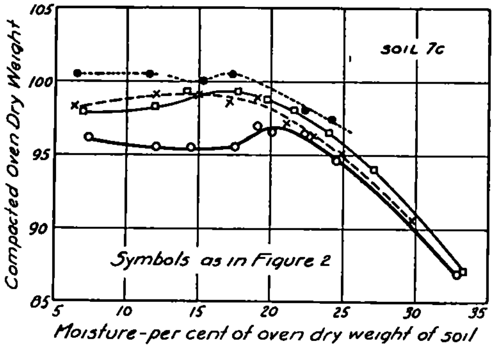

Figure 14. Moisture-Density. Missouri clay subsoil, No. 7c, Soil Group A-7-6.

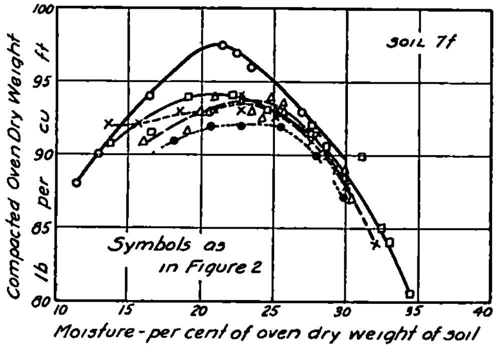

Figure 17. Moisture-Density. Illinois light silty clay loam top-soil (Bates Road), No. 7f, Soil Group A-7-4.

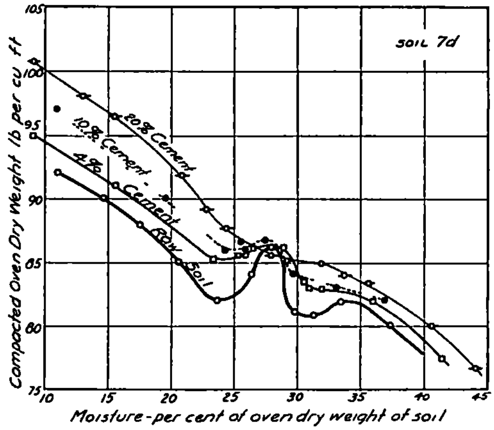

Figure 15. Moisture-Density. Mississippi clay subsoil, No. 7d, Soil Group A-7.

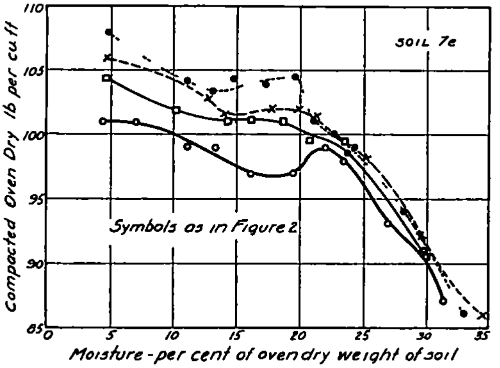

Figure 16. Moisture-Density. Mississippi (Sharkey) clay subsoil, No. 7e, Soil Group A-7.

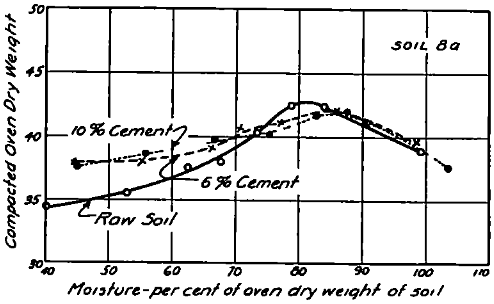

Figure 18. Moisture-Density. Minnesota peaty muck top-soil, No. 8a, Soil Group A-8.

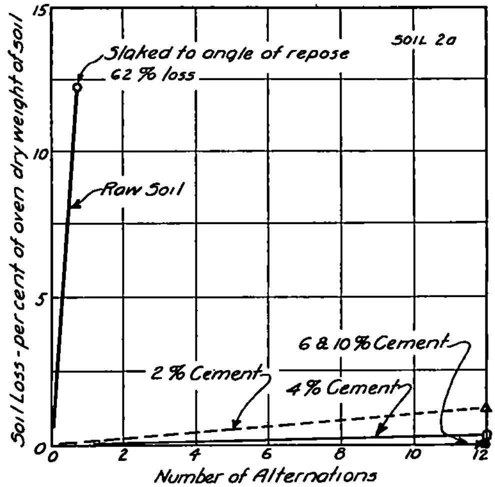

Figure 19. Alternate Wetting and Drying. Soil losses at end of drying period; curves are averages of two specimens; South Carolina fine sandy loam top-soil, No 2a.

Preparation of Specimens for Durability Tests

Specimens of raw soil and soil-cement mixtures were first molded at optimum moisture to maximum density. The specimens were then removed by placing the mold in a special assembly in a compression machine. Split molds may also be used to obtain compacted specimens.

The specimens were exposed to laboratory air for seven days during which daily measurements of volume and moisture content were made. It has since been found desirable to simulate field conditions more nearly by storing the specimens in air of high humidity or damp sand to reduce moisture losses to a minimum for a 7-day period.

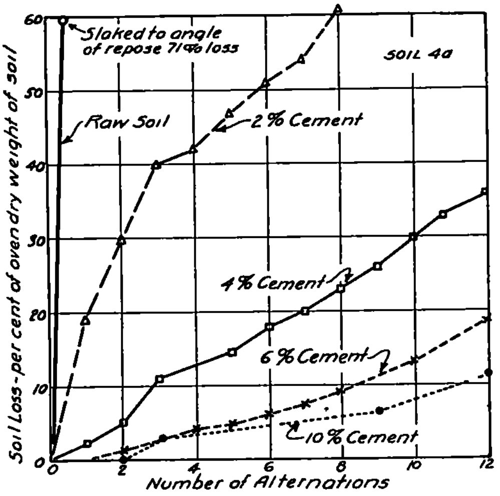

Figure 20. Alternate Wetting and Drying. Soil losses at end of drying period; curves are averages of two specimens; Missouri silty clay loam subsoil, No. 4a.

Wetting and Drying Procedure

After seven days preparation, the specimens were placed in an oven at 160°F for 42 hours. They were then weighed and measured to give a base for determining slaking losses during repeated wetting and drying. After this initial period of about nine days drying, the specimens were ready for the wetting and drying test.

As soon as the specimens had been weighed and measured after removal from the oven, they were immersed in tap water for five hours, removed and again weighed and measured. They were then placed in an oven at 160°F. for 42 hours, removed, weighed and measured.

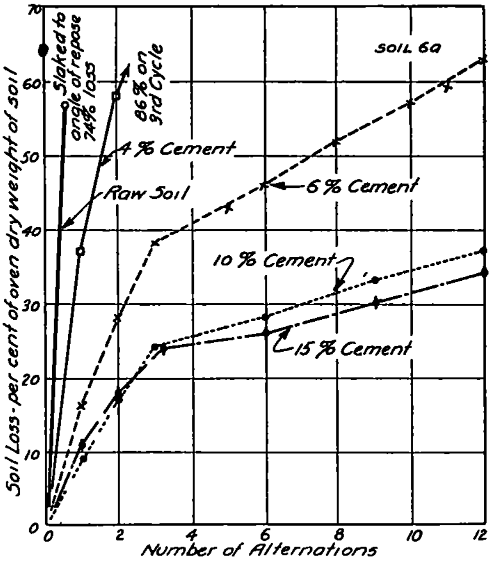

Figure 21. Alternate Wetting and Drying. Soil losses at end of drying period; curves are averages of two specimens, Missouri clay subsoil, No. 6a.

The foregoing wetting and drying constituted one cycle which was repeated at least 12 times or until the specimens slaked to their angle of repose.

Freezing and Thawing Procedure

After seven days preparation, the specimens were placed on moist felt pads in the moist room for 5 to 7 days to permit complete capillary absorption of moisture. Measurements of weight and volume were made daily. After this initial

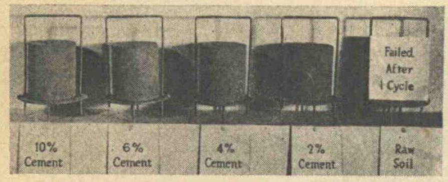

Figure 22. Alternate Wetting and Drying. South Carolina Fine Sandy Loam Top-Soil, Sample 2a.

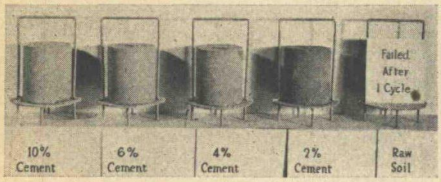

Figure 23. Alternate Wetting and Drying. California Fine Sand Top-Soil, Sample 3a.

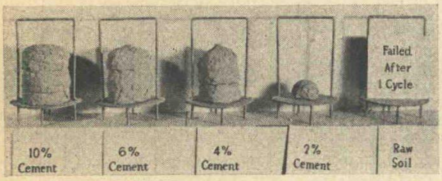

Fig. 24. Alternate Wetting and Drying. Missouri Silty Clay Loam Subsoil, Sample 4a.

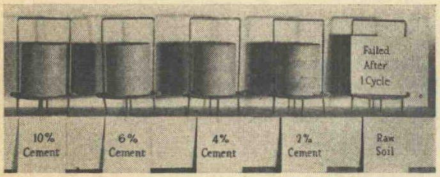

Figure 25. Alternate Wetting and Drying. Maryland Micaceous Sandy Loam Top-Soil Sample 5c.

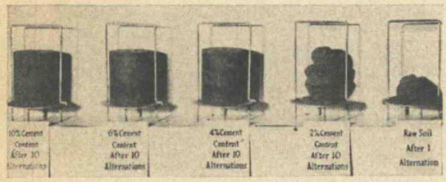

Figure 26. Alternate Wetting and Drying. Idaho Heavy Silt Loam Top-Soil, Sample 5d.

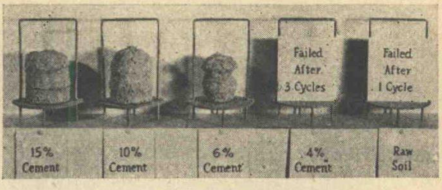

Figure 27. Alternate Wetting and Drying. Missouri Clay Subsoil, Sample 6a.

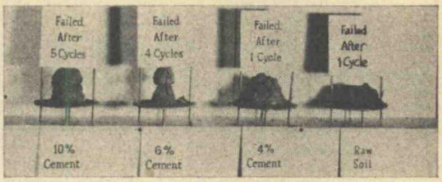

Figure 28. Alternate Wetting and Drying. California Clay Adobe Top-Soil, Sample 6d.

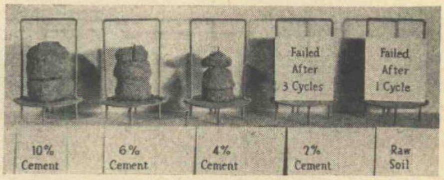

Figure 29. Alternate Wetting and Drying. Kansas Light Silty Clay Subsoil, Sample 7a.

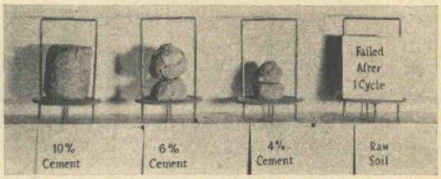

Figure 30. Alternate Wetting and Drying. Michigan Clay Subsoil, Sample 7b.

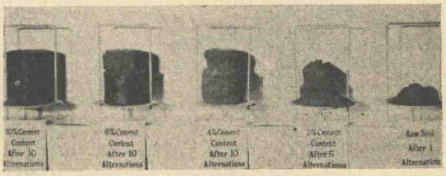

Figure 31. Alternate Wetting and Drying. Bates Test Road Soil, Illinois, Light Silty Clay Loam Top-Soil, Sample 7f.

12 to 14-day preparation period, the specimens were ready for repeated freezing and thawing

The specimens were placed on special carriers, illustrated in Figure 22, in a refrigerator capable of freezing the center of the specimens in about three hours and lowering the temperature of the centers to −15°F in 20 hours A typical curve of freezing conditions is shown in Figure 32 After 20 hours in the refrigerator, the specimens were removed, weighed, measured and placed on wet felt pads in the moist room to thaw for 24 hours with free water added to the pads as needed to permit complete capillary absorption of water by the specimens The specimens were then weighed and measured again This constituted one alternation of freezing and thawing. All specimens were subjected to the test for at least 12 cycles or until measurements were no longer of value

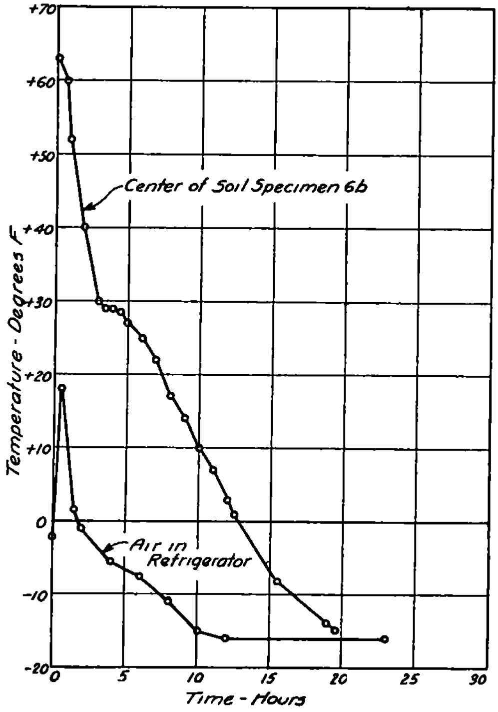

Figure 32. Freezing and Thawing Tests. Rate of Freezing

GENERAL SUMMARY

Test Series 1, 2 and 3 were completed on all soils Moisture-density results are shown in Figures 2 to 18 inclusive The durability tests, Series 4 and 5, were completed on all top-soils and the subsoils of common occurrence Results are given in Tables 4, 5, 6 and 7, and illustrated in Figures 19 to 51 inclusive

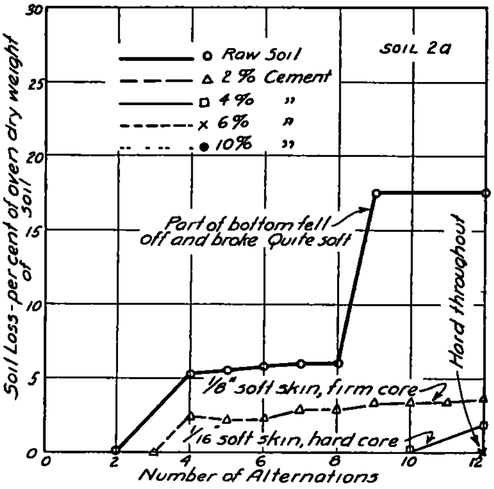

Figure 33. Alternate Freezing and Thawing. Soil losses at end of thawing period, South Carolina fine sandy loam top-soil, No 2a.

The durability tests have not been completed on several unusual subsoils of limited occurrence having high clay and colloidal content which were selected so that eventually the entire range of existing soils would be studied

The major findings of fundamental nature in these tests are

1 Moisture-density relations of soils also hold for soil-cement mixtures
2 Moisture content at optimum is from 3 to 10 times the quantity required to hydrate the cement added

3. Cement hydration is a primary contribution to the increase in stability and durability achieved with cement treated soils
4. The physical-chemical relations of soils and cement are of fundamental importance
5. All of the above relations vary with soil types
6 The stability and durability of most soils commonly occurring in the United States can be improved materially by the addition of cement

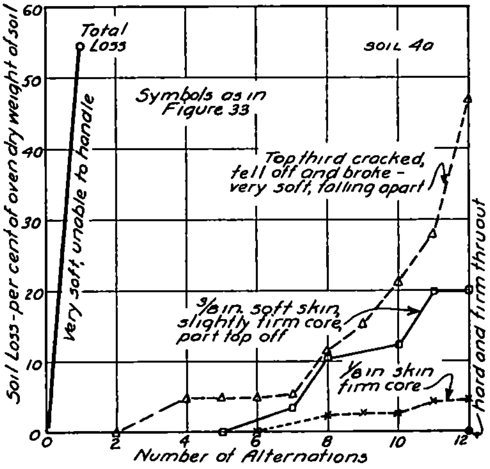

Figure 34. Alternate Freezing and Thawing. Soil losses at end of thawing period; Missouri silty clay loam subsoil, No. 4a.

This preliminary exploratory work also showed that three fundamental principles are involved in the production of stable, durable soil-cement mixtures. They are

1. Incorporation of optimum moisture
2 Compaction to uniform, maximum density
3. Incorporation of sufficient cement to reduce soil losses, moisture and volume changes to negligible amounts during the 12 cycles of durability tests provided

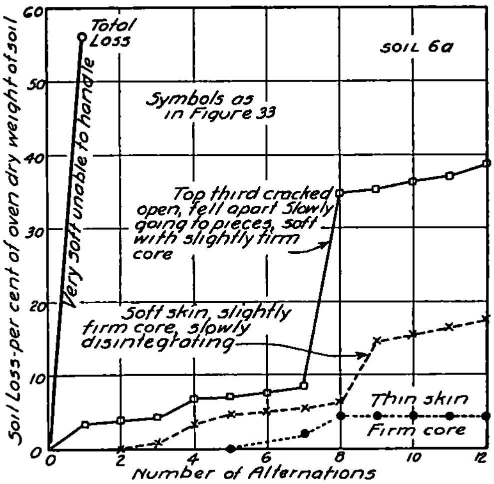

Figure 35. Alternate Freezing and Thawing. Soil losses at end of thawing period; Missouri clay subsoil, No. 6a.

In analyzing the test data it has been helpful to divide the soils into three general treatment groups based upon the durability test results obtained from Series 4 and 5. A summary of these data is given in Table 3 Soils showing very marked hardening with the addition of cement were placed in Treatment Group 1, soils showing marked hardening with the addition of cement were placed in Treatment Group II, soils showing substantial hardening with the addition of a reasonable amount of cement were placed in Treatment Group III Work on soils 6b, 6c, 7c, 7d, 7e and 8a, unusual, bad subsoils of limited occurrence has not been completed. The moisture-density curves of these soils have different characteristics than the curves for the other soils and considerably more laboratory work is involved in their evaluation Figure 15 of soil 7d, Mississippi clay, is a typical example of these irregular type curves In subsequent discussions, these soils on which tests have not been completed have been placed together in a Group IV as a means of ready identification. However, it should not be inferred that successful means of treatment will not be evolved from the tests now under way on these soils.

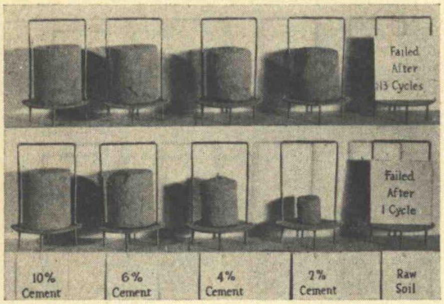

Figure 36. Freezing and Thawing. South Carolina Fine Sandy Loam Top-Soil, Sample 2a. Above—Unbrushed Specimens, Below—Brushed Specimens after 20 cycles.

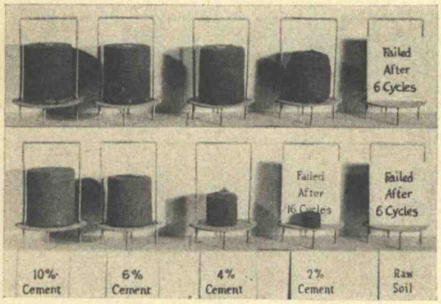

Figure 37. Freezing and Thawing. California Fine Sand Top-Soil, Sample 3a. Above—Unbrushed Specimens, Below—Brushed Specimens after 20 cycles.

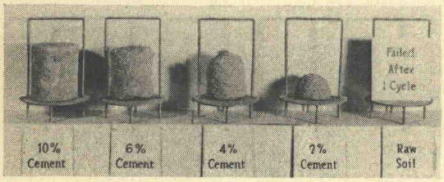

Figure 38. Freezing and Thawing. Missouri Silty Clay Loam Subsoil, Sample 4a, Unbrushed Specimens.

The following discussion relative to the three treatment groups is based on cement addition expressed as a percentage of the dry weight of the soil, which is in accordance with the control methods used on the exploratory work.

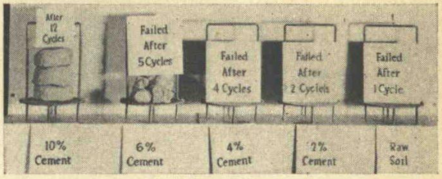

Figure 39. Freezing and Thawing. Minnesota Clay Subsoil, Sample 5a, Brushed Specimens.

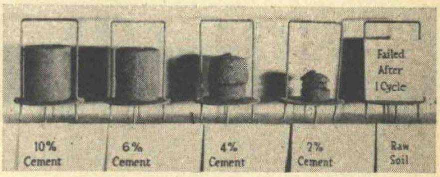

Figure 40. Freezing and Thawing. Maryland Micaceous Sandy Loam Top-Soil, Sample 5c. Specimens brushed after third cycle.

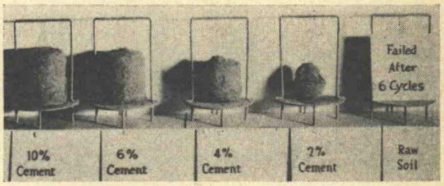

Figure 41. Freezing and Thawing. Idaho Heavy Silt Loam Top-Soil, Sample 5d, Unbrushed Specimens.

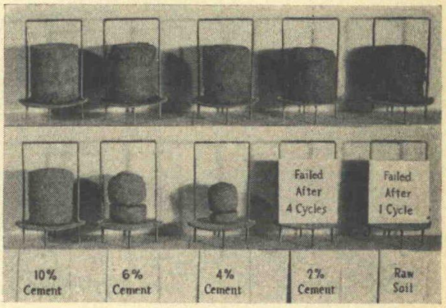

Figure 42. Freezing and Thawing. Kansas Light Silty Clay Subsoil, Sample 7a. Above—Unbrushed Specimens, Below—Brushed Specimens.

The influence of cement can be evaluated most accurately on a volume basis since

TABLE 3

General Summary into Treatment Groups of Results from Durability Tests

Soil Characteristics	Treatment GROUP I				Treatment GROUP II				Treatment GROUP III			
	Very marked hardening with added cement High resistance to (1) wetting and drying and (2) freezing and thawing				Marked hardening with added cement Good resistance to (1) wetting and drying and (2) freezing and thawing.				Substantial hardening with reasonable cement content Substantial resistance to (1) wetting and drying and (2) freezing and thawing with reasonable cement content			
	Soil Lab No	U S B P R Soil Class	Description	Test Values	Soil Lab No	U S B P R. Soil Class	Description	Test Values	Soil Lab No	U S B P R. Soil Class	Description	Test Values
Liquid Limit	2a	A-2	S C fine sandy loam	19	4a	A-4	Mo silty clay loam	30	5a	A-5	Minn clay	65
	3a	A-3	Calif fine sand	18	5d	A-4	Idaho heavy silt loam	32	6a	A-6	Mo clay	58
	5c	A-5	Md micaceous sandy loam	36	7a	A-4	Kans light silty clay	35	6d	A-6	Calif adobe	48
					7f	A-7-4	Ill light silty clay loam	46	7b*	A-6-7	Mich clay	44
Plasticity Index	2a	A-2	S C fine sandy loam	2	4a	A-4	Mo silty clay loam	7	5a	A-5	Minn clay	30
	3a	A-3	Calif fine sand	0	5d	A-4	Idaho heavy silt loam	7	6a	A-6	Mo clay	36
	5c	A-5	Md micaceous sandy loam	3	7a	A-4	Kans light silty clay	14	6d	A-6	Calif adobe	28
					7f	A-7-4	Ill light silty clay loam	17	7b*	A-6-7	Mich clay	20
Clay Content	2a	A-2	S C fine sandy loam	22	4a	A-4	Mo silty clay loam	24	5a	A-5	Minn clay	70
	3a	A-3	Calif fine sand	11	5d	A-4	Idaho heavy silt loam	18	6a	A-6	Mo clay	49
	5c	A-5	Md micaceous sandy loam	16	7a	A-4	Kans light silty clay	30	6d	A-6	Calif adobe	38
					7f	A-7-4	Ill light silty clay loam	20	7b*	A-6-7	Mich clay	76
Per Cent Solids at Maximum Density	2a	A-2	S C fine sandy loam	73	4a	A-4	Mo silty clay loam	66	5a	A-5	Minn clay	53
	3a	A-3	Calif fine sand	65	5d	A-4	Idaho heavy silt loam	65	6a	A-6	Mo clay	63
	5c	A-5	Md micaceous sandy loam	63	7a	A-4	Kans light silty clay	66	6d	A-6	Calif adobe	63
					7f	A-7-4	Ill light silty clay loam	60	7b*	A-6-7	Mich clay	64
Nature of Moisture-Density Curve	2a	A-2	S C fine sandy loam	Regular	4a	A-4	Mo silty clay loam	Regular	5a	A-5	Minn clay	Regular
	3a	A-3	Calif fine sand	Regular	5d	A-4	Idaho heavy silt loam	Regular	6a	A-6	Mo clay	Regular-Irregular
	5c	A-5	Md micaceous sandy loam	Regular	7a	A-4	Kans light silty clay	Regular	6d	A-6	Calif adobe	Regular
					7f	A-7-4	Ill light silty clay loam	Regular	7b*	A-6-7	Mich clay	Regular

* Soil 7b, Michigan clay subsoil, almost falls in Treatment GROUP II The characteristics of soils in Treatment GROUP II predominate and additional testing may identify it definitely with this group

this will permit incorporating a constant amount of cement in each unit volume of compacted soil regardless of its weight or other characteristics. The data included in this progress report have supplied the information needed to add cement on an apparent volume basis. This procedure is being followed on future work with volumes converted to equivalent weight for laboratory control by considering 94 lb. of cement to be one cubic foot.

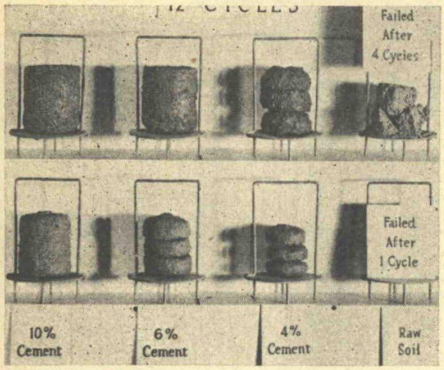

Figure 43. Freezing and Thawing. Michigan Clay Subsoil, Sample 7b. Above—Unbrushed Specimens, Below—Brushed Specimens.

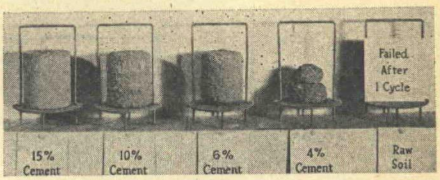

Figure 44. Freezing and Thawing. Missouri Clay Subsoil, Sample 6a, Unbrushed Specimens.

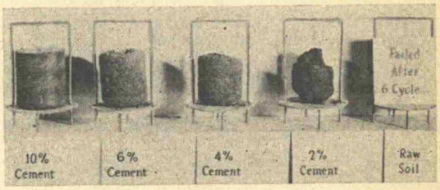

Figure 45. Freezing and Thawing. Bates Test Road Soil, Illinois Light Silty Clay Loam Top-Soil, Sample 7f, Unbrushed Specimens.

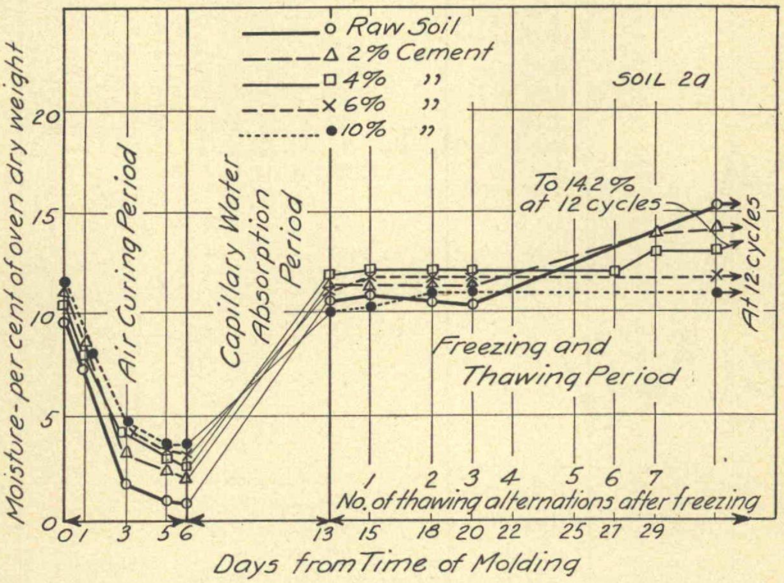

Figure 46. Alternate Freezing and Thawing. Moisture content of specimens when thawed after freezing; South Carolina fine sandy loam top-soil, No. 2a.

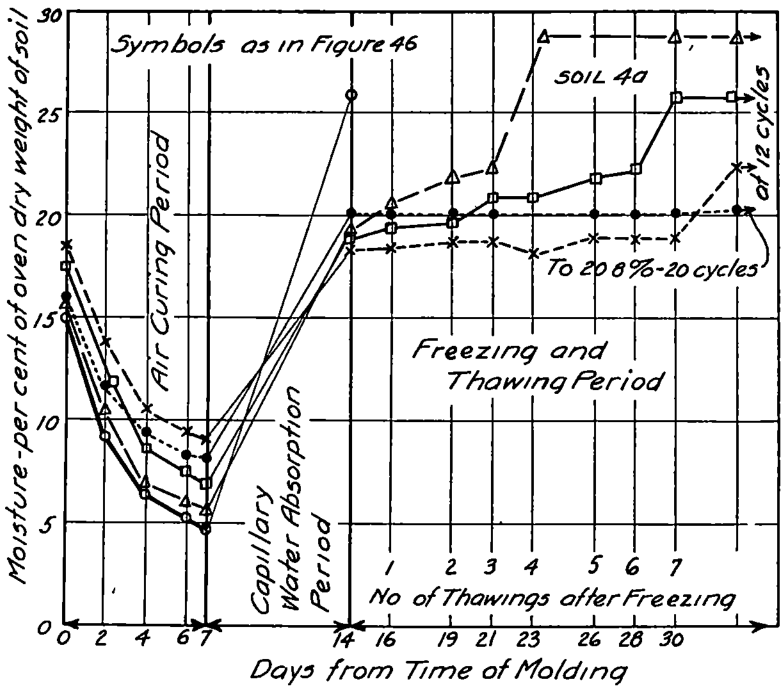

Figure 47. Alternate Freezing and Thawing. Moisture content of specimens when thawed after freezing; Missouri silty clay loam subsoil, No. 4a.

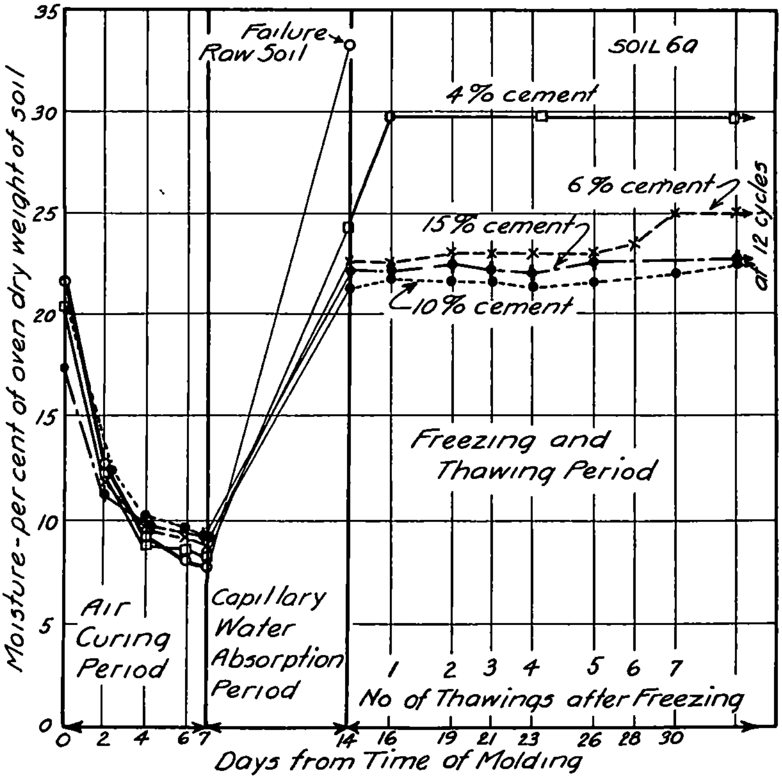

Figure 48. Alternate Freezing and Thawing. Moisture content of specimens when thawed after freezing; Missouri clay subsoil, No. 6a.

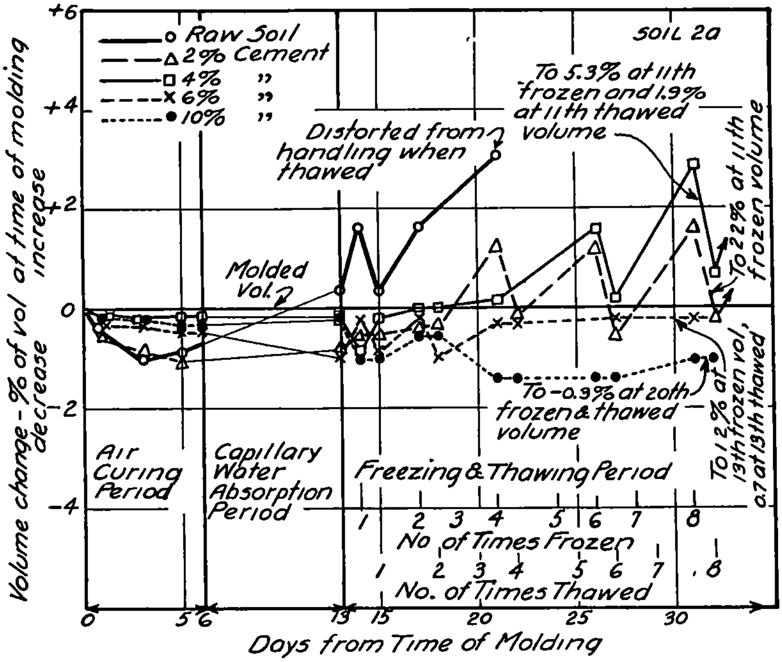

Figure 49. Alternate Freezing and Thawing. Volume changes; South Carolina fine sandy loam top-soil, No 2a.

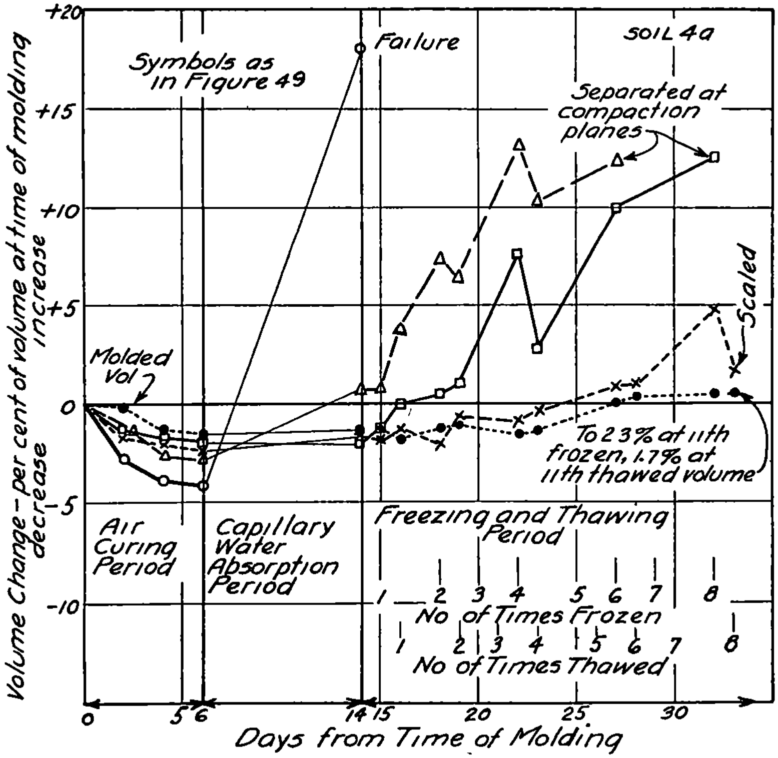

Figure 50. Alternate Freezing and Thawing. Volume changes; Missouri silty clay loam sub-soil, No. 4a.

Discussion of Soils in Treatment Groups I and II

The soils falling in Treatment Group I, Numbers 2a, 3a and 5c, sandy soils, give outstanding beneficial results from small quantities of added cement The addition of 4 to 6 per cent cement hardened the soil appreciably and decreased soil losses to negligible quantities in 12 cycles of wetting and drying or 12 cycles of freezing and thawing Figures 19 and 23 show typical results Volume and moisture changes in these same soil-cement mixtures after repeated freezing and thawing are quite small Figures 33, 37, 46 and 49 show typical results

Soils of Treatment Group II, Numbers 4a, 5d, 7a (U S B P R soil groups A-4), and 7f, (U S B P R soil group A-7-4), are of a silty character and were decidedly hardened with an addition of 6 to 8 per cent cement, and reduced soil losses during wetting and drying or freezing and thawing to small amounts and also reduced moisture changes and volume changes to a minimum Figures 20, 24, 34, 38, 47 and 50 show typical results

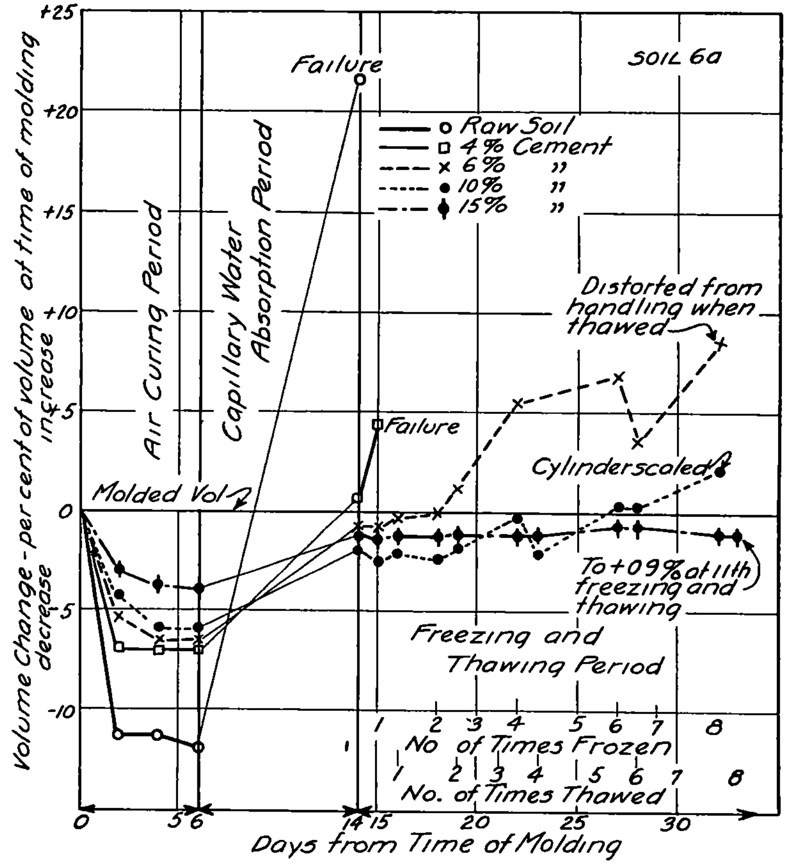

Figure 51. Alternate Freezing and Thawing. Volume changes, Missouri clay subsoil, No. 6a.

Inasmuch as the durability tests employed in this investigation were quite severe, it is anticipated that soil-cement mixtures passing these tests will have high resistance to natural weathering conditions In fact, the results are so consistent that definite recommendations can now be made for laboratory analysis to determine treatment requirements, and further recommendations can now be made for field construction methods for projects built of soils within the character range of those represented by Treatment Groups I and II as well as Treatment Group III discussed later

TABLE 4

ALTERNATE WETTING AND DRYING—DURABILITY TESTS

Soil Loss in Slaking, percentage of oven dry weight

Averages of two specimens—losses at end of drying periods

Soil Number	Raw Soil		2% Cement		4% Cement		6% Cement		10% Cement		15% Cement	
	No of Cycles	Loss %	No of Cycles	Loss %	No of Cycles	Loss %	No of Cycles	Loss %	No of Cycles	Loss %	No of Cycles	Loss %
2a	1	62	12	1	12	0 3	12	0	12	0	—	—
3a	1	73	12	1	12	0	12	0	12	0	—	—
4a	1	71	12	83	12	36	12	19	12	11	—	—
5a	1	75	1	73	3	85	6	87	8	80	—	—
5c	1	72	12	0	12	0	12	0	12	0	—	—
5d	1	48	10	54	10	2	10	1	10	0 5	—	—
6a	1	74	—	—	3	86	12	63	12	37	12	34
6d	1	80	—	—	1	73	4	89	5	78	—	—
7a	1	70	3	84	12	72	12	55	12	32	—	—
7b	1	78	—	—	12	78	12	52	12	14	—	—
7f	1	40	5	60	12	21	12	5	12	2	—	—

TABLE 5

ALTERNATE FREEZING AND THAWING—DURABILITY TESTS

Soil Loss, percentage of oven dry weight

Averages of two specimens—losses at end of thawing periods

Soil Number	Raw Soil		2% Cement		4% Cement		6% Cement		10% Cement		15% Cement	
	No of Cycles	Loss %	No of Cycles	Loss %	No of Cycles	Loss %	No of Cycles	Loss %	No of Cycles	Loss %	No of Cycles	Loss %
2a	12	18	12	4	12	2	12	0	12	0	—	—
3a	6	9	12	6	12	1	12	0	12	0	—	—
4a	1	55	12	47	12	20	12	5	12	0	—	—
5a	1	36	—	—	5	38	6	46	12	29	—	—
5c	1	65	12	84	12	48	12	9	12	1	—	—
5d	11	100	11	29	12	27	12	12	12	9	—	—
6a	1	56	—	—	12	39	12	18	12	5	12	0
6d	No freezing and thawing Exterior became soft and sticky and expanded when subjected to capillary water											
7a	3	37	4	44	12	76	12	53	12	19	—	—
7b	1	75	—	—	12	61	12	35	12	17	—	—
7f	5	17	12	14	12	4	12	3	12	3	—	—

Relations between liquid limit, plasticity index and clay content of the soils of these two groups are shown in Figures 52 and 53 It will be noted that the constants for these soils fall together in the lower left hand corner of the charts. The liquid limits are below 50, the plasticity indices are below 25 and the clay contents are below 35 per cent These

TABLE 6

Alternate Freezing and Thawing—Durability Tests

Moisture Contents, percentage of oven dry weight

Soil No.	Cement in Soil %	Molded Moisture Content %	Moisture After 6 to 9 Day Air Drying %	Moisture After 4 to 8 Day Capillary Absorption %	Freezing and Thawing Period	
					No of Cycles	Moisture Content %
2a	0	10.0	1.0	10.5	12	15.2
	2	11.4	2.0	11.3	12	14.2
	4	11.0	2.5	11.7	12	14.2
	6	10.6	3.0	11.0	12	11.7
	10	10.4	3.6	10.2	12	11.0
3a	0	10.0	0.3	15.8	1—Failed	18.8
	2	10.0	1.0	15.2	12	19.0
	4	10.0	2.2	14.0	12	15.4
	6	10.0	2.6	13.0	12	14.5
	10	10.0	3.0	12.3	12	14.2
4a	0	15.0	4.7	26.0	1—Failed	—
	2	15.5	5.5	19.2	12	28.7
	4	17.5	6.7	18.8	12	25.7
	6	18.5	9.0	18.3	12	22.3
	10	16.0	8.0	20.0	12	20.2
5a	0	31.0	10.0	43.0	1—Failed	43.0
	2	29.0	9.5	38.6	3—Failed	41.2
	4	27.7	8.0	37.4	4—Failed	43.3
	6	27.2	10.8	35.0	5—Failed	35.0
	10	26.7	12.0	32.3	12	32.3
5c	0	17.0	1.3	24.5	1—Failed	29.5
	2	15.7	2.7	20.0	12	24.0
	4	15.3	3.5	20.0	12	21.5
	6	16.5	4.2	20.6	12	21.0
	10	16.0	4.5	20.0	12	20.0
5d	0	17.0	2.7	21.7	11—Failed	29.3
	2	17.5	4.8	21.2	11—Failed	26.0
	4	20.0	6.8	21.7	12	25.0
	6	18.5	7.0	20.5	12	25.6
	10	18.7	9.5	21.0	12	21.8
6a	0	21.5	8.0	33.2	1—Failed	33.2
	4	20.5	8.2	24.2	12	29.7
	6	20.0	8.8	22.5	12	25.0
	10	20.2	9.2	21.3	12	27.5
	15	17.3	9.2	22.2	12	27.8
6d	0	18.5	7.2	34.0	Determinations not made Specimens too soft to handle	
	4	15.5	8.0	24.0		
	6	15.0	7.5	22.0		
	10	16.3	9.0	21.5		

TABLE 6—*Concluded*

Soil No	Cement in Soil %	Molded Moisture Content %	Moisture After 6 to 9 Day Air Drying %	Moisture After 4 to 8 Day Capillary Absorption %	Freezing and Thawing Period	
					No of Cycles	Moisture Content %
7a	0	16 2	4 2	23 0	12	28 5
	2	16 5	5 7	21 0	12	27 2
	4	15 4	6 2	19 6	12	24 4
	6	14 5	6 0	19 2	12	23 7
	10	14 2	6 4	20 2	12	21 0
7b	0	19 3	5 0	26 0	5—Failed	27 0
	4	21 0	5 5	22 0	12	22 0
	6	19 7	6 8	20 5	12	21 0
	10	18 5	6 0	20 0	12	20 0
7f	0	19 0	7 0	31 5	12	40 6
	2	22 0	8 2	27 0	12	36 5
	4	23 2	9 3	25 0	12	31 3
	6	23 5	11 7	24 6	12	30 1
	10	23 5	11 7	23 3	12	26 9

data are also summarized in Table 3 Relations between other physical test constants were also studied but are not in this report since no consistent relations were found between these constants and the durability tests or hardening.

The percentage of solids at optimum moisture and the type of moisture-density curve obtained from each soil are also given in Table 3 It will be seen that all of the soils falling in Treatment Groups I and II possess moisture-density curves of a "regular" character and that the percentage of solids, when compacted at optimum moisture, is 60 or more

Discussion of Soils in Treatment Group III

The investigation of the influence of cement has not been entirely completed on soils in Treatment Group III. By referring to the liquid limit, plasticity index and clay content relations for the soils of Treatment Group III shown in Figures 52 and 53, it will be seen there is no simple relation between these constants. The clay contents range between 38 and 76 per cent. Also referring to Table 3 it will be seen that the percentage of solids at optimum moisture varies from 53 to 64 and the Proctor curves are regular or regular-irregular in nature. The soils in Treatment Group III were hardened appreciably by the addition of about 10 per cent cement which also materially reduced volume and moisture changes and the weight losses in the durability tests Figures 21, 27, 35, 44, 48, and 51 show typical results

It is known now that normal cement hydration plays a large part in producing hardness in soil-cement mixtures Therefore, it is very desirable to reduce moisture losses to a minimum during the early preparation period to allow the specimen to gain strength normally by the hydration of the cement and reduce shrinkage stresses to a minimum This will produce a specimen of uniform characteristics throughout, permit more accurate evaluation of the influence of cement on the soil and, also, more nearly simulate field conditions Therefore, future laboratory and field work on all soil-cement mixtures will be conducted so as to reduce moisture losses to a

TABLE 7

ALTERNATE FREEZING AND THAWING—DURABILITY TESTS

Volume Change, percentage of volume at time of molding

Soil Number	Cement in Soil %	Volume Change After 6 to 9 Day Air Drying %	Volume Change After 4 to 8 Day Capillary Absorption %	Freezing and Thawing Period		
				Number of Cycles Tested	Maximum Volume Change Frozen %	Maximum Volume Change Thawed %
2a	0	−0 90	+0 40	4	+3 0	+2 6
	2	−1 05	−0 80	11	+2 2	−0 8
	4	−0 20	−0 20	11	+5 3	+1 9
	6	−0 45	−1 00	13	+1 2	+0 7
	10	−0 40	−0 20	20	−0 3	−0 3
3a	0	−1 0	0	1	+1 2 Failed	—
	2	−1 4	0	8	+0 2	−0 2
	4	−0 5	−0 2	11	+0 3	−1 4
	6	−0 4	0	11	0	0
	10	0	0	11	+0 5	−1 2
4a	0	−4 2	+18 0 Failed	—	—	—
	2	−2 7	+0 7	6	+13 0	+11 4
	4	−2 0	−1 8	8	+12 5	+7 0
	6	−2 3	−1 6	8	+4 8	+1 6
	10	−1 5	−1 4	11	+2 3	+1 7
5a	0	−10 0	+12 5	1	+17 0 Failed	—
	2	−5 5	+9 8	1	+12 7 Separated at compaction plane	
	4	−5 5	+3 8	1	+9 0 Separated at compaction plane	
	6	−4 8	Brittle, broke on compaction planes in handling			
	10	−4 0	−0 5	3	+5 5	+2 9
5c	0	−2 3	+8 5	1	+14 0 Failed	—
	2	+0 2	+1 0	4	+11 0	+8 2
	4	+0 2	+0 3	4	+4 8	+2 5
	6	+0 2	+0 6	4	+1 3	+0 6
	10	+0 2	+0 3	4	+0 6	+0 6
5d	0	−3 2	+5 5	4	+18 0	+9 0
	2	−2 8	+0 2	4	+10 0	+8 3
	4	−2 5	−0 5	6	+9 8	+4 0
	6	−2 5	−0 9	7	+6 0	+3 0
	10	−2 0	0	7	+1 0	−0 5
6a	0	−12 0	+21 5 Failed	1—Failed	—	—
	4	−7 0	+4 5	—	—	—
	6	−6 5	−1 0	8	+8 5	+3 5
	10	−5 9	−1 9	8	+2 0	+0 2
	15	−4 0	−1 3	11	−0 9	−0 7

TABLE 7—*Concluded*

Soil Number	Cement in Soil %	Volume Change After 6 to 9 Day Air Drying %	Volume Change After 4 to 8 Day Capillary Absorption %	Freezing and Thawing Period: Number of Cycles Tested	Freezing and Thawing Period: Maximum Volume Change Frozen %	Freezing and Thawing Period: Maximum Volume Change Thawed %
6d	0	−14 5	+32 5 Fail			
	4	−9 2	+22 5 Fail		Measurements not made	Specimens too
	6	−8 7	+22 0 Fail		soft to be handled	
	10	−6 5	+9 0 Fail			
7a	0	−6 5	+8 3	1	+8 4	—
	2	−3 0	+2 0	5	+11 3	+10 2
	4	−2 5	+0 5	9	+12 5	+9 0
	6	−2 2	−0 5	11	+14 5	+7 8
	10	−2 0	+0 2	11	+6 6	+4 9
7b	0	−7 2	+9 0	1	+11 5	+11 7
	4	−5 4	−1 0	3	+6 0	+4 2
	6	−4 0	−1 7	5	+5 0	+2 5
	10	−3 3	−1 3	5	+3 5	+2 0
7f	0	−5 7	+11 3	3	+22 0	+15 0
	2	−5 3	+2 7	5	+13 0	+13 0
	4	−5 0	−0 3	6	+8 7	+6 2
	6	−4 0	−1 3	6	+6 0	+3 0
	10	−2 8	−1 8	7	+0 8	+0 2

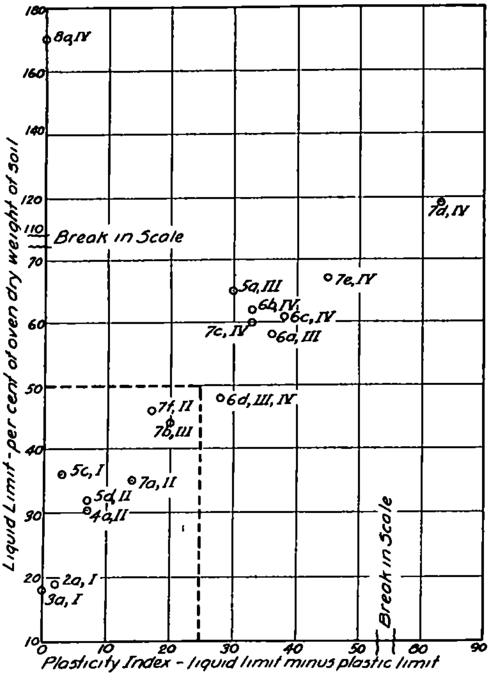

Figure 52. Liquid Limit-Plasticity Relations of All Soils Tested. The Roman numerals indicate treatment group of soil according to Table 3.

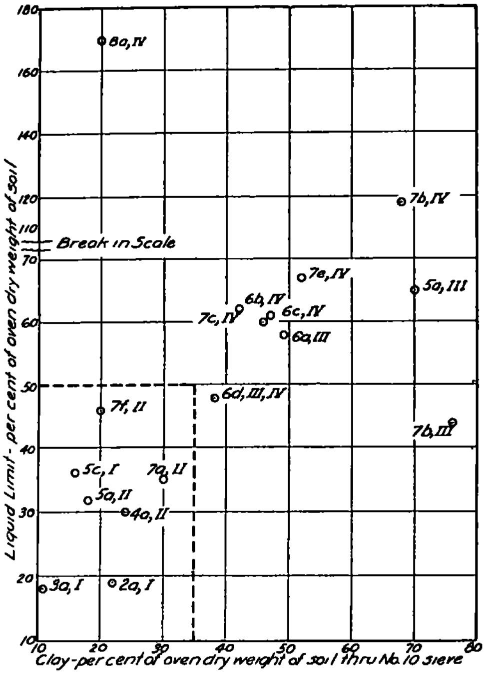

Figure 53. Liquid Limit-Clay Content Relations of All Soils Tested. The Roman numerals indicate treatment group of soil according to Table 3. Clay is the soil fraction having a diameter less than 0 005 mm

minimum during a seven day preparation period to produce mixtures of uniform characteristics

While the exploratory laboratory work has not been fully completed on the soils in Treatment Group III, the results show that these soils, which represent the commonly occurring subsoils of the country, respond very definitely to cement treatments Laboratory durability tests should be made on any soil having characteristics similar to those in Group III to evaluate the influence of cement and to set up treatment requirements The laboratory investigations now under way, which permit normal cement hydration for 7 days, indicate more hardening of the soil-cement mixtures and more satisfactory results than are here reported

Discussion of Soils in Group IV

As previously mentioned, work on the unusual, bad subsoils of limited occurrence (samples 6b, 6c, 7c, 7d, 7e and 8a) has not been completed These soils have been placed in Group IV to permit easy identification They include soils of high clay and colloidal content, as well as a peaty muck, and were selected so that eventually the entire range of soils would be studied These soils are shown to be more complex by the nature of the moisture-density curves and hence require considerably more laboratory work to evaluate soil-cement relations Also, the physio-chemical properties of some of these soils become more important However, it should not be inferred that successful means of treatment will not be evolved from the tests now under way on these soils.

GENERAL CONCLUSION

The foregoing information has been summarized in Table 3. A study of this table of soil groupings and test constants, together with the foregoing discussion of each group, shows a direct correlation between the hardening influence of cement on soil-cement mixtures and soil characteristics As this study is intensified, it is expected that more correlation will be found and that it will be possible to set up more exact relations between the hardening influence of cement and soil characteristics This will permit predetermination of treatment requirements on many soils without recourse to detail durability tests

At the present time, no effort has been made to draw sharp lines between soil characteristics and treatment requirements However, the following general conclusions are justified regarding the characteristics of soils which can be classified as belonging to Treatment Group I or II

1 The liquid limit must be below 50
2 The plasticity index must be below 25
3 The clay content must be below 35.
4 The percentage of solids at maximum density must be 60 or greater.
5 The soil must possess a "regular" moisture-density curve

It is evident that a soil meeting these requirements can be effectively hardened by the addition of a reasonable amount of cement which will be approximately the same as that producing effective hardening in a similar soil in the same treatment group

If a soil meets or closely approximates two or three of these requirements, but not the remaining ones, it will probably fall in Treatment Group III Durability tests similar to those used in this investigation will establish the treatment group and definitely evaluate the quantity of cement required for treatment

At the present time more statistical data are needed to define treatment groups closely so that durability tests may be omitted In order to accumulate these data as rapidly as possible and to check each soil investigated so as to be absolutely sure of satisfactory results, it is recommended that all tests outlined in this report be performed on each soil as it is encountered for study

All of the laboratory results obtained have been most encouraging It has been possible to evolve basic principles governing soil-cement mixtures Their application permits the production of consistent, predictable results which have been applied on many field projects with success Specimens prepared and tested in the laboratory have shown substantial durability when subjected to severe tests

As a result of this work a large field for research on a new building material is opening up It will require the resources of all interests to define its characteristics and bring our knowledge of it up to a par with our knowledge of other building materials

SOUTH CAROLINA INVESTIGATION OF SOIL-CEMENT MIXTURES

By W H Mills, Jr

Testing Engineer, South Carolina State Highway Department

The early experiments of the South Carolina Highway Department were described at the meeting of the Highway Research Board in November 1936[1] These original installations are still in excellent condition and although one has been removed on account of new construction, the others are all carrying the traffic satisfactorily without indication of breakdown or disintegration.

Construction of this type of road has been continued and in 1937 approximately 18 4 miles of cement stabilized base were completed

A one half mile project at Clemson, S C, was planned to give information on the minimum quantity of cement which would stabilize soil The soil in this experiment was a red clay typical of that found in large areas of the state It contained 40 per cent clay, no coarse material and had a plasticity index of 25 As a result of laboratory tests, which included alternate wetting-drying and freezing-thawing of specimens of soil molded at optimum moisture content with various percentages of cement, it was concluded that 7 per cent of cement by weight should be used This quantity was used on one section 6 per cent on one and 5 per cent on the third section Usual methods of mixed-in-place procedure were followed. The 5 per cent cement section did not harden so rapidly as the others, but there have been no failures in this project during the six months it has been subjected to very light traffic In planning the project the idea was to reduce the quantity of cement for one section below the minimum required for stabilization in order to have field information which could be correlated with laboratory durability tests to use as a criterion in setting the cement content for future work in similar soils Failures are expected to develop in the section containing 5 per cent cement

During the winter of 1936 and 1937 10 5 miles of Route 63, Hampton County were constructed by contract The specifications required a compacted base 22 ft wide and 6 in thick This base was covered with a mixed-in-place bituminous wearing surface ½ in thick, 20 ft wide The bid price for the base was $0 495 per square yard and for the surfacing $0 18 per square yard. Work was begun on December 5, 1936 but the

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[1] *Proceedings*, Highway Research Board, Vol 16, p 322