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SOIL-CEMENT MIXTURES FOR ROADS

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PART II

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A SYMPOSIUM
ON
SOIL-CEMENT MIXTURES FOR ROADS

PART II

PROCEEDINGS, SEVENTEENTH ANNUAL MEETING
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EDITED BY
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Director, Highway Research Board

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CONTENTS

FOREWORD

Experiments with soil-cement roads started by the South Carolina State Highway Department at the suggestion of Dr Chas. H Moorefield in 1932, and continued in 1933 and 1934, were reported at the meeting of the Highway Research Board in 1936

In 1935 the Portland Cement Association undertook an extensive research program to get at the fundamental scientific principles required to produce suitable soil-cement mixtures for light traffic road use Cement was combined with soil samples representing the range found in the United States. The first year's work in this research program developed basic principles and scientific methods for producing suitable soil-cement mixtures and indicated essential laboratory control tests

Subsequently, a number of state highway departments, employing the principles which had been developed, built a number of soil-cement road projects for observation under traffic and weather conditions and to develop efficient construction methods and field control procedure

In order that the results of these researches and the experience in these demonstration road projects may be made available, the following reports have been prepared by the State highway departments of Illinois, Iowa, Michigan, Missouri, Wisconsin and South Carolina, and by the Portland Cement Association

The reports were collected by W H Mills, Jr for the Project Committee on Stabilized Roads of the Department of Soils Investigations, Highway Research Board, C A Hogentogler, Chairman A summary of the reports is given in Part I, Vol 17, Proceedings, Highway Research Board

BASIC PRINCIPLES OF SOIL-CEMENT MIXTURES AND EXPLORATORY LABORATORY RESULTS

By Miles D Catton

Development Department, Portland Cement Association, Chicago, Illinois

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

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

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

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.

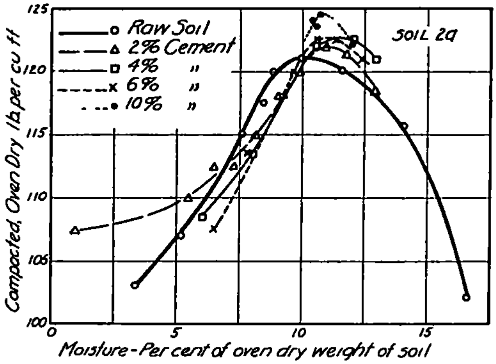

Figure 2. Moisture-Density. South Carolina fine sandy loam top-soil No. 2a, Soil Group A-2.

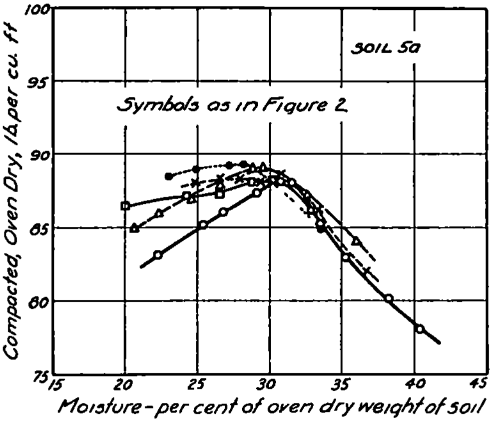

Figure 5. Moisture-Density. Minnesota clay subsoil, No. 5a, Soil Group A-5.

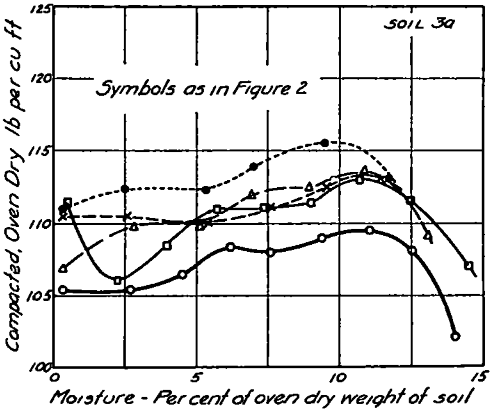

Figure 3. Moisture-Density. California fine sand top-soil, No. 3a, Soil Group A-3.

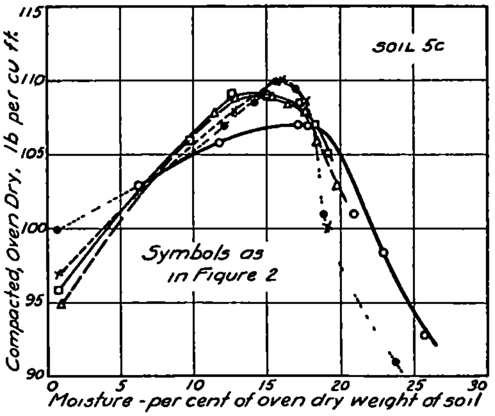

Figure 6 Moisture-Density Maryland micaceous sandy loam top-soil, No. 5c, Soil Group A-5.

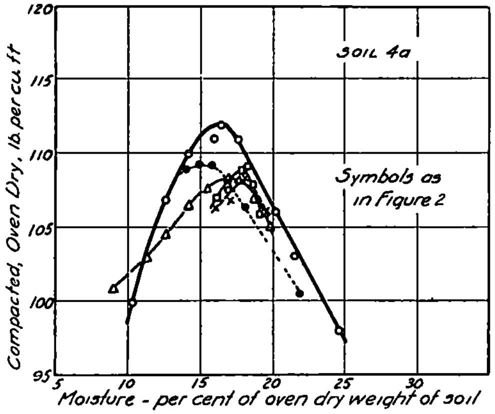

Figure 4. Moisture-Density. Missouri silty clay loam subsoil, No. 4a. Soil Group A-4.

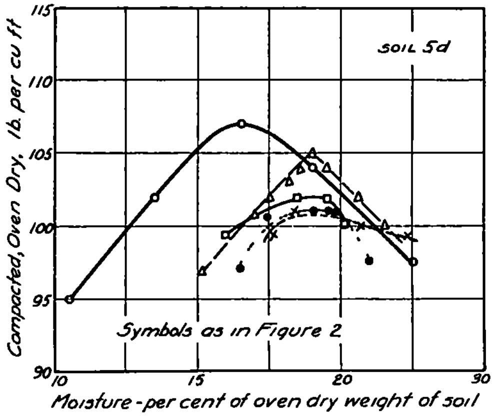

Figure 7. Moisture-Density. Idaho heavy silt loam top-soil, No. 5d, Soil Group A-4.

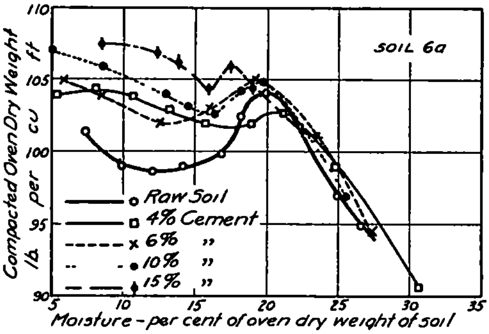

Figure 8 Moisture-Density Missouri clay subsoil, No 6a, Soil Group A-6.

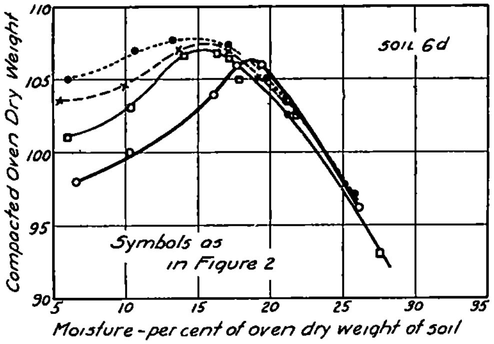

Figure 11. Moisture-Density. California clay (adobe) top-soil, No 6d, Soil Group A-6

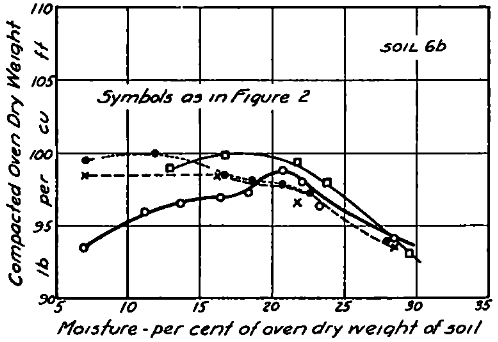

Figure 9. Moisture-Density. Virginia clay subsoil, No 6b, Soil Group A-7-6.

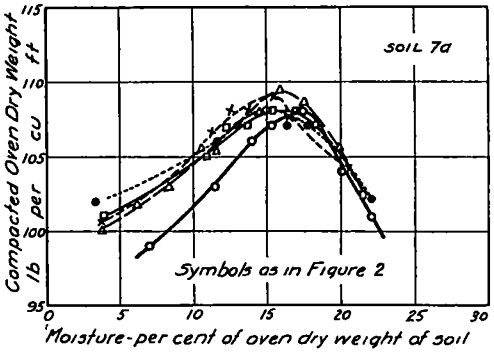

Figure 12. Moisture-Density. Kansas light silty clay subsoil, No. 7a, Soil Group A-4

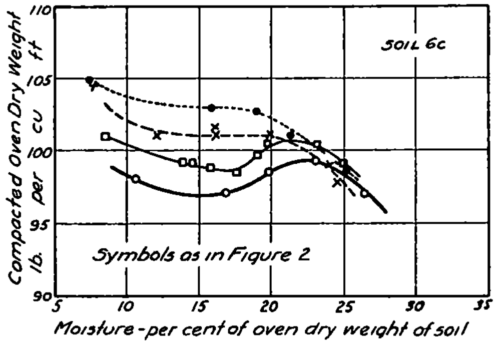

Figure 10. Moisture-Density Texas clay subsoil, No. 6c, Soil Group A-6.

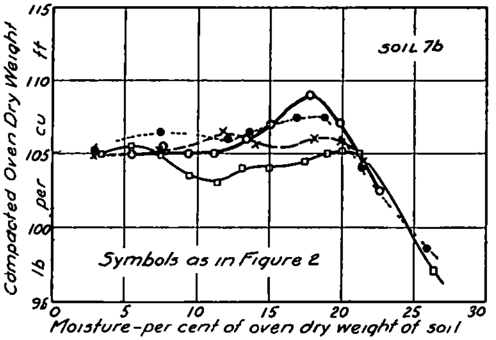

Figure 13 Moisture-Density Michigan clay subsoil, No 7b, Soil Group A-6-7.

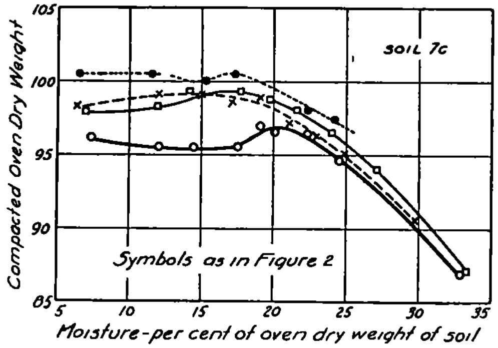

Figure 14. Moisture-Density. Missouri clay subsoil, No. 7c, Soil Group A-7-6.

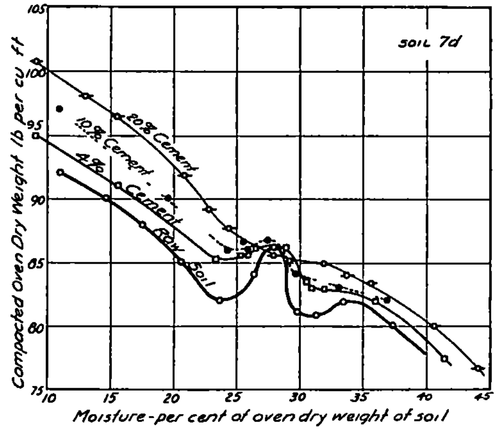

Figure 15. Moisture-Density. Mississippi clay subsoil, No. 7d, Soil Group A-7.

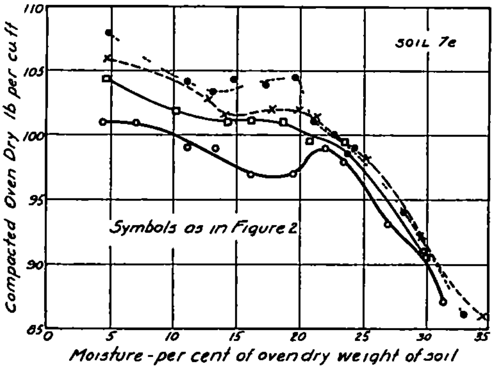

Figure 16. Moisture-Density. Mississippi (Sharkey) clay subsoil, No. 7e, Soil Group A-7.

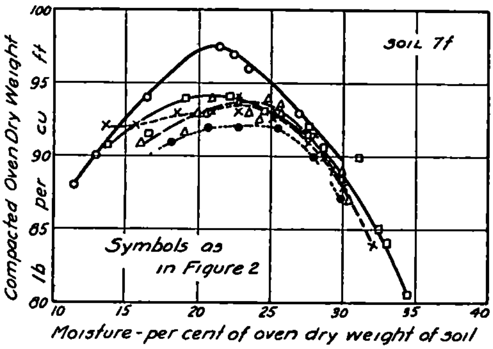

Figure 17. Moisture-Density. Illinois light silty clay loam top-soil (Bates Road), No. 7f, Soil Group A-7-4.

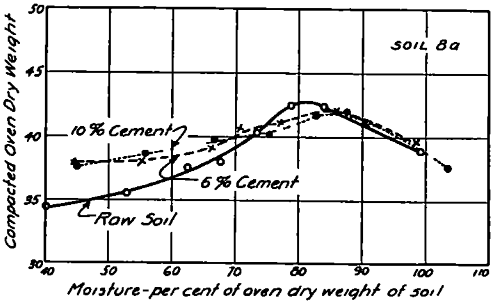

Figure 18. Moisture-Density. Minnesota peaty muck top-soil, No. 8a, Soil Group A-8.

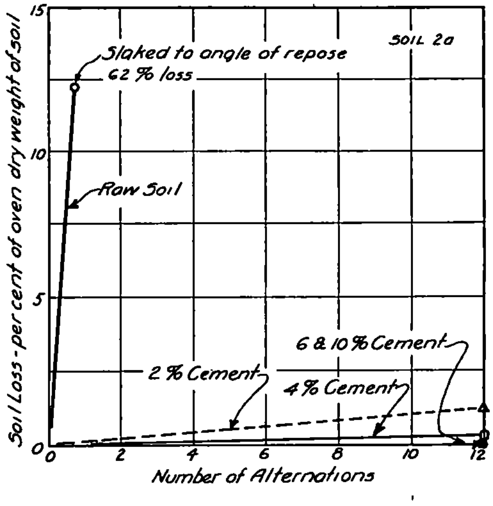

Figure 19. Alternate Wetting and Drying. Soil losses at end of drying period; curves are averages of two specimens; South Carolina fine sandy loam top-soil, No 2a.

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

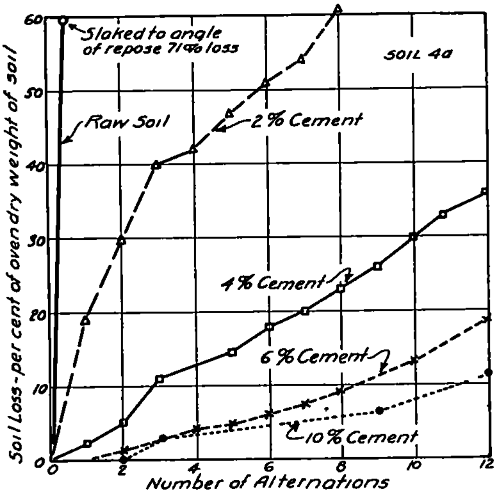

Figure 20. Alternate Wetting and Drying. Soil losses at end of drying period; curves are averages of two specimens; Missouri silty clay loam subsoil, No. 4a.

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

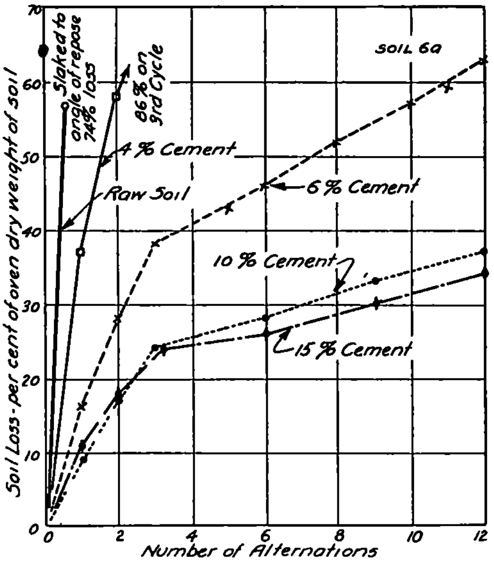

Figure 21. Alternate Wetting and Drying. Soil losses at end of drying period; curves are averages of two specimens, Missouri clay subsoil, No. 6a.

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

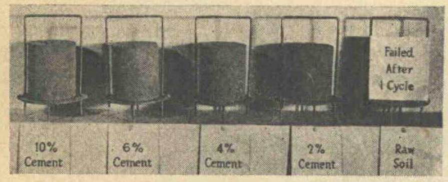

Figure 22. Alternate Wetting and Drying. South Carolina Fine Sandy Loam Top-Soil, Sample 2a.

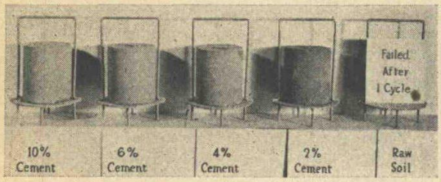

Figure 23. Alternate Wetting and Drying. California Fine Sand Top-Soil, Sample 3a.

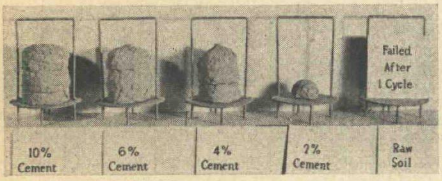

Fig. 24. Alternate Wetting and Drying. Missouri Silty Clay Loam Subsoil, Sample 4a.

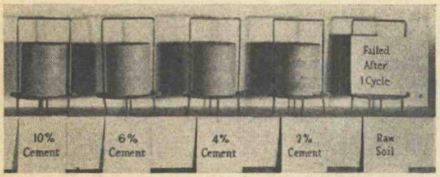

Figure 25. Alternate Wetting and Drying. Maryland Micaceous Sandy Loam Top-Soil Sample 5c.

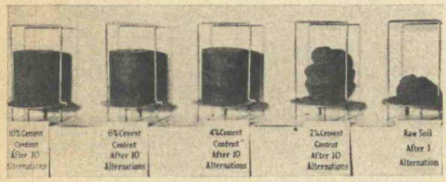

Figure 26. Alternate Wetting and Drying. Idaho Heavy Silt Loam Top-Soil, Sample 5d.

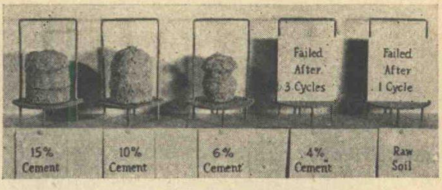

Figure 27. Alternate Wetting and Drying. Missouri Clay Subsoil, Sample 6a.

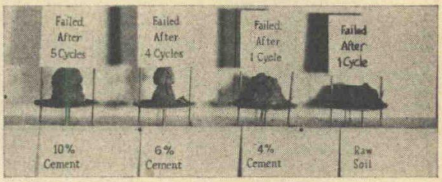

Figure 28. Alternate Wetting and Drying. California Clay Adobe Top-Soil, Sample 6d.

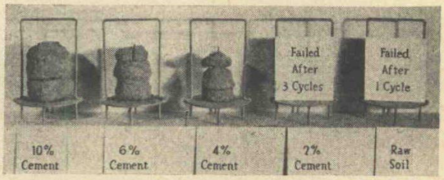

Figure 29. Alternate Wetting and Drying. Kansas Light Silty Clay Subsoil, Sample 7a.

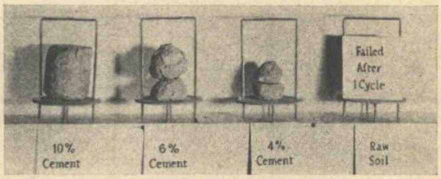

Figure 30. Alternate Wetting and Drying. Michigan Clay Subsoil, Sample 7b.

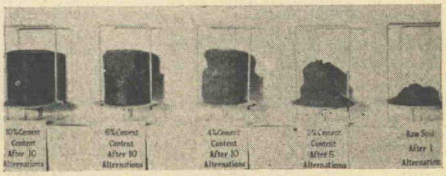

Figure 31. Alternate Wetting and Drying. Bates Test Road Soil, Illinois, Light Silty Clay Loam Top-Soil, Sample 7f.

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

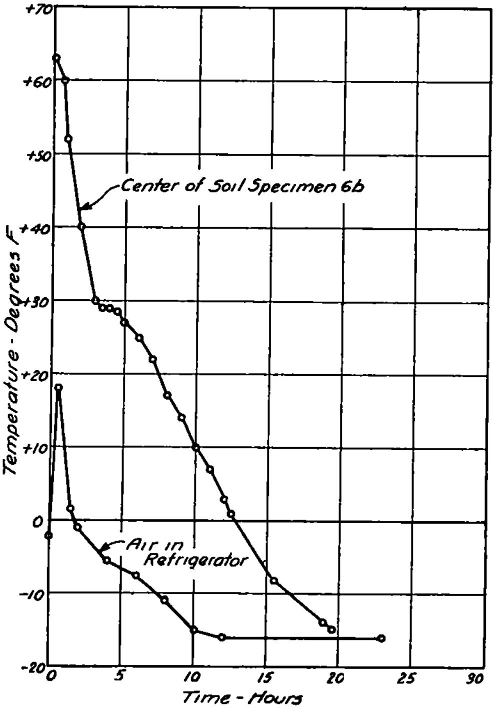

Figure 32. Freezing and Thawing Tests. Rate of Freezing

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

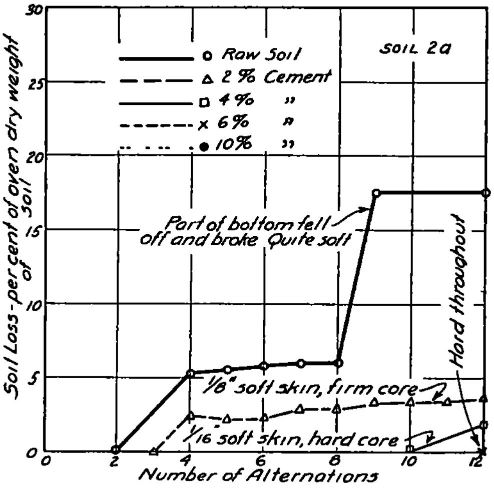

Figure 33. Alternate Freezing and Thawing. Soil losses at end of thawing period, South Carolina fine sandy loam top-soil, No 2a.

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

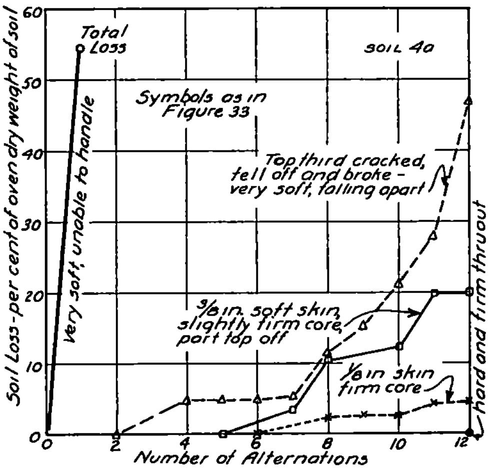

Figure 34. Alternate Freezing and Thawing. Soil losses at end of thawing period; Missouri silty clay loam subsoil, No. 4a.

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

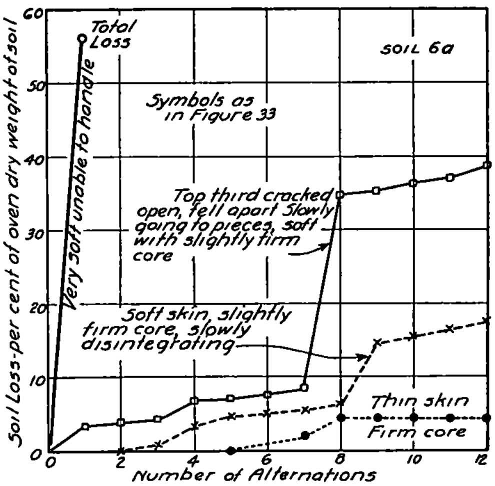

Figure 35. Alternate Freezing and Thawing. Soil losses at end of thawing period; Missouri clay subsoil, No. 6a.

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.

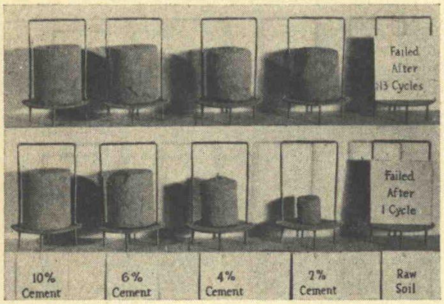

Figure 36. Freezing and Thawing. South Carolina Fine Sandy Loam Top-Soil, Sample 2a. Above—Unbrushed Specimens, Below—Brushed Specimens after 20 cycles.

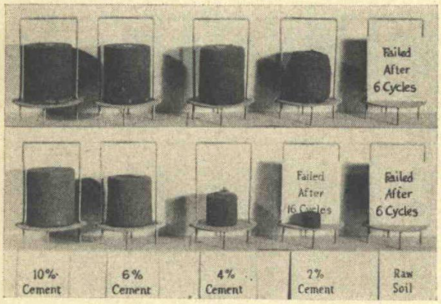

Figure 37. Freezing and Thawing. California Fine Sand Top-Soil, Sample 3a. Above—Unbrushed Specimens, Below—Brushed Specimens after 20 cycles.

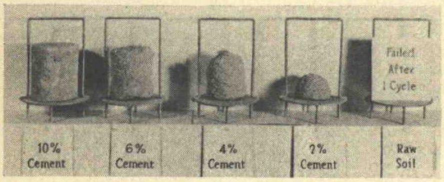

Figure 38. Freezing and Thawing. Missouri Silty Clay Loam Subsoil, Sample 4a, Unbrushed Specimens.

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.

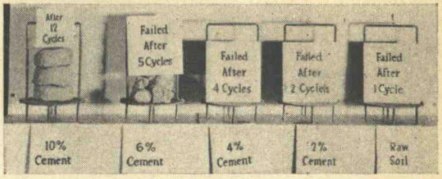

Figure 39. Freezing and Thawing. Minnesota Clay Subsoil, Sample 5a, Brushed Specimens.

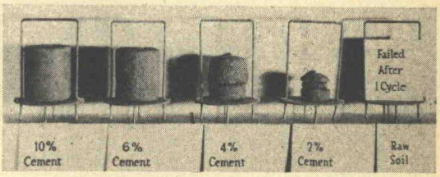

Figure 40. Freezing and Thawing. Maryland Micaceous Sandy Loam Top-Soil, Sample 5c. Specimens brushed after third cycle.

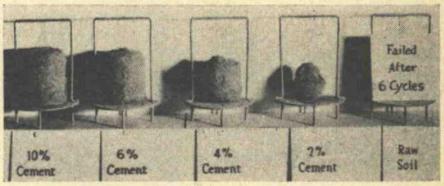

Figure 41. Freezing and Thawing. Idaho Heavy Silt Loam Top-Soil, Sample 5d, Unbrushed Specimens.

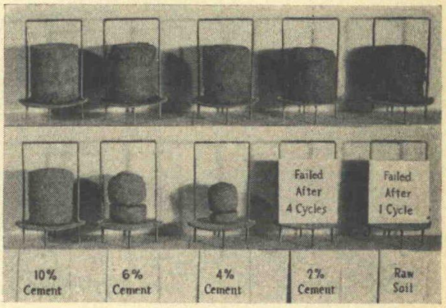

Figure 42. Freezing and Thawing. Kansas Light Silty Clay Subsoil, Sample 7a. Above—Unbrushed Specimens, Below—Brushed Specimens.

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.

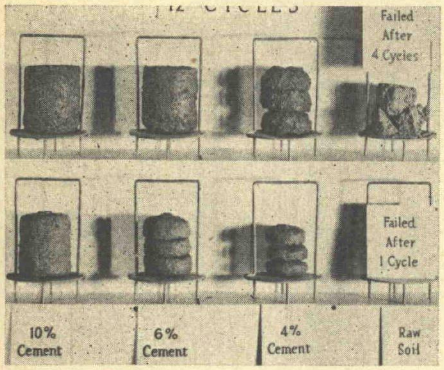

Figure 43. Freezing and Thawing. Michigan Clay Subsoil, Sample 7b. Above—Unbrushed Specimens, Below—Brushed Specimens.

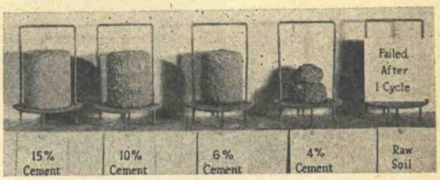

Figure 44. Freezing and Thawing. Missouri Clay Subsoil, Sample 6a, Unbrushed Specimens.

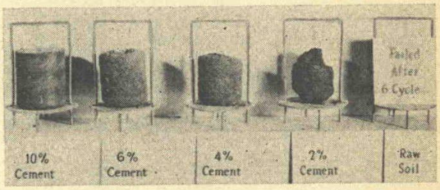

Figure 45. Freezing and Thawing. Bates Test Road Soil, Illinois Light Silty Clay Loam Top-Soil, Sample 7f, Unbrushed Specimens.

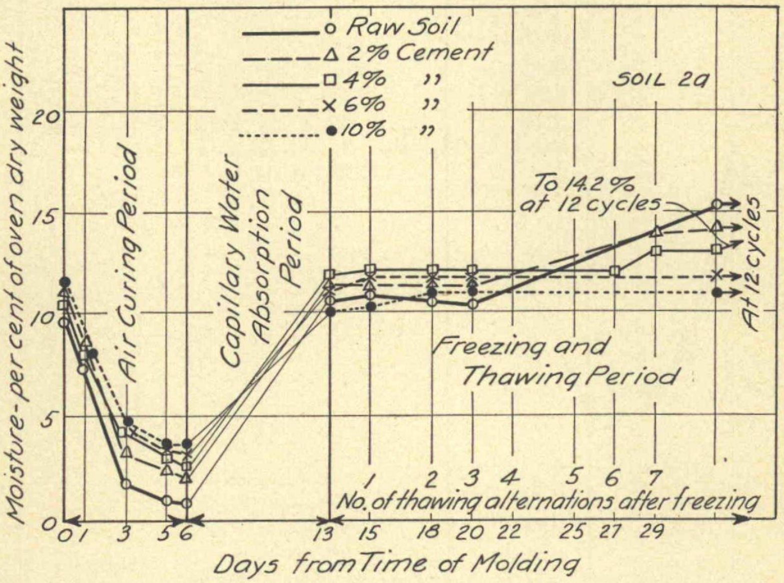

Figure 46. Alternate Freezing and Thawing. Moisture content of specimens when thawed after freezing; South Carolina fine sandy loam top-soil, No. 2a.

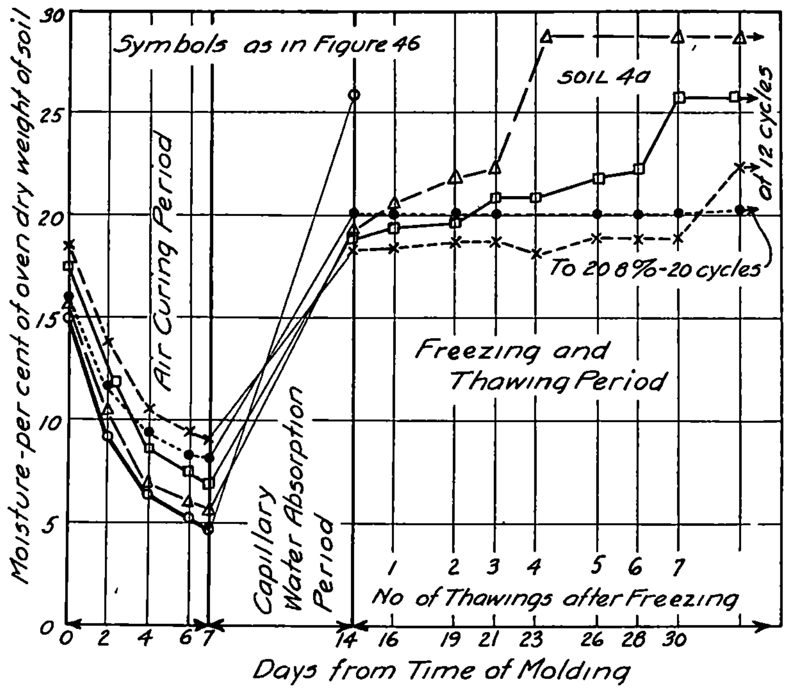

Figure 47. Alternate Freezing and Thawing. Moisture content of specimens when thawed after freezing; Missouri silty clay loam subsoil, No. 4a.

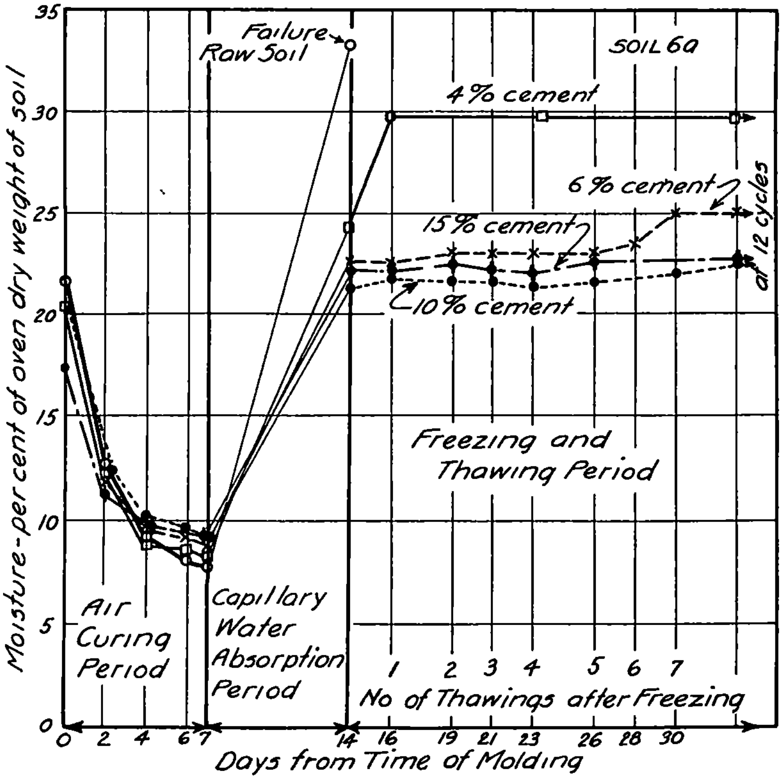

Figure 48. Alternate Freezing and Thawing. Moisture content of specimens when thawed after freezing; Missouri clay subsoil, No. 6a.

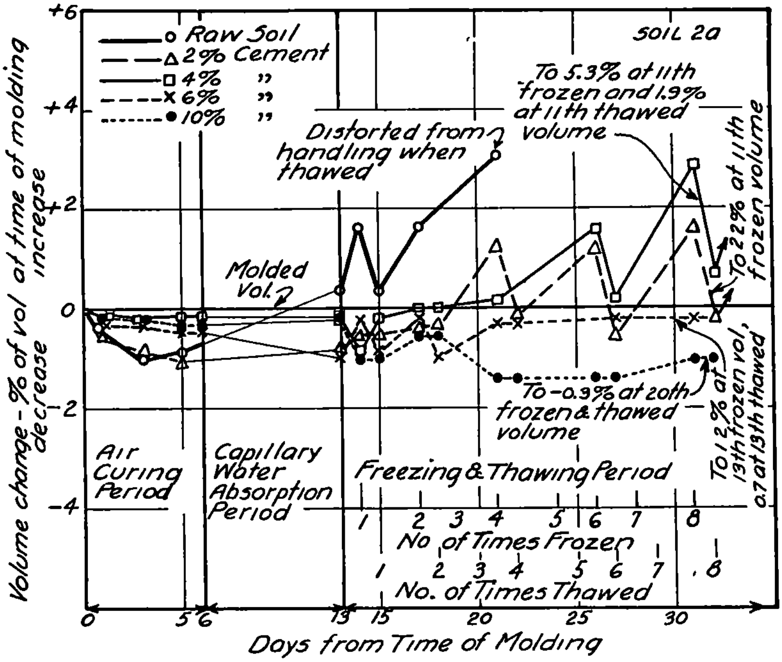

Figure 49. Alternate Freezing and Thawing. Volume changes; South Carolina fine sandy loam top-soil, No 2a.

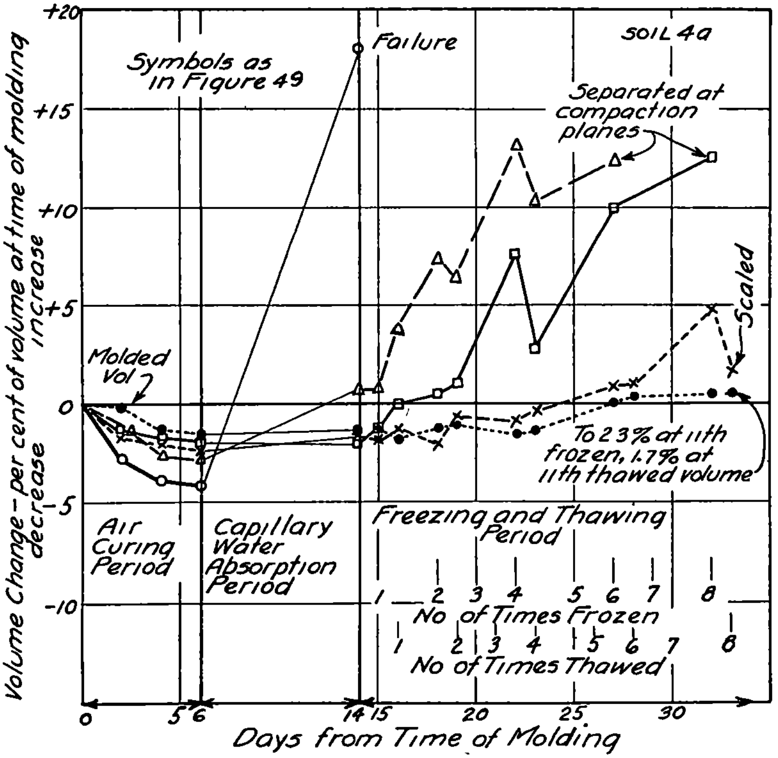

Figure 50. Alternate Freezing and Thawing. Volume changes; Missouri silty clay loam sub-soil, No. 4a.

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

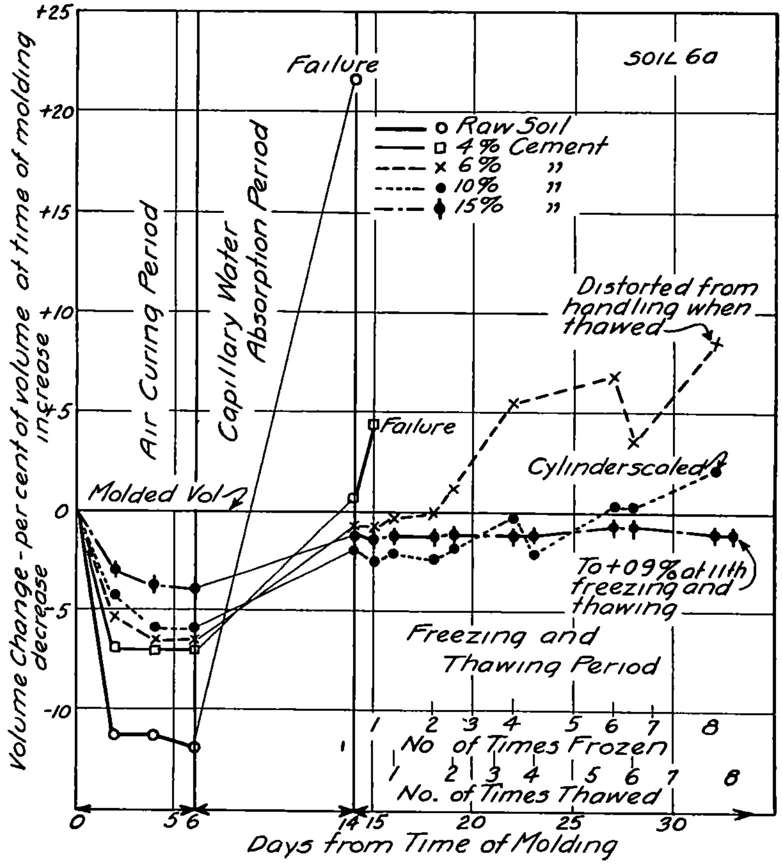

Figure 51. Alternate Freezing and Thawing. Volume changes, Missouri clay subsoil, No. 6a.

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

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 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	—	—

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	Maximum Volume Change Frozen %	Maximum Volume Change Thawed %
6d	0	−14.5	+32.5 Fail	Measurements not made soft to be handled		Specimens too
	4	−9.2	+22.5 Fail			
	6	−8.7	+22.0 Fail			
	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

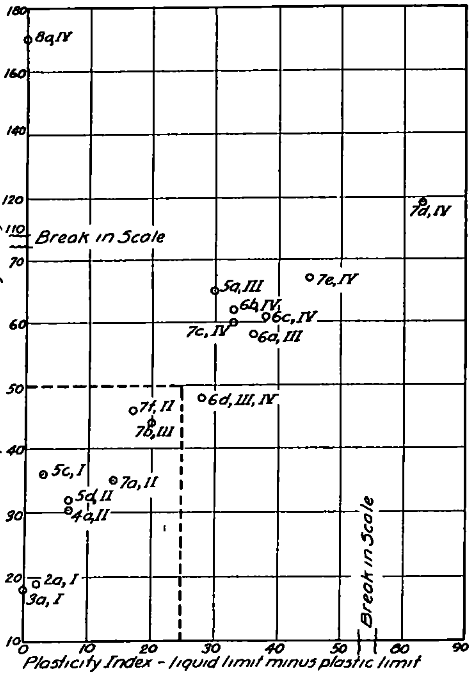

Figure 52. Liquid Limit-Plasticity Relations of All Soils Tested. The Roman numerals indicate treatment group of soil according to Table 3.

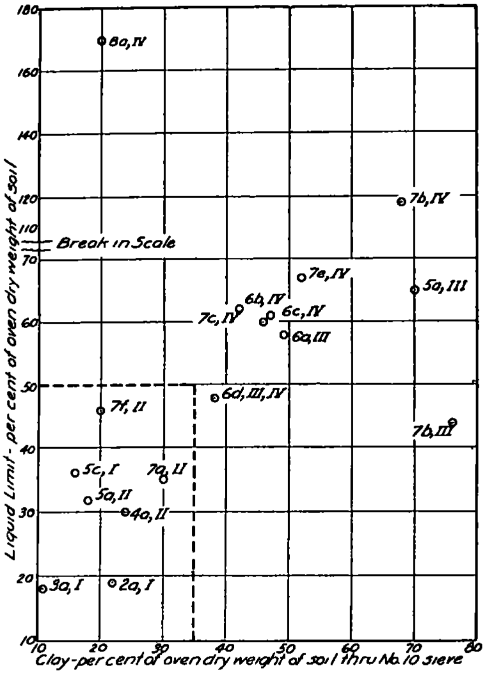

Figure 53. Liquid Limit-Clay Content Relations of All Soils Tested. The Roman numerals indicate treatment group of soil according to Table 3. Clay is the soil fraction having a diameter less than 0.005 mm

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

last of the base was not placed until May 6, 1937 due to many delays on account of bad weather

The soil in this project varied from almost pure fine sand to soil containing as much as 25 per cent clay Six per cent cement by weight was used with sandy soil and 8 per cent with soil containing considerable clay No curing was provided but in most instances weather conditions were favorable to retarding evaporation of moisture

The contractor used a travelling mixing plant The soil was scarified, pulverized, and windrowed to the center of the road, picked up from the windrow by the travelling mixing plant and emptied into a bin from which it flowed by gravity through a measuring gate into the pug mill Cement was applied from a bin on the platform of the mixer A continuous feed belt from the cement bin was interlocked with the feed belt from the soil bin so that cement and soil flowed into the mixer at a constant rate The moisture content of the soil in the windrow was within the requirements for compaction on many sections but when necessary to increase the moisture to the optimum for compaction, water was applied to the mixture after the cement had entered the pug mill The completed mixture was discharged from the end of the pug mill, shoveled into place by hand, and packed with a sheepsfoot roller operated back and forth parallel to the centerline of the road When the feet of the roller had compacted the mix to within about 1½ in of the top, the surface was bladed to the correct grade and cross section, compaction planes were removed by light scarifying, and the mulch thus obtained was compacted with loaded trucks or a pneumatic roller The final surface was obtained with a multiple blade drag, but the riding qualities of the road were not entirely satisfactory due to the short sections finished as a unit

During the construction of this project the necessity for a stable subgrade was definitely shown when an attempt was made to construct a short section over subgrade in which the moisture content was considerably above the optimum Cracking appeared during compaction and the mix did not harden satisfactorily The base at this location was reconstructed

A four mile section of this project was primed with tar in March 1937 and soon afterwards "blow-ups" occurred in 23 places These "blow-ups" were characterized in a few cases by cracking and shattering of the base for the full depth and approximately two linear feet, but in most places only the top 2 in were visibly affected by shattering although there was one crack completely through the base Shattered portions of the base were removed and easily patched with soil-cement mixture There has been no recurrence of this trouble nor has it appeared on any other project

A failure due to improper construction occurred in a section of road one half mile long after the base had been surfaced and under traffic for a short time The surfacing shoved and it was discovered that the top of the cement stabilized base was soft for a depth of 1 in No serious trouble has developed from this failure and it has been necessary to patch only a few square yards

A contract was awarded at 48 cents per square yard for the cement stabilized base and 18 cents per square yard for the bituminous surfacing for 7 8 miles of Route 92 near Union, S C Specifications for this work are similar to those on the Hampton project The soil consists mostly of disintegrated granite which gives very excellent results in the laboratory durability tests and only 5 per cent by weight of cement was used with it However, the cement content was increased to 8 per cent when red clay soil was encountered The contractor used equipment and methods similar to those on the Hampton project but obtained a much better riding surface Progress has been slow due to adverse weather conditions but approximately 4 8 miles have been completed In one week a total of 11,500 ft was built

The highway department constructed with its own forces several miles of cement stabilized roads These projects consisted of 1 8 miles on U S Route 178 between Saluda and Greenwood, approximately 0 5 mile in the Town of Estill, 0 5 mile at Clemson and 0 25 mile near Greenville Regular mixed-in-place procedure was followed Compacted depths varied from 4 to 6 in depending on traffic, and cement contents were varied to suit the soil encountered

The project between Saluda and Greenwood was the repair of a bituminous surfaced road which has always given trouble due to bad subgrade and inferior top soil base The old surface treatment was broken by scarifying and included in the mix Cement was applied at the rate of 7 per cent by weight and the theoretical compacted thickness was 6 in The cement stabilized base was covered with a $\frac{1}{2}$ in bituminous mat As no detour was available, it was necessary to construct the road in half width sections

This project has not been in use long enough to judge the adequacy of the stabilization, but it is believed that it will furnish a severe test as the subgrade is very plastic clay, unstable in wet weather, and traffic over it is very heavy with a large proportion of trucks A portion of this project was stabilized with another material in order to compare the economy and durability of the two methods as there is a considerable mileage of bituminous surfaced road which could be repaired if either method proves economical and durable

Contracts have been let for 13 more miles of cement stabilized roads and bids have been requested on this type as an alternate to others on 15 3 miles

The preliminary laboratory durability tests and the moisture density control test used by this department vary in some particulars from the procedure adopted by the Portland Cement Association The optimum moisture content for compaction of laboratory specimens and field mixtures is determined by the Proctor method with the exception that the tamper is applied to the soil with more force than is obtained with the 12 in free drop This additional force was adopted because it appeared that in some instances the 12 in drop gave an optimum moisture content so high that the particles were lubricated and the mix cracked during final rolling At present, a definite standard has not been adopted because the compacting force is varied for different soils depending on the clay content and other characteristics Tests will be correlated with field results and the laboratory method adjusted so that laboratory densities will check with field densities

Laboratory durability tests consisting of alternate wetting-drying and freezing-thawing are conducted on cycles similar to those used by the Portland Cement Association but due to the large construction program it has been necessary to reduce the quantity of laboratory work and the size of the samples The procedure used is to make one Proctor specimen at each cement content, cure it in the moist room for 7 days and then saw it into four approximately equal parts parallel to the long axis Wetting-drying tests are performed on one of these specimens and freezing-thawing on the other One is used for moisture determination for the initial dry weight of the freezing-thawing specimen and the other is retained as a reserve

In determining losses all loose material is removed from the specimen after each cycle by brushing with a rather soft bristle brush Brushing with a stiff bristle wire brush apparently causes greater losses than actually occur from the disintegrating forces of the durability tests and specimens made with sandy soil and low cement contents can be entirely destroyed by vigorous brushing

Much remains to be learned about designing and constructing this type of road The work to date has shown that adequate preliminary field soil surveys and laboratory tests as well as thorough field control are essential to the successful construction of cement stabilized roads

AN EXPERIMENTAL SOIL-CEMENT ROAD IN ILLINOIS

By V L Glover

Engineer of Materials, Illinois Division of Highways

During September, 1936, a soil-cement road, the first to be constructed in Illinois, was built near Rockford, Winnebago County The preliminary tests were made jointly by the Division of Highways, Springfield, and the Portland Cement Association, Chicago Construction work was done by the Winnebago County Highway Department The section was 6,000 ft long and the soil-cement surface was 18 ft wide and 6 in thick The section was entirely experimental and was constructed at approximately the same time that several other experimental sections were under way in the middle west

Preliminary soil samples were taken before the grading work was completed It was believed that they would be sufficiently representative of the soils involved in the project that the field control information could be satisfactorily based upon the test data for these samples and that the construction work could be started as soon as the tests were completed

LABORATORY SOIL TESTS

Except for a few minor changes, the laboratory tests were made in accordance with the recommended procedure outlined in the Portland Cement Association Progress Report on Laboratory Investigation of Soil-Cement Mixtures, dated May 1, 1936

Physical Test Constants and Grain Size The test data in Table 1 indicated that with the exception of a short section of clay loam on the north end of the project, the soil would classify as a sandy loam, and as an A-2 subgrade material grading to either the A-3 or A-4 groups

These data also showed that the soils represented by Samples 36-2282, 36-2283, and 36-2285 were very similar but that Sample 36-2285 had the highest liquid limit and plasticity index Therefore, it was recommended that the laboratory control tests be confined to this last named sample because previous tests indicated that the cement required increased as the liquid limits and plasticity indices increased It was decided, however, to conduct the complete control tests on all of the samples taken

Moisture-Density Tests The optimum moisture content-maximum density data determined for each soil sample and for each soil sample combined with 4, 6, and 10 per cent cement, by weight, are shown in Table 2 The selection of these percentages of cement was based upon a comparison of the data shown in Table 1 with similar data for soils previously tested and for which complete soil-cement data had been obtained

The curves plotted from the data secured by these tests are shown in Figures 1 to 5, inclusive An inspection of these curves appears to establish a lack

TABLE 1

Physical Test Constant and Grain Sizes

Sample Number	Station	Classification	U S B P R Group	Mechanical Analysis Per Cent Passing Sieve Number						
				3/8	4	10	20	40	100	200
36-2281	0 + 60	Clay Loam	A-4-2	100	97 4	97 1	96 4	93 7	78 9	75 8
36-2282	19 + 75	Sandy Loam	A-2			100	99 6	91 6	20 0	14 7
36-2283	37 + 50	Sandy Loam	A-2			100	99 8	91 6	29 0	24 0
36-2284*	37 + 50	Fine Sand	A-3			100	99 8	93 8	13 1	6 6
36-2285	45 + 00	Sandy Loam	A-2			100	99 6	95 0	53 4	48 2

Sample Number	Sand +0 05	Silt 05- 005	Clay 005- 000	Colloids −0 001	Liquid Limit	Plastic Index	Field Moisture	Shrinkage Limit	Shrinkage Ratio
36-2281	33	40	27	17	26 5	11 2	18 0	16 0	1 8
36-2282	88	5	7	4	13 6	—	16 0	9 0	2 0
36-2283	81	10	9	4	14 0	—	16 0	12 0	2 0
36-2284*	95	2	3	2	17 4	—	18 0	13 0	1 8
36-2285	59	24	17	5	22 4	4 9	21 0	16 0	1 8

* Subgrade, sampled 2 feet below No 36-2283

TABLE 2

Proctor Moisture-Density Data

Sample Number	Per Cent Cement		Optimum Moisture Content, %	Maximum Density lb per cu ft
	By Weight	By Volume*		
36-2281	0	0	15 4	112 6
	4	4 57	15 7	112 0
	6	6 81	15 3	112 8
	10	10 85	15 0	111 7
36-2282	0	0	8 7	121 2
	4	5 00	9 0	122 4
	6	7 45	8 4	123 8
	10	12 02	9 6	124 5
36-2283	0	0	9 4	125 8
	4	5 11	9 7	124 5
	6	7 45	9 7	124 4
	10	12 02	9 6	124 0
36-2284	0	0	10 5	112 9
	4	4 79	9 0	117 5
	6	7 13	9 1	118 8
	10	11 81	8 0	121 7
36-2285	0	0	13 6	113 4
	4	4 68	13 2	113 4
	6	6 81	13 5	112 4
	10	10 85	13 4	112 7

* Calculated

of any definite relationship between the moisture-density and the various cement contents However, the curves for samples 36-2282 and 36-2284 (Figures 2 and 4) show that the density of these soils increased with increasing percentages of cement, but the increases were not in direct proportion to the increments of cement incorporated in the raw soils The optimum moisture contents, how-

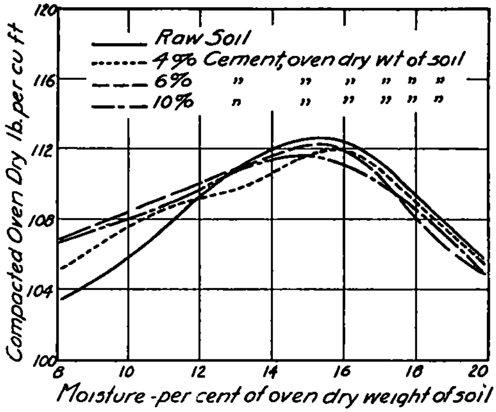

Figure 1. Moisture-Density Relations. Clay Loam, Group A-4-2, Sample 36-2281

ever, for even these particular soils did not vary in any definite manner

In some of the earlier work, there was a tendency for the curves, plotted from the data secured for soils with higher clay contents, to be more or less irregular in shape However, when such soils were broken down until they would pass a No 8 sieve, moistened, and allowed to remain in a moist closet for approximately 18 hours, the resulting curves were no longer so irregular in shape

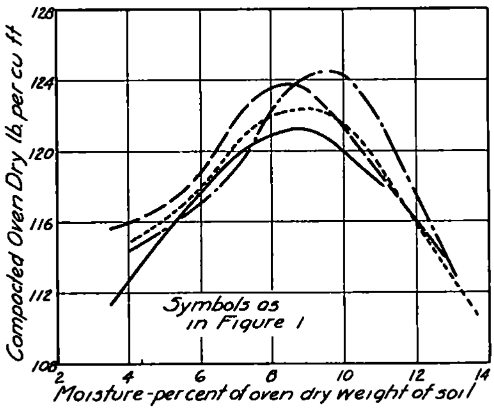

Figure 2. Moisture-Density Relations. Sandy Loam, Group A-2, Sample 36-2282.

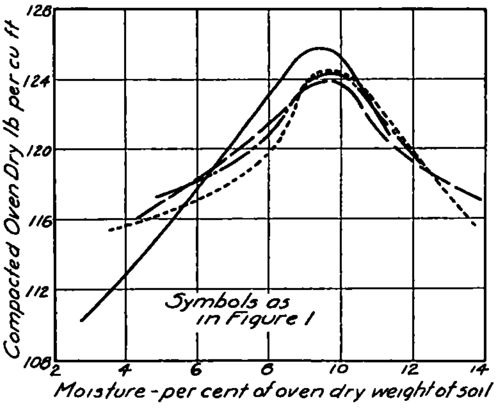

Figure 3 Moisture-Density Relations. Sandy Loam, Group A-2, Sample 36-2283.

Moisture-Penetration Tests After each of the soil cylinders used in the moisture-density tests had been weighed, an effort was made to secure moisture-penetration data, but the results were so obviously erratic that they were disregarded

Durability Tests Up to this point, the soil-cement mixtures were made by adding 4, 6, and 10 per cent cement to the raw soil on the basis of the oven dry weight of the soil The same increments of cement, by volume, were used in the durability test specimens

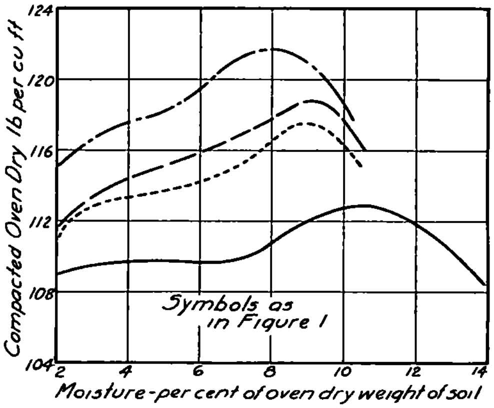

Figure 4 Moisture-Density Relations. Fine Sand, Group A-3, Sample 36-2284

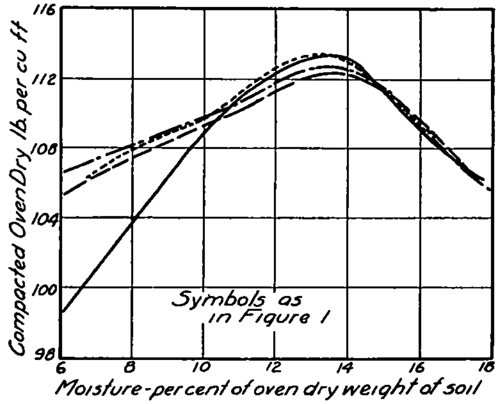

Figure 5. Moisture-Density Relations Sandy Loam, Group A-2, Sample 36-2285.

The following formula was used to convert the cement contents of the moisture-density soil-cement mixtures, compacted at their optimum moisture contents, to the volume basis

$$\frac{W - \frac{W(100)}{100+C}}{94} \times 100 = \text{the equivalent}$$

percentage of cement, by volume,

when W = Weight of one cubic foot of soil-cement mixture compacted at its optimum moisture content,
C = Percentage of cement based on oven dry weight of the soil,
94 = Weight of one cubic foot of cement

The percentages of cement, by weight, used for the moisture-density tests and the equivalent percentages on the volume basis are shown in Table 2 These equivalent percentages, by volume, were plotted against the unit oven dry weights of the corresponding mixtures, compacted at their optimum moisture contents (Fig 6) and the resulting curves used to determine the unit oven dry weight which should be obtained for any of the soils in question in either their raw state or when combined with any percentage of cement, by volume, when compacted at their optimum moisture content The cement contents, by volume (4, 6, and 10 per cent), were in turn converted to equivalent percentages, by weight, for laboratory control, during the durability tests

The equivalent percentages of cement, by volume, were also plotted against the optimum moisture contents determined for the raw soils and the various soil-cement mixtures (Figure 7) and the resulting curves used to determine the optimum moisture contents for the various soil-cement mixtures used in the durability tests

As soon as the above mentioned work was completed, the test specimens used for the durability tests were made up according to the data given in Table 3. The actual optimum moisture content and the density secured for the different specimens varied somewhat from the figures given, but these variations were well within the specified limits

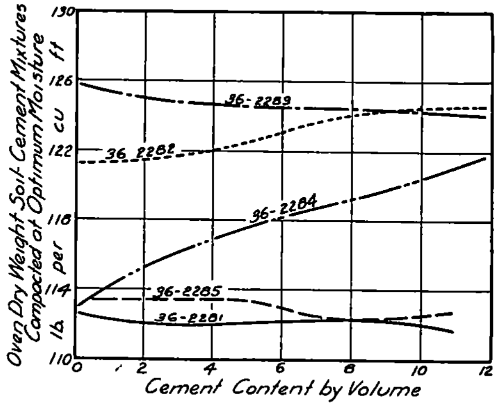

Figure 6. Chart for determining the unit oven dry weight of laboratory samples compacted at optimum moisture containing various percentages of cement by volume.

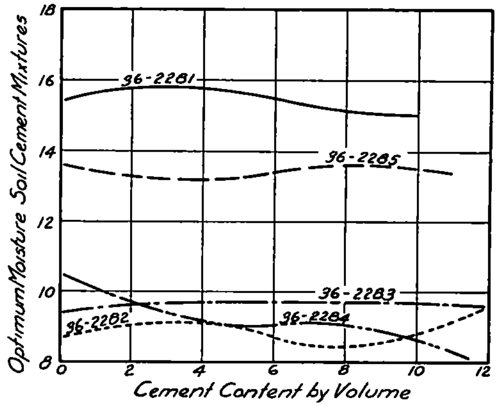

Figure 7 Chart for determining the optimum moisture contents of laboratory samples containing various percentages of cement by volume.

The durability specimens were cured for 7 days in a moist room instead of being exposed to the laboratory air according to the procedure outlined. Despite the fact that the relative humidity of the moist room was maintained above 90 per cent during the curing period, a slight loss of weight was recorded after the first day's curing. This was remedied by covering the specimens with a damp canvas, care being taken that the canvas did not touch the specimens and add moisture rather than prevent loss.

TABLE 3

Data for Molding Durability Test Specimens

Sample Number	Per Cent Cement		Optimum Moisture Content, %*	Maximum Density lb. per cu. ft.*
	By Volume	By Weight		
36-2281	0	0	15.4	112.6
	4	3.47	15.7	112.0
	6	5.29	15.5	112.2
	10	9.16	15.0	112.0
36-2282	0	0	8.7	121.2
	4	3.18	9.1	122.0
	6	4.81	8.7	123.0
	10	8.17	8.8	124.4
36-2283	0	0	No specimens made.	
	4	3.11	9.7	124.6
	6	4.75	9.7	124.4
	10	8.19	9.7	124.2
36-2284	0	0	No specimens made.	
	4	3.32	9.1	116.9
	6	5.01	9.0	118.2
	10	8.47	8.6	120.4
36-2285	0	0	13.6	113.4
	4	3.43	13.2	113.4
	6	5.25	13.4	113.0
	10	9.12	13.5	112.5

* Interpolated.

Wetting and Drying Test. The recommended wetting and drying test procedure was followed for 18 cycles. Pictures of the specimens were taken after 12 and 18 cycles. The condition of the specimens at the end of the 18 cycles is shown in Figures 8 to 11, inclusive. No pictures were taken of the specimens for Sample No. 36-2284, because this material represented the subsoil and was tested for only 12 cycles. No volume changes were noted.

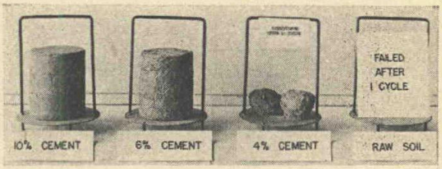

Figure 8. Brushed specimens for sample 36-2281 after 18 cycles of wetting and drying.

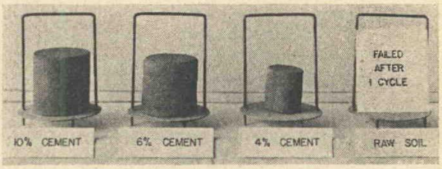

Figure 9. Brushed specimens for sample 36-2282 after 18 cycles of wetting and drying.

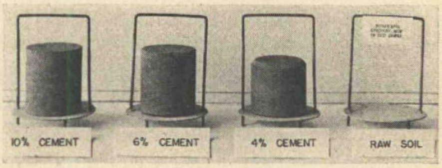

Figure 10. Brushed specimens for sample 36-2283 after 18 cycles of wetting and drying.

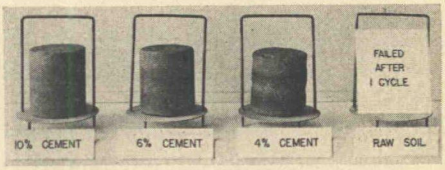

Figure 11. Brushed specimens for sample 36-2285 after 18 cycles of wetting and drying.

The moisture absorbed by the soil-cement specimens during the 5-hour period of immersion was so nearly constant from cycle to cycle that no detailed record of the results is shown Sample 36-2283, with 4 per cent cement, showed a maximum variation of about 3 per cent at 6 cycles, after which the specimen began slaking Other samples showed variations of less than one per cent throughout the duration of the test or until slaking losses prevented measurements.

TABLE 4

Durability Tests Showing the Effect of Cement on the Soil Samples

Sample Number	Per Cent Cement by Volume	Wetting and Drying Data			Freezing and Thawing Tests		
		Volume Change, %	Soil Loss, %	Maximum Moisture Change*	Volume Change, %	Soil Loss, %	Maximum Moisture Change*
36-2281	0	Raw soil failed after 1 cycle			7 0 at 5	+70 0 at 2	5 0 at 3
	4	No	78 0 at 15	1 0 at 4	5 0 at 8	77 0	3 0 at 5
	6	No	9 0	1 0 at 5	1 0 at 12	18 0	2 0
	10	No	No	1 0	No	1 0	2 0
36-2282	0	Raw soil failed after 1 cycle				+70 0 at 2	4 0 at 2
	4	No	72 0	No	No	+70 0 at 5	3 0 at 7
	6	No	17 0	1 0	No	86 0 at 13	4 0 at 7
	10	No	6 0	No	No	50 0	2 0
36-2283	0			No raw soil specimens			
	4	No	16 0	No	No	+70 0 at 6	2 0 at 4
	6	No	No	No	No	25 0	1 0
	10	No	No	No	No	No	No
36-2284	0			No raw soil specimens			
	4	No	26 0 at 12	No at 7	No	38 0 at 12	2 0 at 6
	6	No	7 0 at 12	1 0 at 12	No	5 0 at 12	1 0 at 12
	10	No	1 0 at 12	No	No	2 0 at 12	1 0 at 12
36-2285	0	Raw soil failed after 1 cycle				+70 0 at 2	7 0 at 2
	4	No	11 0	No at 14	No	85 0	5 0 at 11
	6	No	1 0	No	No	32 0	5 0
	10	No	No	No	No	No	4 0

Note Percentages are based on results after 18 cycles, unless designated by at 12, etc

* Maximum moisture change represents the difference in the moixture content at the time of molding and the maximum moisture absorbed during the duration of the durability tests or until soil losses prevented further determinations

The soil losses and moisture changes are given in Table 4

Freezing and Thawing Tests At the end of the 7-day curing period the remaining two specimens of each set of the durability specimens were tested according to the recommended freezing and thawing procedure, except that 24-hour freezing periods were used instead of the recommended 20-hour periods, because the temperature of the room was maintained at from 0° to 5°F, instead of the lower temperature recommended

This test was continued for 18 cycles of freezing and thawing Pictures of the specimens were taken after 12 and 18 cycles had been completed The condition of the specimens at the end of the 18-cycle period is shown in Figures 12 to 15, inclusive. No pictures were taken of the specimens for Sample No. 36-2284. The soil losses are shown in Table 4.

All of the raw soil specimens showed some volume change, but accurate measurements could not be made due to softening and distortion. The soil-cement specimens showed no appreciable volume change, except in the case of the 4 per cent specimen for Sample No. 36-2281, which developed a volume change of less than 7 per cent.

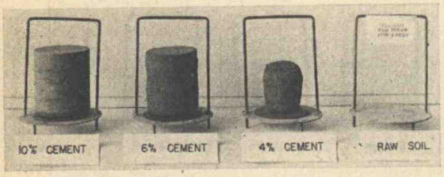

Figure 12. Brushed specimens for sample 36-2281 after 18 cycles of freezing and thawing.

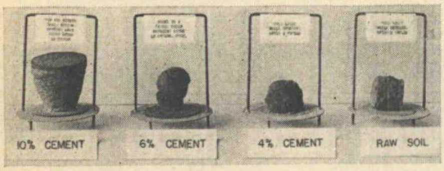

Figure 13. Brushed specimens for sample 36-2282 after 18 cycles of freezing and thawing.

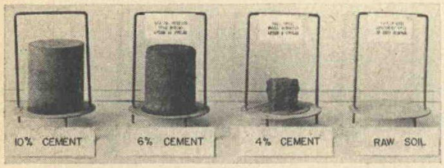

Figure 14. Brushed specimens for sample 36-2283 after 18 cycles of freezing and thawing.

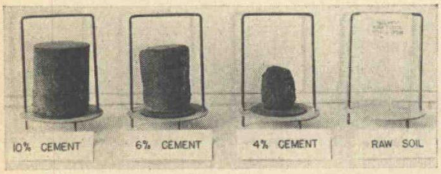

Figure 15. Brushed specimens for sample 36-2285 after 18 cycles of freezing and thawing.

The individual moisture contents of the specimens were determined throughout both the curing period and the freezing and thawing test, the latter at the end of each thawing period, and are shown in Table 4.

Check and Compression Tests. After completion of the grading on this project, a second set of samples was taken. The physical test constants and grain sizes checked the data determined for the preliminary samples.

Compression test cylinders for each sample combined with 6 and 10 per cent cement, by weight, were molded and broken at the end of two and six day periods. These data showed sufficient similarity to the strengths obtained from similar tests which had been made on soils satisfactorily hardened with cement to indicate that the soils on this project should react favorably with cement.

Conclusions. Upon completion of the laboratory tests, the data obtained by the Division of Highways were compared with the data obtained by the Portland Cement Association. This comparison showed a remarkable similarity in results, especially in view of the fact that the samples were not taken at the same locations.

The agreement of the data obtained by the two laboratories and between the data for the preliminary samples and the samples taken after the grading was completed, indicated that it would not be necessary to make additional tests.

Since the clay loam on the north end of the project had been replaced with sandy loam during the grading operations, the physical test constants and grain size data showed that the soil on this entire section corresponded very closely to the sandy loam represented by Sample No. 36-2285.

The results of the durability tests (Table 4) showed quite definitely the stabilizing influence of the cement on the type soil predominating on this project and also indicated that the addition of 10 per cent cement, by volume, to the soil would produce better results than the lower percentages tested

Based upon the Proctor moisture-density data for the representative soil-cement mixture, containing 10 per cent cement, by volume, an optimum moisture content of 16 per cent and a density or dry weight per cubic foot, compacted at the optimum moisture content, of 112 pounds were selected for field control during the construction work on this project

CONSTRUCTION

Due largely to a lack of experience with this type of work, considerable equipment was used which should have been replaced by more satisfactory equipment Equipment was made up but never used, and other equipment was rented and shipped to the job but never used

The following equipment was used on the project

One 60-ton tractor, used with scarifier and blade grader

Two 35-ton tractors, used with disk harrows

One No 2 blade grader

One 7-tooth scarifier

Two 20-inch disk harrows, used for pulverizing and mixing

One 24-inch disk harrow, tried out in an attempt to pulverize and mix to the full depth in a single operation

Two sheepsfoot rollers, one single section and one double section

One No 6 road maintainer, used for shaping after compaction and for spreading curing material

Two distributors, one 700 gallon and one 900 gallon, used to apply water

One dual-pneumatic tired tractor, used for final compaction

One 8-ton three-wheel roller, used for finishing

Trucks, several used for hauling cement, turn-around material, and compacting

The facts that a 700 and 900 gallon distributor were used on this project, that they were filled at a stream about a mile away, that about 45 minutes were required to fill and empty each distributor, made the application of water slow and expensive, increased the mixing time, and tended to reduce the effectiveness of the cement

The compaction work carried on with the sheepsfoot rollers would have been speeded up and been more satisfactory if the rollers used had been the type with the larger feet

The 8-ton smooth roller used for the final finishing operations gave some trouble because it had a tendency to shove and crack the surface and to pick up the material from the roadway It is necessary to work out a definite technique in the use of smooth rollers for this type of work

The data in Table 5 shows that the construction work was divided into eight increments, varying from 500 to 900 feet in length The average time required for treatment was two hours per 100 ft of surface, which included the time required to spread and mix the cement, apply the water, and to compact and finish the surface This average time, however, does not include the scarifying and pulverizing operations which were carried on when there was no actual processing in progress, although these operations together with the curing preparations, moving turn-arounds, and incidentals increased the total time

In general, the following construction procedure was used

Scarifying, Pulverizing, and Shaping The section to be treated was scarified to the full width and depth shown on the plans and brought to grade with the blade grader The soil was then pulverized with disk harrows and all lumps were completely broken down Whenever the moisture content of the soil exceeded the specified optimum moisture content by more than 2 per cent, the pulverizing was continued until the moisture content was within the specified 2 per cent As soon as the soil was pulverized, it was shaped to the approximate cross-section shown on the plans In shaping, however, the soil was pulled about 2 ft away from the edges to prevent waste or segregation of the cement

TABLE 5

Construction Data for Each Section

	Section Number							
	1	2	3	4	5	6	7	8
Length (Feet)	500	500	800	900	900	800	900	700
Date Treated	9–18	9–19	9–22	9–24	9–26	9–29	10–2	10–3
Temperature (high)	73	76	87	61	62	69	61	65
Temperature (low)	42	44	55	45	51	43	34	42
Original Moisture	9 0	8 0	8 5	6 0	7 5	12 0	12 0	11 0
Final Moisture	15 0	15 0	15 5	13 0	15 0	16 0	15 0	15 5
Approximate time of each operation during treatment (hours)								
Spreading Cement	1½	1	1½	1	1½	1½	1	1½
Mixing Cement	3½	3½	5	4	4	4½	6	4½
Applying Water	4	4	6½	5½	5½	3	5	2½
Compacting	2	2½	3	1½	3	3	2	1½
Finishing	2	2	2	5	—*	2	2	2
Total Time	13	13	18	17	14	14	16	12
Density tests run by sand method								
Date Tested	9–21	9–21	10–1	10–1	10–4	10–4	10–4	—
Moisture Content	11 1	11 1	11 7	8 7	11 1	11 7	14 9	—
Wt Per Cu Ft	117 8	120 1	118 1	122 6	122 7	121 6	119 1	—

* Rain during final compaction

Applying, Checking, and Mixing the Cement The cement was spread at the rate of 9 bags to each 10 linear feet of roadway to give the 10 per cent by volume specified The cement was spread uniformly over the surface with rakes and shovels, and mixed with the pulverized soil by means of disk harrows. An inspection of the resulting mixture, however, disclosed the fact that the cement had not been incorporated to the full depth of the pulverized soil Therefore, the mixed portion was halved into windrows on either shoulder The remaining portion was then loosened with disk harrows and spread over the previously mixed and windrowed material, after which each windrow of mixed and unmixed material was bladed into the roadway and thoroughly mixed with the disk harrows

Applying Water After satisfactorily mixing the cement and pulverized soil the full depth of the section, approximately 40 per cent of the mixture was windrowed in preparation for application of water, to avoid repetition of the difficulties experienced in mixing the cement to the full depth The addition of water in two lifts necessitated a constant check on the moisture content of the mixture to prevent the use of water in excess of the optimum moisture content

The moisture content of the soil-cement mixture was determined from an average of several moisture tests and the amount of water necessary in order to satisfy the optimum moisture of the mixture was calculated from the data given in Table 6

This table is based on the weight per cubic foot of the oven dry soil-cement mixture compacted at optimum moisture content, i e , 112 lb per cu ft , compacted with 16 per cent moisture For example suppose after having applied and thoroughly mixed the required amount of cement, the average moisture content is found to be 7 0 per cent As 16 0 per cent is the optimum, it is, therefore, necessary to add 9 0 per cent Since this particular section is 800 feet in length, 8 times 1089 gallons, from the table, is the total amount of water necessary

The original and final moisture contents shown in Table 5 represent the averages of several determinations made on each section The original moisture data represent the percentage of moisture contained in the mixture after the cement had been thoroughly mixed with the soil, and the final moisture data show the percentage in the mixture at the time of starting compaction

Difficulties experienced in applying water did not materialize except on Section 6 and this was probably due to lack of drainage Whenever the original moisture content varied somewhat throughout a section, it was expected that the rate of applying water would have to be varied accordingly However, there appeared to be a natural balance between the original moisture and the optimum moisture that tended to counteract this variable As an example, on Section 4, the original moisture varied from 6 4 per cent at the north end to 4 1 per cent near the south end This section appeared to contain more sand than the other sections, with the sand content increasing toward the south end of the section, consequently having less water holding capacity and a low optimum moisture content toward that end Water was applied at the same rate, however, throughout the entire section, and although the final moisture content varied, the consistency of the mixture appeared the same for the entire section

TABLE 6

Data Used to Determine the Gallons of Water Necessary to Bring the Moisture Content of the Soil-Cement Mixture to the Optimum

Per Cent Water to be Added	Gallons per Linear Foot of Roadway	Gallons per 100 Linear Feet of Roadway	Gallons per Square Yard of Roadway
1	1 2101	121 01	605
2	2 4202	242 02	1 210
3	3 6303	363 03	1 815
4	4 8404	484 04	2 420
5	6 0505	605 05	3 025
6	7 2606	726 06	3 630
7	8 4707	847 07	4 235
8	9 6808	968 08	4 840
9	10 8909	1089 09	5 445
10	12 1010	1210 10	6 050
11	13 3111	1331 11	6 655
12	14 5212	1452 12	7 260

Shaping and Compacting After making sure that the moisture content was within 2 per cent of the optimum, the mixture was loosened as much as possible shaped to the lines and grade shown on the plans, and compacted to the required density with sheepsfoot rollers The compacted section was then shaped to conform to the lines and grade shown on the plans, and the roller marks removed with a blade maintainer, after which the surface was given a final rolling with an 8-ton 3-wheel roller

Curing The first two increments were left uncured after completion The other increments, however, were cured with wet earth for seven days A pneumatic tired maintainer was used to spread the curing material to prevent marring the finishing surface

Turn-Arounds Before starting the work on a new section, that part of the previous treated section to be used for turning equipment was covered with at least 6 inches of earth to protect the surface Planks or plates were placed to grade on the end of the completed section to protect it during the subsequent construction operations A thin section of traffic tread plate proved more satisfactory than planks as the protective layer of earth was not necessarily so thick and consequently the mixture did not build up and compact so much above grade at this point

Experimental Surface The last increment, which was 700 ft long, was given a surface application of pea gravel After compaction, the section was shaped to the lines and grade shown on the plans, and a mulch was spread evenly over the section to act as a mortar for the pea gravel surface. The washed pea gravel was then spread over the surface at the rate of 25 pounds to the square yard by adjusting the end gates of the trucks to the desired rate of flow The surface was then wetted slightly and compacted with trucks, after which the final rolling was done with the 8-ton 3-wheel roller The 25-lb treatment of gravel was apparently excessive, because there was considerable loose gravel on the surface after the rolling was completed, and it is probable that about 15 lb per sq yd would have been sufficient

Density Tests Density tests of the surface of all increments excepting the one treated with pea gravel were made by the sand method The material was removed to the approximate depth of the surface with a 4-inch soil auger after the surface had hardened sufficiently to prevent spalling during boring All of the material so removed was retained and its oven dry weight determined The hole left by the auger was filled with standard Ottawa sand, the sand being poured at a constant rate of flow from a receptacle containing a known weight of sand The weight of sand poured into the hole was then determined and the weight per cubic foot of the compacted surface computed by the following formula

$$W_1 = \frac{WS_1}{S}$$

in which—W = the weight of the material removed from the surface,
S = the weight of the sand used to fill the hole,
W_1 = the weight per cubic foot of the material in surface,
S_1 = the weight per cubic foot of the sand

All weights were on an oven dry basis The densities determined by this method are shown in Table 5

RESULTS

When first completed, this project had the characteristic appearance of this type of surface Within two days after the first two increments were placed, hair checking appeared on the surface and it was supposed that these were caused by the rapid and excessive drying out which resulted from lack of curing, therefore, all other increments were cured for seven days In spite of this, transverse cracks and some hair checking appeared on these increments within three days after completion

When examined in December, 1936, approximately three months after completion, the interval between transverse cracks was about 15 feet on all increments except the one covered with gravel, on that increment, the interval was about 30 feet At that time, longitudinal cracking was apparent in only one increment, where a continuous crack, at approximately the centerline, extended through the entire length of the increment, a distance of about 800 feet

When examined in April, 1937, scaling and pitting had developed, but aside from being somewhat rough, the surface was in fair condition In order to protect the surface and to provide better riding qualities, all but 400 feet of the project was given a bituminous surface treatment in August, 1937

TABLE 7

CONSTRUCTION COSTS, EXCLUSIVE OF CEMENT

	Cost for 12000 Sq Yds	Cost per Sq Yd
Moving to and from Section	$294 77	$0 02457
Assembling Machinery and Machinery Costs	158 30	0 01319
Greasing and Gasing Costs	41 07	0 00342
Scarifying Costs	52 79	0 00439
Trenching Costs	202 47	0 01687
Grading Surface	63 55	0 00529
Discing Costs	376 77	0 03139
Mixing Costs	117 76	0 00981
Tamping Costs	68 12	0 00568
Cement Costs (Delivery and Handling)	615 47	0 05129
Water	713 85	0 05949
Rolling	22 91	0 00190
Joints	51 05	0 00425
Curing Pavement	50 55	0 00421
Lights	60 93	0 00508
Miscellaneous Labor Costs and Materials	264 13	0 02202
Freight Costs	222 79	0 01858
Total Costs	$3,377 28	$0 28144

Construction costs, exclusive of cement, are shown in Table 7 The cost per square yard is not so high as would be expected after considering the experiences with the equipment, the number of operations required, the cost of labor, and the fact that the work was delayed by a lack of experience

SUBSEQUENT STUDIES

The average density of the finished surface, determined by the sand method was 120 3 lb per cu ft or 8 3 lb per cu ft more than the density requirement for this project It was assumed that this increased density was due to one or more of the following reasons overcompaction of the soil-cement mixture, an error in the average density of the finished surface as determined by the sand method, or an error in the density requirement

Therefore, Proctor moisture-density tests were made on samples taken from each of the remaining five increments, prior to compaction, in an effort to determine the reason for the density increase noted above. The average density secured by these tests amounted to 118 6 lb per cu ft or only about 1 per cent less than the average density obtained by the sand method, thus discrediting the first two assumptions and indicating that the third assumption was true However, since the job was underway and because of the time required to duplicate the control tests, the project was completed on the basis of the preliminary data

After the job was completed, a composite sample was made in the laboratory from 60 samples of the soil on this project, taken at 100-ft intervals just before the cement was added Ten per cent of cement, by weight, was added to this sample and moisture-density tests made by the Proctor method The curve established by these tests showed a maximum density of 125 5 lb per cu ft and an optimum moisture content of 9 5 per cent The densities determined on the job by the Proctor method were then plotted, at their respective moisture contents, with the curve mentioned above, which showed that the individual tests made in the field checked very closely the laboratory results for the composite sample These two studies showed that the material in the finished surface was not compacted to its maximum density, probably due to the fact that it had been compacted at 6 5 per cent in excess of its optimum moisture content, that there was no appreciable error in the densities obtained for the finished surface by the sand method, that there was no appreciable error in the densities obtained in the field by the Proctor method, and that the density and optimum moisture content requirements for this project were undoubtedly in error due to the fact that the preliminary sample selected for the control tests did not represent the material on the project

Since gradation is unquestionably an important factor in the density of soils, and especially so with respect to surfaces of this type, mechanical analyses and hydrometer tests were also made in the laboratory on each of the 60 samples mentioned above The average results for these tests indicated that the soil on this project consisted of 74 per cent sand, 15 per cent silt, and 11 per cent clay, or 15 per cent more sand, 9 per cent less silt, and 6 per cent less clay than was present in the preliminary sample selected for job control This difference in gradation and character of the material undoubtedly proves that the sample upon which the job requirements were based was not representative of the soil on this project

CONCLUSIONS

1 Preliminary samples on which the job control data are to be based should not be taken until the grading operations have been completed

2 Extreme care should be exercised in taking the samples on which the job control data are to be based The locations at which the samples are taken should be carefully selected and a sufficient number of samples secured to represent satisfactorily the soil types and variations within these types

3 The equipment for preparing the soil, mixing the cement, distributing and incorporating the water, and compacting the mixture, should be such that the actual time of processing will be reduced to the minimum

4 Comprehensive field tests should be conducted during the progress of the job

EXPERIMENTAL SOIL-CEMENT STABILIZATION AT CHEBOYGAN, MICHIGAN

By W S Housel

Research Consultant, Michigan State Highway Department

During the summer of 1936 the Michigan State Highway Department undertook the experimental soil-cement stabilization of a section of the Shore Line Highway near Cheboygan The Portland Cement Association cooperated in the project by conducting preliminary laboratory tests to supplement those conducted by the Research and Testing Division of the State Highway Department and also assisted in the control and supervision during construction

Construction was started on August 15 Because of frequent rains the first section of 350 ft was not processed until August 25 The last section of 700 ft was processed on October 22 and the project was discontinued on November 6 when it appeared hopeless to attempt further construction in the face of adverse weather conditions Special mention is made of the weather as it constituted the greatest difficulty encountered in the work There were 22 days out of the total 82 days of the construction period on which it rained sufficiently to stop the work During the latter part of the job Sisalkraft paper was used to protect the section under construction While this proved to be of substantial assistance it did not eliminate the difficulty which indicates that the success of this type of soil stabilization by road mix methods depends to a considerable extent upon limiting the construction to a period of less frequent rainfall The adverse weather necessarily affected the quality of the work as well as the speed with which it was conducted This factor must, in fairness, be considered in judging the Michigan project as an example of this type of construction

Some of the details employed on this particular project have been described elsewhere[1] Consequently, this discussion will present information on the design and control of soil-cement mixtures and will make only occasional reference to construction procedure and equipment Some tentative conclusions will be presented with the object of suggesting a basis for designing such mixtures and of outlining procedures to control the construction in the field

PRELIMINARY SOIL SURVEY AND SOIL CLASSIFICATION

The Michigan State Highway Department has for some years included a preliminary soil survey as an essential step in road design A soil survey based upon field surveys and soil classification used by the Soil Survey Division of the U S Bureau of Chemistry and Soils was made of the Cheboygan section of the Shore Line Highway and serves as an excellent illustration of the practical value and adaptability of this type of soil classification to highway design and construction In Figure 1 is shown a strip map giving the different soil types and their boundaries found on the section of road under discussion The characteristics of each soil profile are given in detail in the descriptions furnished with the standard soil maps, and a complete legend of the Michigan area has been prepared for department use The profiles and descriptions of each soil series on the strip map in Figure 1 have been reproduced in Figure 2 There are nine soil series identified on the map and these may be grouped into two classes In one the parent material is sand while in the other the parent material is clay One profile series, Ogemaw, is a special case, being two or three feet of imperfectly drained sand, over clay This series has been included in the clay group because, as will be seen in later discussion, the grading operations brought this clay to the surface and it played an important part in the composition of the subgrade soil The soil series are typical northern podzols with an A_0 horizon of organic debris with a characteristic leached A_1 horizon In general the surface soils were acid as might be expected in podzol soils, a fact which appeared to affect the soil stabilization in one case, which will be discussed later

The grading operations mixed the soils in the original profiles, but a correlation of these two factors can be made by a study of the grading plans, which are shown on the lower part of Figure 1 Three lines are shown which represent the finished grade in plan and also serve as the base line to show cut and fill on the center line and at points 25 ft right and left of the center line The circles on the center line represent balance points for cut and fill and, in general, indicate the disposal of soil from the cuts By comparing the profiles on Figure 2 with the

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[1] (a) "Soil-Cement Road Project-Cheboygan County, Michigan"—J W Kushing Paper for the 29th Annual Mississippi Valley Conference, February 6, 1937

(b) "Principles of Soil Stabilization"—W S Housel, Civil Engineering, May, 1937

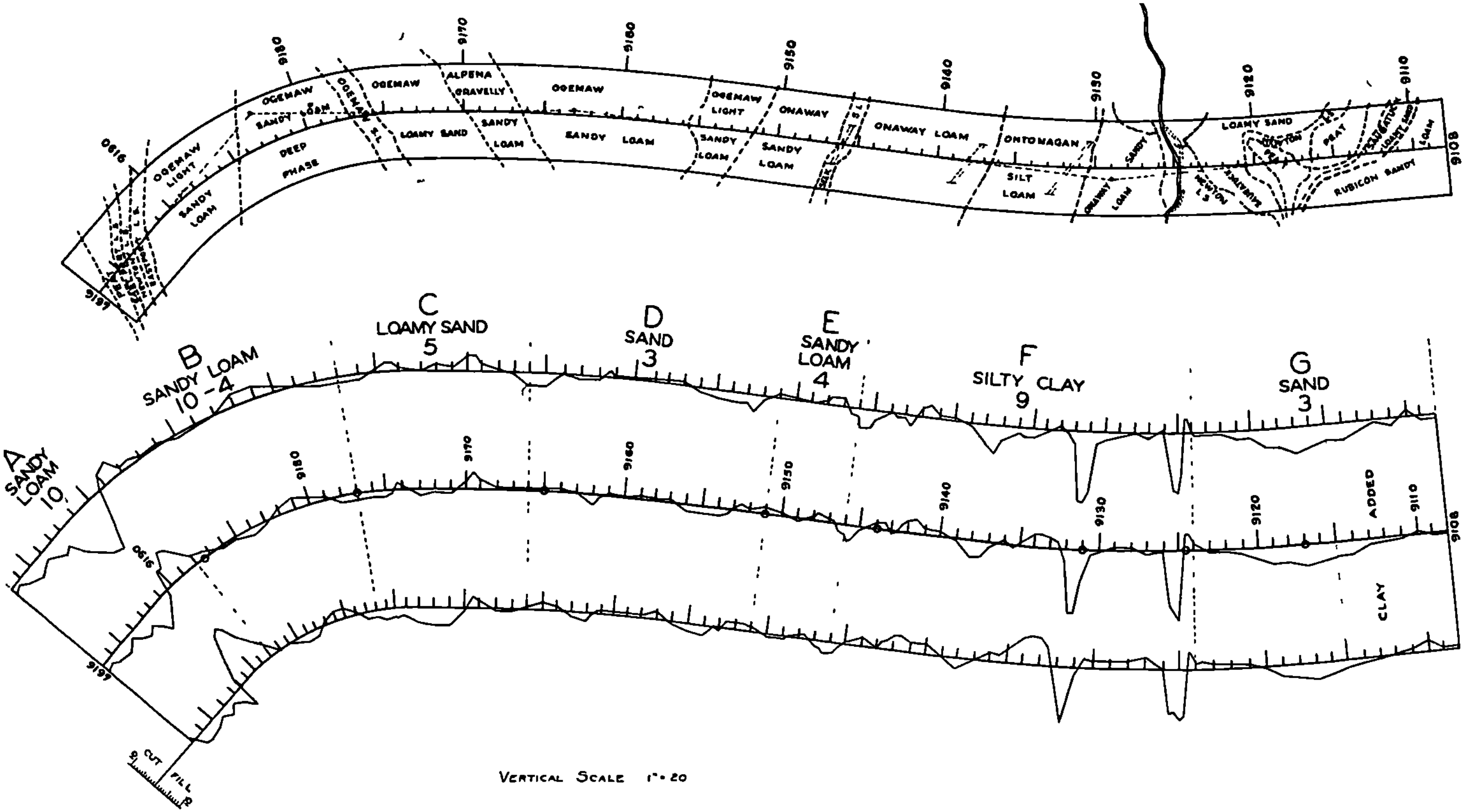
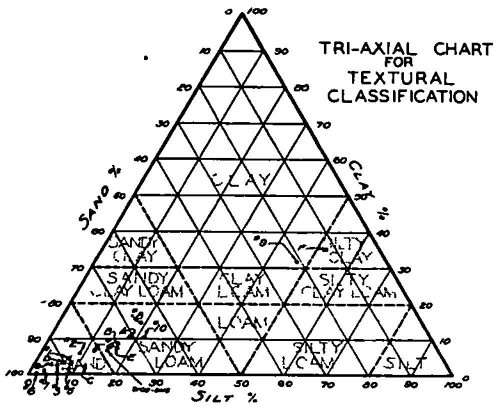


Figure 1. Soil classification from preliminary survey and grading operations



MECHANICAL ANALYSIS - PER CENT

		#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Gravel		21 0	13 5	7 0	8 0	19 5	1 0	1 0	17 0	0 0	7 0
Fine Gravel		4 2	2 8	3 4	3 0	9 4	3 0	3 0	10 0	0 1	3 0
Coarse Sand		9 9	7 0	7 4	14 2	23 7	12 2	8 5	6 0	1 2	4 4
Medium Sand		22 3	20 9	22 2	30 0	29 3	40 5	40 5	17 0	2 5	19 6
Fine Sand		28 2	34 8	49 2	21 2	5 6	37 5	38 0	16 0	5 0	22 5
Very Fine Sand		5 2	6 5	3 8	6 1	3 3	4 0	4 7	6 0	11 9	13 5
Silt		5 8	7 5	5 0	11 5	6 5	1 5	3 3	16 0	47 3	20 4
Clay		3 4	5 0	2 0	6 0	2 7	0 3	1 0	12 0	32 0	9 6
Adjusted Soil Mortar Percentage	Sand	88 4	85 2	92 5	81 0	88 5	98 2	95 7	66 2	20 7	67 7
	Silt	7 3	8 9	5 4	12 5	8 1	1 5	3 3	19 3	47 3	22 0
	Clay	4 3	5 9	2 1	6 5	3 4	0 3	1 0	14 5	32 0	10 3

Figure 3

The soil profile is still Ogemaw with one fairly heavy cut of sufficient magnitude to supply from the deeper clay horizon a considerable amount of soil fines for combination with the sand of the upper horizon

In Section C between Sta 9177 and Sta 9166 there is one cut through an Alpena profile in which the parent material is described as coarse sand or gravel, being a beach ridge of an extinct glacial lake This material is scattered over the adjacent Ogemaw profile and the resulting soil in finished grade is classified as loamy sand with a mechanical analysis of 86 per cent sand, 12 per cent silt, and 2 per cent clay which may be compared to Laboratory Sample No 5.

From Sta 9166 to Sta 9151, the grade is laid in the sand horizon of the Ogemaw profile and there is very little cut and fill The soil in the finished grade is described as sand with a mechanical analysis of 90 per cent sand, 6 5 per cent silt, and 3 5 per cent clay, very close to the No 3 sample used in laboratory tests

TABLE 1

Classification of Soil Textures

Section	Station Numbers	Soil Texture (Field)			Laboratory Sample Number	Texture
		Sand	Silt	Clay		
A	9197 to 9188	71 1	17 8	11 1	10	Sandy loam
B	9188 to 9177	76 1	17 3	7 6	10-4	Sandy loam
C	9177 to 9166	86 0	12 0	2 0	5	Loamy sand
D	9166 to 9151	89 9	6 6	3 5	3	Sand
E	9151 to 9146	75 4	17 4	7 2	4	Sandy loam
F	9146 to 9124	11 5	51 5	37 0	9	Clay
G	9124 to 9108	92 6	4 1	3 3	3	Sand
15% Clay Added	9155 to 9108	78 4	14 4	7 2	4	Sandy loam

depth of cut it can be determined reasonably well whether or not any substantial amount of soil from the deeper horizons has been brought up and mixed with surface layers in the finished grade A detailed description of soils in the finished grade will be attempted on this basis

Before discussing the grading operation, however, it appears desirable to present the data in Figure 3 which gives the mechanical analysis of ten preliminary samples taken from the finished grade These ten samples were taken by the project engineer without reference to the original soil survey and represented his attempt to distinguish by visual inspection the different types of soil in the finished grade As later analysis reveals, four types would have been sufficient for preliminary tests, but as a matter of fact complete laboratory tests were made on all ten It is believed that the later analysis also shows that an intelligent correlation of the soil survey and grading operation would have established that four different textural classes were sufficient to establish an adequate design of the soil-cement mixture

In Figure 3 the ten soils have been classified on the basis of the texture of the soil mortar or material passing the No 10 sieve The results are plotted on a triaxial chart with the textural classes used by Eno [2] From this triaxial chart four types of soil may be selected and these will be referred to in subsequent discussion as sand, loamy sand, sandy loam, and clay

The sand includes Samples 3, 6, and 7.

The loamy sand includes Samples 1, 2, 4, and 5.

The sandy loam includes Samples 8 and 10

The clay is Sample 9

During construction, check samples were taken of the soil at frequent intervals in each section and sent to the laboratory for mechanical analysis These data are shown in Table 1 which gives the percentage of sand, silt and clay in composite analyses between the stations selected as nearly as possible to coincide with balance points These data have been plotted with the ten original samples shown in Figure 3 and a notation shown in Figure 1 gives the original sample number which is most representative It will be noted that of the original ten samples used in laboratory tests only five were shown in the final classification, namely, 3, 4, 5, 9, and 10 These samples, however, may be represented by the four textures used in the final classification, i e, sand, loamy sand, sandy loam, and clay

As the first step in construction, it is required that the organic material, black muck and leaf mold, be stripped and wasted Starting at the left-hand end of the stabilized section, at Sta 9197 to the balance point near Sta 9188, marked Section A, the soil in the finished grade is described as sandy loam This includes a fairly heavy cut and fill in the Ogemaw profile of two or three feet of loamy sand over clay, the clay containing some sand and gravel The mixture produced a sandy loam with 71 per cent sand, 18 per cent silt and 11 per cent clay, which is fairly well represented by Sample No 10 on Figure 3 with 68 per cent sand, 22 per cent silt, and 10 per cent clay For Section B between balance points at Sta 9188 and Sta 9177 the check samples showed 76 per cent sand, 17 per cent silt and 8 per cent clay, which is a sandy loam and may be compared to Laboratory Sample No 4 with 81 per cent sand, 13 5 per cent silt, and 6 5 per cent clay, although it is more accurately described as intermediate between Laboratory Samples 10 and 4

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[2] "Some Effects of Soil, Water, and Climate Upon the Construction, Life and Maintenance of Highways"—Eng Exp Station, Bulletin No 85, Ohio State University

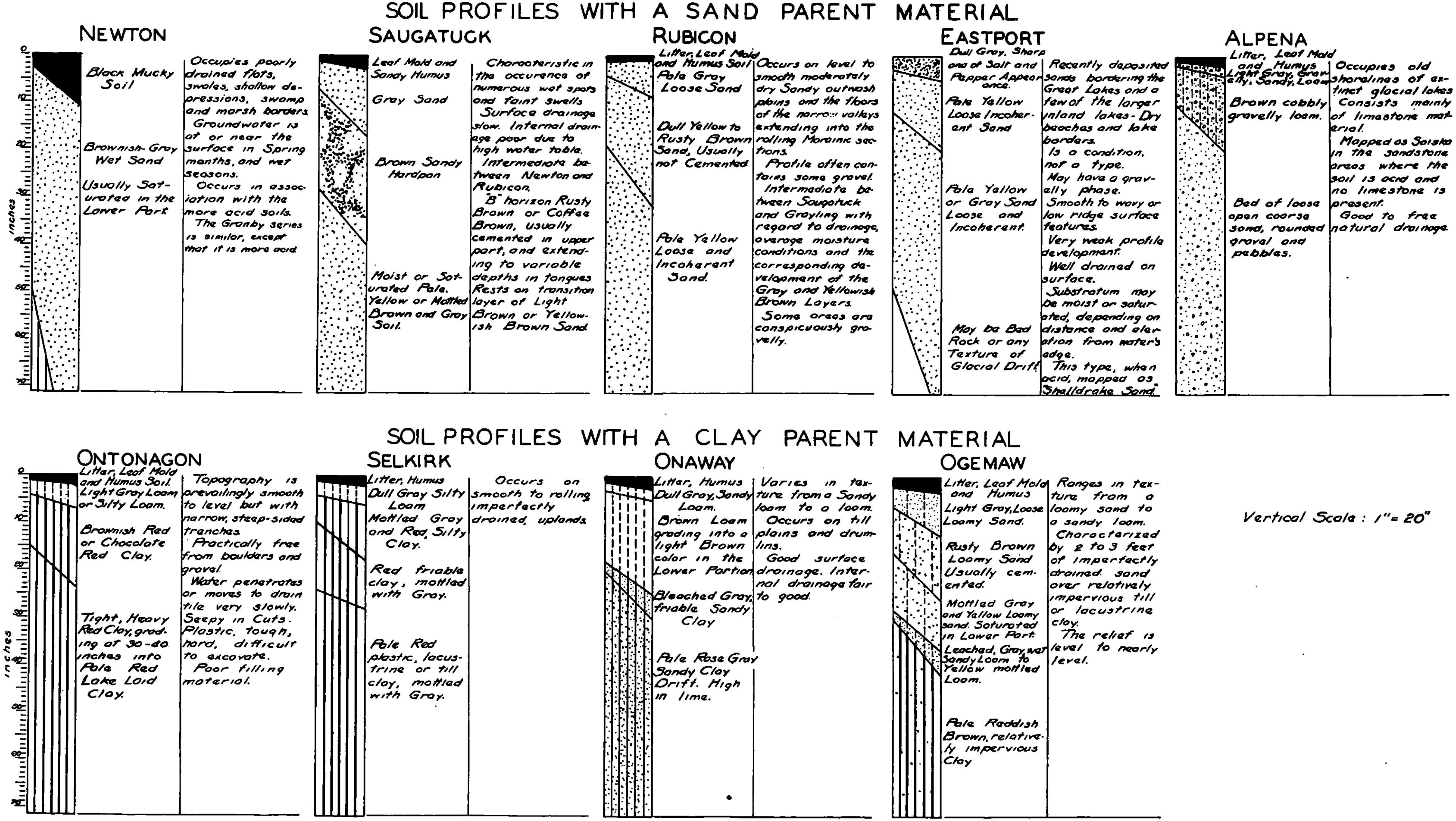

Figure 2. Soil series mapped on Cheboygan County Cement Stabilization Project

The short Section E between Sta 9151 and Sta 9146 is in the Onaway profile of a sandy clay parent material The mechanical analysis of the grade sample shows 75 per cent sand, 17 per cent silt, and 7 per cent clay, which is a sandy loam very similar to that in Section B and comparable to Laboratory Sample No 4 This texture is in substantial agreement with the upper horizon of the Onaway profile although the sand appears to be somewhat high

Section F from Sta 9146 to Sta 9124 is the clay section left unstabilized The grading is fairly deep sidehill cut through the Onaway and Ontonagon profiles with clay parent material The mechanical analysis from the check samples shows 12 per cent sand, 52 per cent silt, and 37 per cent clay, classified as silty clay, and is fairly close to Laboratory Sample No 9

Section G from Sta 9124 to Sta 9108 is through several low-lying profiles of Newton, Saugatuck and Rubicon, all of which are from sand parent materials There is considerable waste including peat excavation and, as most of the section is in fill, material has been borrowed from an adjacent Rubicon area to supplement the excavation from roadside ditches The resulting soil is classified as sand and the grade samples are 93 per cent sand, 4 per cent silt, and 3 per cent clay giving a texture very close to Laboratory Sample No 3 Some difficulty was encountered in stabilizing this section and 15 per cent clay by weight was added in the section from Sta 9115 to Sta 9108 This changed the texture to a sandy loam with 78 5 per cent sand, 14 5 per cent silt, and 7 per cent clay which is fairly close to Laboratory Sample No 4 The addition of clay assisted the stabilization process very materially and was adopted as a tentative procedure for future work with sands of the character here encountered

LABORATORY INVESTIGATION

Purpose of Laboratory Tests

It appears from the preceding discussion that the determination of prevailing soil types or series combined with a consideration of grading operations constitutes a practical basis of soil classification for the purpose of designing the stabilized mixture Even though the final classification of these soils into four groups has been made only after a review and correlation of all available data, the same result could have been accomplished by a careful study of the soil series profiles. Although the submission of an excessive number of samples to the laboratory led to some unnecessary duplication of work which should be eliminated in regular construction procedure, this very duplication provided a rather desirable feature for an experimental project

The primary objective of the laboratory tests was to determine the proper proportions of soil, cement, and water to facilitate compaction and produce a durable stabilized mixture The tests indicated that this purpose would have been served by a few representative samples It might also appear that the results of such tests on samples taken at frequent intervals along the grade would serve as the basis for controlling construction procedure

A comparison of results produced in the field operation with the results of laboratory tests on this project, indicate that the laboratory tests are inadequate as control tests except to determine the quantity of cement which would produce durable stabilization While the preliminary tests did serve this purpose and were useful in the soil classification, they did not reflect changes in gradation and void characteristics from station to station with sufficient accuracy to serve as control tests for construction operations After some experience with control tests in the field, laboratory tests were abandoned as a measure of the proper amount of compaction or optimum moisture content It was found that one experienced operator with an occasional helper could run the density-moisture tests for each day's work without holding up the construction and could control the stabilization procedure much more effectively

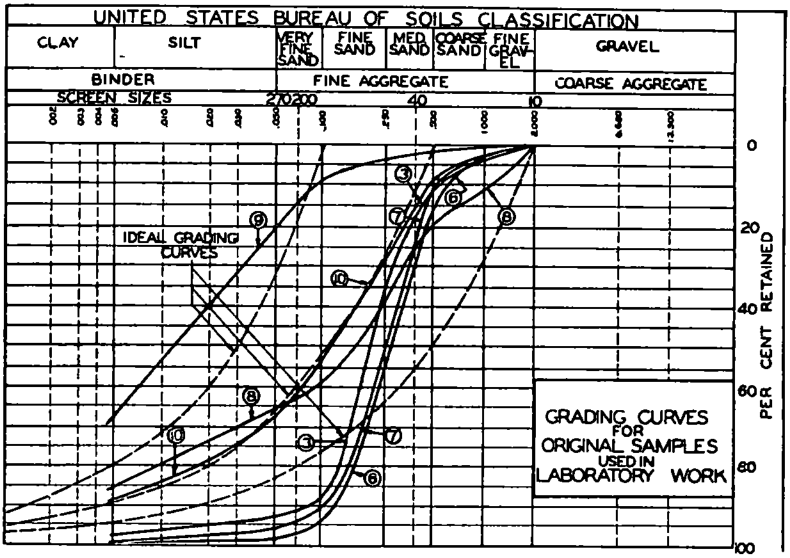

Figure 4

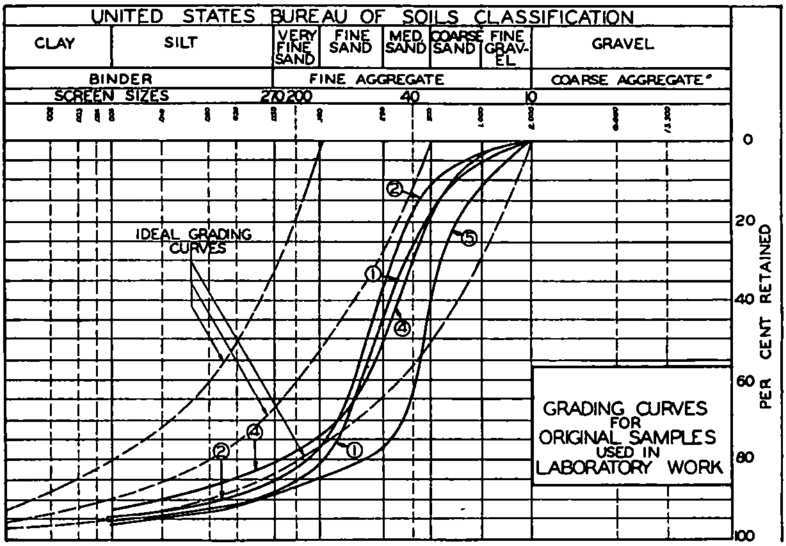

Figure 5

The laboratory investigation was conducted and practically completed before the field work could be undertaken In addition to the tests of the department, the Portland Cement Association conducted a parallel series which were the basis for their recommendations The results of tests in the two laboratories were in substantial agreement, although methods used varied in some respects This discussion will be limited to those tests conducted by the department on the ten laboratory samples previously identified

Gradation and Maximum Density

The mechanical analyses of all samples are shown in Figure 3 The material passing the No 10 sieve, soil mortar, was used in subsequent laboratory tests The gradings of the soil mortar in the various samples are shown on Figures 4 and 5 The distribution of particle size as shown by the conventional method of plotting, shows some characteristics not evident in the textures plotted on the triaxial chart, which show a definite relation to densities obtained in compaction tests The heavy dashed curves in Figures 4 and 5 represent so-called ideal gradings for maximum density for any given maximum size

In Figure 4 are shown gradings for the sand, Samples 3, 6, and 7, the sandy loam, Samples 8 and 10, and the clay, Sample 9 Samples 3, 6, and 7 are the most poorly graded and, as will be seen later, give the lowest compacted densities The clay, Sample 9, is also a poorly graded material, though not so much so as the sands, a fact which is also reflected in a higher compacted density Samples 8 and 10, the sandy loams, are the best graded materials encountered, Sample 10 being particularly close to the ideal curve for a maximum size of 0 5 mm In Figure 5 are shown the gradings of the loamy sands, Samples 1, 2, 4, and 5 Their grading is somewhat better than the sands and poorer than the sandy loams, as might be expected with an intermediate percentage of soil fines, but they do depart substantially from the ideal gradings The addition of soil fines would be a substantial improvement, but all of these materials compacted fairly well and resulted in satisfactory stabilized mixtures

The void characteristics of the ten samples and the grouping into four textures is clearly shown by the compacted densities in Figure 6 The moisture-density relations which show the optimum moisture content and maximum density were obtained by compacting the soil using the procedure developed by the California State Highway Department and described by Proctor The compacted dry densities of the sands vary from 107 2 to 109 lb per cu ft with an average of approximately 108 The loamy sands varied from 115 3 to 116.2

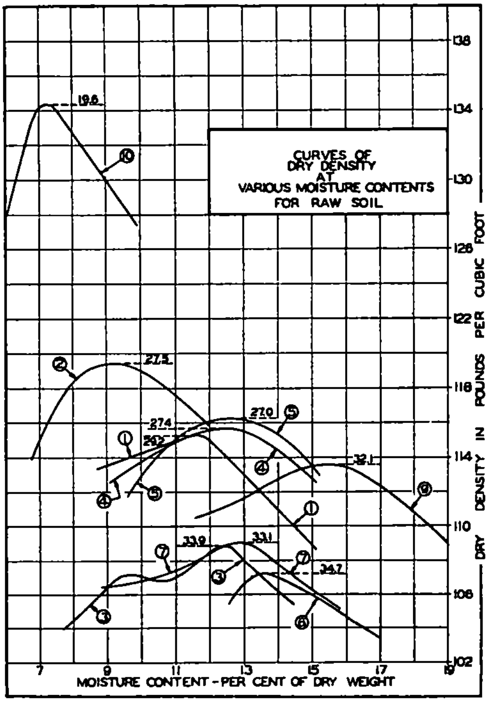

Figure 6

with the exception of Sample 2 which compacted to 119 4 lb per cu ft The sandy loam, Sample 10, gave a dry density of 134 4 lb per cu ft , the highest of any sample No tests were made on Sample 8 which was discarded as a separate classification before the laboratory investigation was started The percentage of total voids in the compacted soil is shown in connection with each curve and will be referred to later

The consistent relation between density and mechanical analysis expressed either in terms of texture or by the grading curves is the most striking feature of the data The variation in density can be predicted from the comparison between the ideal gradings and the actual grading in every case except Sample 2 Sample 2 has a percentage of voids comparable to the other loamy sands but due to a higher specific gravity, 2 64 as compared to 2 55–2 61 for the others of the group, the dry density is higher The optimum moisture content is also lower indicating less absorption which is also consistent with the higher value of specific gravity The consistent relations shown furnish a reliable basis for the grouping of the ten samples into four texture groups previously discussed

It also appears that variation in texture and grading is so accurately reflected in the compacted density that the routine density tests may be the most practical basis of designing the stabilized mixture A further fundamental advantage of the test which measures compacted density is that it directly measures the total voids which later serve as the basis for determining the required cement content

Void Characteristics of Soil-Cement Mixtures

The next step in the laboratory investigation was to compact mixtures of soil and cement using various percentages of cement in order to determine the characteristics of each mixture and to prepare samples for durability tests The mixtures were proportioned by absolute volume, the cement content being expressed as a percentage of the absolute volume of soil plus cement The moisture content was expressed as a percentage of the dry weight of the soil and cement Cement contents of 4, 6, 8, and 10 per cent were used in the preliminary tests The following example illustrates the method of proportioning the trial mixtures

Let s = absolute volume of soil
" c = " " " cement
" v = " " " voids

$$\text{Cement Content} = \frac{c}{s + c}$$

Assume 6% cement content
4000 grams oven dry soil
2 62 specific gravity of soil
3 15 " " " cement

$$s = \frac{4000}{2\ 62} = 1527 \text{ cc} = 94\% \text{ of } s + c$$

$$\frac{1527}{94} = \frac{c}{06}$$

$$c = 97\ 4 \text{ cc}$$

$$97\ 4 \times 3\ 15 = 307 \text{ g cement}$$

Assume 10% water (Per cent dry weight soil and cement)

$$\text{Water} = 10 \times 4307 = 430\ 7 \text{ g of water}$$

$$" \quad = \frac{430\ 7}{4737\ 7} = 9\ 1\% \text{ (Wet Basis)}$$

Mixtures using the same cement content and various moisture contents were compacted in cylindrical molds 4 in in diameter and 6½ in high The compacted sample was weighed and, knowing the volume of the mold, the dry weight per cubic foot or dry density was computed The percentage of voids in the mixture and the total voids in the compacted soil, excluding the cement, were also computed and are used in later analyses The following example is given for illustration.

Weight of compacted mixture = 2050 g
Moisture 091 × 2050 = 227 5 g

Dry soil and cement = 1822 5 g
Volume of mold 1027 9 cc

$$\text{Dry bulk specific gravity} = \frac{1822\ 5}{1027\ 9} = 1\ 775$$

Density = 1 775 × 62 4 = 110 5 lb per cu ft

The voids in the soil-cement mixture may be computed by finding the specific gravity of combined solids which is the weighted average of the specific gravities of the soil and cement as follows

$$2\ 65 \times 94 = 2\ 49$$
$$3\ 15 \times 06 = 19$$
$$2\ 68 \text{ Sp gr combined solids}$$
$$\frac{2\ 68 - 1\ 775}{2\ 68} = 338 \text{ Voids in mixture}$$
$$s + c + v = 1$$
$$s + c = 1 - 338 = 662 \qquad 66\ 2\% \text{ solids}$$
$$s = 94 \times 662 = 622 \qquad 62\ 2\% \text{ soil}$$
$$c = 06 \times 662 = 040 \qquad 4\ 0\% \text{ cement}$$

The total voids in the compacted soil without cement is the sum of voids in the mixture and the absolute volume of cement If the cement-voids ratio is defined as the ratio of absolute volume of cement to the absolute volume of voids it may be computed as follows

$$\text{Total voids } v = 33\ 8 + 4\ 0 = 37\ 8\%$$
$$\text{Cement-voids ratio } \frac{c}{v} = \frac{4}{37\ 8} = 10\ 6\%$$

The void characteristics of typical compacted mixtures are shown in Figure 7 where the moisture density curves are given for a sand, Sample 3, a loamy sand, Sample 1, and the sandy loam, Sample 10 Sample 9, the silty clay, has been omitted as the clay section was not stabilized and no comparative field results are available. The laboratory density curves for the clay were more erratic than for the other samples, due to greater difficulty in obtaining uniform compaction by hand tamping.

In all cases the total voids in the soil skeleton were increased by the addition of cement but in the case of sands and loamy sands this trend was much less than for the finer grained soils. In other words, the cement helped to fill voids as well as to supply cohesion. In the sandy loam, No. 10, the density decreases as the cement content increases and there is a marked increase in total voids over the raw soil This tendency was also noted in the silty clay, No 9.

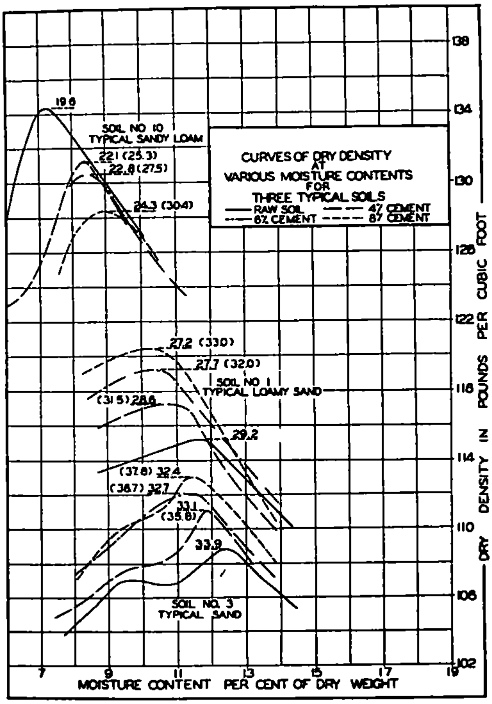

Figure 7

In these finer grained soils the cement apparently forms an expanded structure or results in a bulking effect that produces a decreased density In Figure 7 the percentage of voids in the soil-cement mixtures at maximum density has been indicated and in parentheses the total voids in the mixture, exclusive of the cement, have been shown. The increase in total voids due to bulking action of the cement must be considered in computing the cement-voids ratio and enters into the preliminary design of the mixture

The objective of the analysis of the void characteristics of the soil-cement mixtures is to obtain some practical criterion for design which will accurately reflect the properties of the stabilized mixture, particularly with respect to durability. Throughout the investigation it became increasingly apparent that the behavior of the mixture must be associated in some way with voids and that the efficiency of cement stabilization depends in some way on a relation between voids and cement This is no new idea having been employed as the basis of concrete proportioning theories It may not be too much to say that void characteristics constitute the fundamental conception applicable to any type of mixture and thus offer an obvious line of attack on any such problem

Durability Tests

Two types of durability tests were conducted following the recommendations and general procedure developed by the Portland Cement Association Specimens in the form of 4 by 6½ in cylinders were compacted at optimum moisture content for the various percentages of cement These cylinders were then subjected to cycles of freezing and thawing, and wetting and drying and were brushed and weighed after each cycle

The results are presented graphically in Figures 8 and 9 In each case the loss after 24 cycles has been plotted against the cement-voids ratio The data used in the computation of the cement-voids ratio are given in Table 2 The specimens subjected to durability tests are identified by soil sample number and cement content The specific gravity of the soil was measured by the standard test and the specific gravity of the mixture was computed using the determined value of 3 15 as the specific gravity of the cement The dry density in pounds per cubic foot was determined for each specimen and the total voids in the soil skeleton, the absolute volume of cement per unit volume of compacted mixture, and the cement-voids ratio were all computed as in the example given previously It will be noted that the dry density did not agree exactly with the density at optimum moisture content given in Figure 7 It was impossible to duplicate the maximum density in every specimen, but on the average the agreement is good The results of the durability tests have in every case been correlated with the actual cement-voids ratio of each sample

The comparison between cement-voids ratio and percentage of loss at 24 cycles of freezing and thawing in Figure 8 indicates a definite relationship All but three samples showed a 100 per cent loss or complete failure for a cement-voids ratio of less than 12 per cent All samples with cement-void ratios greater than 12 per cent show a loss of 10 per cent or less with the exception of the specimen containing the No 5 soil with 6 per cent cement, which showed a 50 per cent loss at 24 cycles and failed completely at 28 cycles The various specimens are identified at the bottom of the graph by sample number and cement content

In Figure 9 the results of the wetting and drying cycles have been plotted in exactly the same manner as in Figure 8 The durability of the various specimens also shows a very close relationship between loss and the cement-voids ratio The wetting and drying tests, while not so severe as the freezing and thawing cycles, showed frequent failures for cement-voids ratios less than 12 per cent

It is dangerous to draw sweeping conclusions from only one set of data but until an analysis of a large volume of such information is available it seems proper to discuss tentative conclusions which may serve as temporary criteria To this extent the data indicate that a cement-voids ratio of 15 per cent may produce a mixture as durable as present requirements indicate is essential

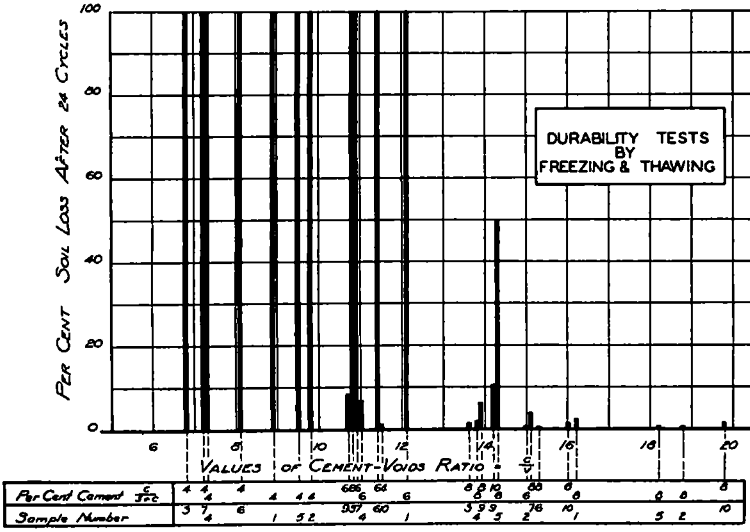

Figure 8

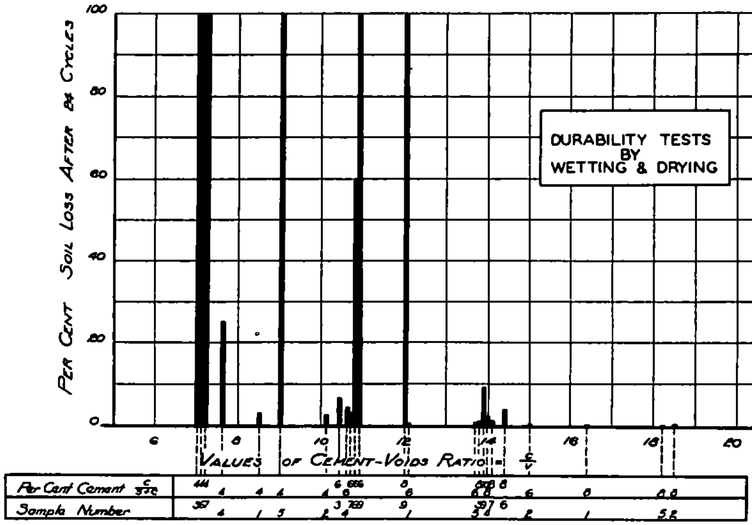

Figure 9

The manner in which the cement acts as a binding medium in a soil-cement mixture with comparatively small cement contents is a matter of speculation The character of the mixture is obviously quite different from mortar in concrete mixtures where the voids in the aggregate are filled with cement paste. The picture which the writer has in mind is a granular soil structure with little more than enough cement paste to join the particles at their points of contact The soil structure is spot-welded, so to speak.

It appears that such a conception is in agreement with the comparatively small cement-voids ratios in which only 15 per cent of the total voids are filled

The data presented in Table 2 and Figures 8 and 9 are all taken from the original laboratory tests The comparison of these data with experience in the field and the success of field control is a matter of great practical importance and

TABLE 2

CEMENT-VOIDS RATIOS FOR LABORATORY DURABILITY TESTS

Laboratory Sample Number	Cement Content $\frac{s}{s+c}$	Specific Gravity		Freezing and Thawing				Wetting and Drying			
		Soil	Mix	Density of Mix Dry	Absolute Volume Cement c	Absolute Volume Total Voids v	Cement-Voids Ratio $\frac{c}{v}$	Dry Density of Mix	Absolute Volume Cement c	Absolute Volume Total Voids v	Cement-Voids Ratio $\frac{c}{v}$
	per cent			*lb per cu ft*	*per cent*	*per cent*	*per cent*	*lb per cu ft*	*per cent*	*per cent*	*per cent*
1	4	2 61	2 63	116 5	2 84	31 8	8 9	114 7	2 80	32 9	8 5
	6	"	2 64	114 8	4 18	34 5	12 1	114 9	4 18	34 5	12 1
	8	"	2 65	117 1	5 66	34 9	16 2	117 6	5 69	34 6	16 4
2	4	2 64	2 66	121 4	2 92	29 8	9 8	122 3	2 95	29 2	10 1
	6	"	2 67	124 3	4 48	29 9	15 0	124 3	4 48	29 9	15 0
	8	"	2 68	124 3	5 94	31 6	18 0	123 8	5 92	31 9	18 5
3	4	2 64	2 66	107 5	2 59	37 9	6 8	109 2	2 63	36 8	7 1
	6	"	2 67	111 3	4 01	37 2	10 8	110 0	3 96	38 0	10 4
	8	"	2 68	111 0	5 31	38 9	13 6	111 3	5 33	38 7	13 8
4	4	2 55	2 57	106 3	2 66	36 3	7 3	107 7	2 69	35 5	7 6
	6	"	2 59	108 8	4 04	36 7	11 0	107 5	3 99	37 5	10 6
	8	"	2 60	108 3	5 34	38 6	13 8	108 9	5 37	38 3	14 0
5	4	2 55	2 57	116 0	2 90	30 5	9 5	114 2	2 85	31 6	9 0
	6	"	2 59	118 8	4 41	30 9	14 3	117 5	4 36	31 7	13 7
	8	"	2 60	119 2	5 88	32 4	18 2	119 2	5 88	32 4	18 2
6	4	2 63	2 65	113 8	2 75	34 0	8 1	108 7	2 63	36 9	7 1
	6	"	2 66	113 8	4 11	35 6	11 5	111 0	4 01	37 1	10 8
	8	"	2 67	115 4	5 54	36 2	15 3	112 9	5 42	37 6	14 4
7	4	2 61	2 63	108 4	2 64	36 6	7 2	108 5	2 64	36 6	7 2
	6	"	2 64	110 7	4 03	36 9	11 0	110 0	4 01	37 2	10 8
	8	"	2 65	114 2	5 52	36 5	15 1	111 2	5 38	38 1	14 1
9	6	2 68	2 71	113 0	4 01	37 1	10 8	113 0	4 01	37 1	10 8
	8	"	2 72	113 5	5 35	38 5	13 9	107 0	5 05	41 8	12 1
	10	"	2 73	106 0	6 23	43 9	14 2	105 2	6 18	44 4	13 9
10A	4	2 68	2 70	129 0	3 06	26 6	11 5	128 2	3 04	26 9	11 3
	6	"	2 71	128 7	4 57	28 5	16 0	127 7	4 53	29 0	15 7
	8	"	2 72	128 2	6 04	30 5	19 8	127 2	6 00	31 0	19 3

will be the next subject of discussion While the more exact control in the laboratory may produce a more accurate measure of the characteristics of the soil-cement mixtures, the practical application of the criteria thus developed will depend very largely on the accuracy of field control.

FIELD CONTROL TESTS

After having selected the cement content, the control of the mixing and compaction procedure was the major problem in field control On the Cheboygan project a house trailer was equipped to serve as a field laboratory for control tests The moisture content of the soil was measured before adding the cement and was also determined on the soil-cement mixture at intervals during the mixing operation Moisture was added when required to bring the mix up to the optimum moisture content

The amount of soil in the mix was controlled by loose volume measurements of the scarified soil and by regulating the depth of scarification to produce the required dry weight of soil. The proper proportion of soil for the compacted mix was first determined from the preliminary laboratory tests already described, but it was found that variations in the soil from station to station were sufficient to necessitate compaction tests to determine optimum moisture content and maximum density for each day's work. Representative samples of the raw soil were collected from the section to be processed on the following day and the moisture-density tests run on the mixture of soil and cement The optimum moisture content and maximum density from these tests were substituted for results derived from previous laboratory tests

After the proper depth of soil had been scarified and the required amount of cement and water added and mixed, a compaction test was also made of the final mixture The density obtained was a measure of the accuracy of the proportioning and mixing and the most reliable basis of checking the degree of consolidation by sheep's foot rollers and other compacting equipment After a section had been stabilized, densities in the road were measured by boring holes in the stabilized surface, measuring the depth and volume of the hole, and weighing the material removed Samples of the soil-cement mixture were also collected and sent to the laboratory to determine the actual cement content These data for the various sections are presented in Tables 3, 4, and 5

Table 3 gives the theoretical proportions in the field, assuming that the mixture contained the selected amount of cement The computations are based on the compaction of the final mixture by hand tamping in the standard cylinder which resulted in the dry density in pounds per cubic foot given in column 7. The theoretical cement content is given in column 3 as a percentage of loose volume of cement per cubic foot of compacted mix, assuming the weight of cement as 94 lb per cu ft, loose volume This gives an arbitrary cement content, shown in column 5, amounting to 7 52 or 8 46 lb per cu ft of compacted mix for 8 or 9 per cent of the loose volume of cement, respectively These cement contents have been related to the actual mix in column 4 which gives the cement content as a percentage by weight of the dry mix. The dry weight of soil per cubic foot of compacted mix is given in column 6. The dry weight of soil and cement can be reduced directly to their absolute volumes by dividing by the product of the specific gravity times 62 4, and are given in columns 8 and 9 as a percentage of the unit volume made up of soil, cement, and voids The cement-voids ratio is given in column 9

It may be noted that the cement-voids ratio provided for in the design is less than 15 per cent in all cases, ranging from a low of 11 per cent to a high of 13 per cent In the light of final results of the durability tests there appears to be good reason to question the proportions used as being somewhat lower than desirable It may also be pointed out that the computations are based on the average dry density over a number of stations and, as shown in Table 5, the density range in individual cases may vary approximately 5 lb per cu ft above or below the average. The cement-voids ratio would also show a larger variation than given in Table 3 as the void space in the soil structure is increased or decreased

TABLE 3

Theoretical Proportions of Field Mixture

Section	Station Numbers	Cement Content Per Cent		Field Mixture Compacted in Cylinder					
				Proportions by Dry Weight			Absolute Volume in Per Cent		
				Lb per Cu Ft					
		Loose Volume (P C A)	Dry Mix	Cement	Soil	Mix	$\frac{s}{s+c+v}$	$\frac{c}{s+c+v}$	$\frac{c}{v}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
A	9197 to 9188	8	6 20	7 52	113 7	121 2	68 9	3 83	12 3
B	9188 to 9177	8	6 15	7 52	114 6	122 1	69 5	3 83	12 6
C	9177 to 9166	8	6 12	7 52	115 3	122 8	70 0	3 83	12 8
D	9166 to 9151	8	6 54	7 52	107 5	115 0	65 2	3 83	11 0
E	9151 to 9146	9	7 12	8 46	110 3	118 8	66 9	4 31	13 0
F	9146 to 9124	—	—	—	—	—	—	—	—
G	9124 to 9108	9	7 54	8 46	103 7	112 2	62 6	4 31	11 5
15% Clay Added	9115 to 9108	8	6 52	7 52	107 6	115 1	65 3	3 83	11 0

Columns 7–8 $s + c + v = 1$ $\frac{s}{s + c + v} = s$ and $\frac{c}{s + c + v} = c$

Column 10 $\frac{c}{v} = \frac{c}{1 - s}$ Theoretical cement-voids ratio

In Table 4 are shown the actual proportions of the soil-cement mixture computed in the same way as in Table 3 except that the cement contents are determined by laboratory analysis of the mixture Samples of the raw soil and cement were taken at identical stations from which samples of the soil-cement mixture were later obtained The laboratory made a determination of the calcium oxide (CaO) in the mixture and in the soil and cement samples and calculated the cement content from these proportions A comparison of the cement content in percentage of the dry mix in Tables 3 and 4 shows that the actual cement content is considerably higher than the theoretical The theoretical values vary from 6 12 to 7 54 per cent while actual values vary from 6 42 to 10 53 per cent The actual cement-voids ratios vary from 13 1 to 15 5 as compared to a range of 11 0 to 13 0 in Table 3

While the higher values of cement-voids ratio actually obtained compare more favorably with the 15 per cent apparently required by the durability tests, they also show a failure to obtain a thorough mixture for the full depth supposed to be stabilized It was observed in the field that it was difficult to obtain the full depth of scarification required with the equipment used It was also difficult to mix for the full depth of the loose soil It is entirely probable under these conditions that either the amount of soil stabilized is less than intended or that cement contents are high in the surface and low at the bottom of the stabilized layer In any event, the high cement contents indicate poor control to some extent and a deficiency either in thickness of stabilized base or uniformity of stabilization, both of which are detrimental

TABLE 4

Actual Proportions of Field Mixture

Section	Station Numbers	Cement Content Per Cent	Field Mixture Compacted in Cylinder						
			Proportions Dry Weight in lb per cu ft			Absolute Volumes in Per Cent			
		Dry Mix	Cement	Soil	Mix	Soil s $\frac{s}{s+c+v}$	Cement c $\frac{c}{s+c+v}$	Total Voids 1 − s	$\frac{c}{v}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
A	9197 to 9188	6 42	7 8	113 4	121 2	68 7	3 97	31 3	12 7
B	9188 to 9177	7 90	9 6	112 5	122 1	68 0	4 89	32 0	15 3
C	9177 to 9166	7 80	9 6	113 2	122 8	68 5	4 89	31 5	15 5
D	9166 to 9151	8 02	9 2	106 8	115 0	64 5	4 68	35 5	13 2
E	9151 to 9146	8 20	9 7	109 1	118 8	66 0	4 94	34 0	14 5
F	9146 to 9124	—	—	—	—	—	—	—	—
G	9124 to 9108	10 53	11 8	100 4	112 2	60 7	6 00	39 0	15 3
15% Clay Added	9115 to 9108	8 11	9 3	105 8	115 1	64 0	4 73	36 0	13 1

Columns 7-8 $s + c + v = 1 \quad \frac{s}{s + c + v} = s$ and $\frac{c}{s + c + v} = c$

Column 10 $\frac{c}{v} = \frac{c}{1 - s}$ Actual cement-voids ratio

Table 5 is a comparison of densities of the stabilized mixture measured in three different ways for comparison The first three columns identify the section and type of soil Column 4 gives the actual cement content in per cent of the absolute volume of soil and cement which is the basis of proportioning the laboratory mixes. Column 5 gives dry densities obtained in the laboratory as shown in Figure 7, the values given, however, having been interpolated from these curves for the actual cement content given in column 4 The densities obtained by compacting the final mixture in the standard cylinders are given in columns 6, 7, and 8, being the maximum and minimum values obtained at any station in each section and the average for the whole section Columns 9, 10, and 11 give similar figures for samples taken from the road surface after compaction In the writer's opinion the figures indicate that the preliminary laboratory tests on random samples are not adequate for field control although the comparison is fairly good in some cases The difficulty is, however, in obtaining representative samples rather than in the technique of the control tests or method of design

TABLE 5

Density of Field Mixture

Section	Station Numbers	Laboratory Sample Number	Cement Content Per Cent	Dry Density of Field Mixture						
					Lb per cu ft —Compacted					
			$\frac{c}{s+c}$	Laboratory Test*	Compacted in Cylinder			Sample from Road		
					Max	Min	Ave	Max	Min	Ave
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
A	9197 to 9188	10	5 50	130 7	123 5	118 0	121 2	127 7	122 0	123 9
B	9188 to 9177	10-4	6 74	123 7	124 5	118 8	122 1	128 8	110 0	120 6
C	9177 to 9166	5	6 68	121 5	126 2	121 0	122 8	—	—	—
D	9166 to 9151	3	6 80	112 5	118 5	107 0	115 0	123 7	104 0	115 6
E	9151 to 9146	4	6 92	117 9	121 5	116 0	118 8	119 0	119 0	119 0
F	9146 to 9124	9	—	—	—	—	—	—	—	—
G	9124 to 9108	3	9 00	113 6	112 9	111 0	112 2	120 7	105 8	115 3
15% Clay Added	9115 to 9108	4	6 84	117 8	115 5	114 3	115 1	112 9	110 8	111 6

* Interpolated from laboratory curves

The samples compacted in the field agree much better with densities in the road and indicate that a rather close control may be obtained in this way. In one case, Section D, the individual maximum and minimum value shows much too wide a range but this was picked up in both the control test and final density in the road This indicates a radical change in soil type which does not fit the classification used for that particular section as a whole, again a question of representative sampling

There are several other observations which deserve comment before completing the discussion During construction some difficulty in stabilizing particular sections appeared to be due to high organic content or acidity Values of pH were determined for the soil in the various sections with ordinary indicator solutions According to these determinations the pH varied from 5 6 for some of the sands to 8 8 for the high lime content clay in Section F Most of the soils were slightly acid and the mixing water taken from small streams adjacent to the work was also questionable Tests conducted by the Portland Cement Association indicated a substantial reduction in compressive strength when using this mixing water and for the soil in question Further tests indicated that the addition of clay with a high lime content corrected the sandy soils Whether this improvement was due to supplying additional soil fines which were needed or to correcting the acidity was not clearly determined While the data are inconclusive, there is definite indication that hydrogen ion concentration or acidity is a factor which requires study in connection with soil stabilization in this particular region of highly podzolized soils

Mention should be made of one construction deficiency which, in the writer's opinion, was quite harmful to the finished surface Final rolling was done with an ordinary steam roller It appeared that those wheels which furnished traction caused horizontal displacement on the top inch or so of the mixture resulting immediately in characteristic cracking or in the formation of a plane of weakness which later caused flaking or breaking away of the top surface It appears that compaction of the mixture should be done with dead-weight rolling equipment which does not furnish traction or introduce horizontal shearing forces

Since completion of the project the road has been subjected to one year of weathering with practically no traffic This section of the Shore Line Highway has not been opened and only occasional vehicles going to isolated lake shore points use it Several inspections have been made and observation will be continued The condition of the road is variable, some sections being in satisfactory condition while others show signs of excessive scaling and disintegration. As yet there has been no attempt to correlate these conditions with the analysis given in this report but this will be done on subsequent observations

CONCLUSION

The experience on the Cheboygan cement stabilization project indicates some rather definite relations based on void characteristics of the soil which may be applied to the design of soil-cement mixtures The cement-voids ratio appears to be a controlling factor in producing a durable stabilized mixture There is need for a considerable amount of additional research in order to demonstrate more conclusively the fundamental relations involved and to improve control procedure under actual construction conditions Studies must be made of the physical chemistry of soils to determine the effect of chemical composition including such factors as hydrogen ion concentration

While a thorough investigation of soils to be stabilized should be made preliminary to actual construction, it appears to the writer that the present durability tests can scarcely be considered as feasible on regular construction projects and should be replaced as soon as possible by much shorter routine tests. Durability tests as used on this project should be regarded as research procedures and eliminated as soon as they have served their purpose and other reliable criteria are available The preliminary laboratory study of moisture-density relations requires much less time and might be supplemented by a compression test or something similar as routine procedure. In addition, it appears that the difficulty of representative sampling necessitates control of compaction by field control tests conducted in the field in conjunction with each day's work In this case the preliminary laboratory tests lose much of their value as control media and are useful only in preliminary design

While it is perhaps too early to eliminate the more elaborate laboratory investigations now being attempted, it appears that there is sufficient evidence to outline the following tentative procedure which gives promise of being adequate for field control

Preliminary to Construction

1 Mapping of soil series by preliminary survey
2 Classification of soils by correlation of soil survey and grading operations
3 Mechanical analysis of samples taken from finished grade at frequent intervals to supplement classification made from the soil survey
4 Preliminary determination of void characteristics of representative soils by moisture-density tests
5 Design of the soil-cement mixture by the cement-voids ratio, proportioning soil and cement by absolute volumes
6 Molding of cylinders for compressive strength tests or for durability tests as long as the latter are needed

During Construction

1 Tests on raw soil, measurement of moisture content and loose volume measurement of scarified soil to control depth of scarification
2 Tests on final soil-cement mixture, moisture determinations to control moisture content, compaction test of final mixture to check proportions and mixing, and for a control of compaction in the road Specimens should be preserved for compression test

In connection with the procedure preliminary to construction it may be pointed out that items 4, 5, and 6 may all be performed in the field if the design of the mixture could be standardized, as for example at a cement-voids ratio of 15 per cent Determination of the total voids could be based on the moisture-density relations for the raw soil, a correction made for estimated bulking, and the cement content fully determined When sufficient data are available to establish a relation, perhaps between compressive strength and durability, the field cylinders could be cured in the field and sent to the laboratory for test The control procedure in soil-cement stabilization would then correspond quite closely to the present procedure in controlling operations in concrete construction

SOIL-CEMENT STABILIZATION IN MISSOURI

By F V Reagel

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The progress report on laboratory work with soil-cement mixtures published in May 1936 by the Portland Cement Association included the results of treating some typical Missouri clay soils These results encouraged the Department to test the practicability of such treatment in certain field test sections which resulted both in demonstrating a place for such a road type and in developing improved construction procedure

Test sections consisted of worn out gravel roads which were programmed for improvement consisting of base construction to support thin bituminous surface treatments

ROUTE 5, TIPTON TO FORTUNA, MONITEAU COUNTY

The first section consisted of cement stabilization of 1 4 miles of roadbed on Missouri Route 5 north of Fortuna in Moniteau County Representative samples of the soil (Table 1) were submitted to the Portland Cement Association and upon their resulting recommendation (Table 2) the work was undertaken in the late Fall of 1936 by the State maintenance forces The Materials Bureau was assigned to study and control the mixtures

TABLE 1

Showing Grain Size and Test Constants for Final Tests of Missouri Soil Samples, Route 5, Moniteau County

Test Constants								Grain Size Per Cent of Total Sample							
P C A Lab No	Liquid Limit	Plastic Limit	P I	F M E	Shrinkage Limit	Shrinkage Ratio	U S B P R Soil Group	Pass 1 in Ret ¾ in	Pass ¾ in Ret ¼ in	Pass ¼ in Ret #10	Coarse sand 2 0 to 0 25 m m	Fine sand 0 25 to 0 05 m m	Silt 0 05 to 0 005 m m	Clay less than 0 005 m m	Colloids* less than 0 001 m m
27	46 5	23 8	22 7	36 2	13 9	1 90	A-7 (Clay loam)	8 27	13 25	0 98	11 4	8 6	31 3	26 2	11 1
29	34 7	21 1	13 6	25 5	19 0	1 76	A-4 (Loam)	7 05	15 55	7 45	9 6	9 35	33 5	17 5	5 5
33	54 0	21 1	32 9	29 0	16 1	1 85	A-6 (Clay)	6 55	7 85	1 78	2 0	8 9	33 7	39 2	13 6

* Also included in clay fraction

From the data presented in Table 2 it was decided to use 12 per cent of cement by volume for the entire road, and that the optimum moisture content should be varied to meet field conditions, using Table 2 as a guide

The surface was to be 22 ft wide except the last 600-ft section, which was 30 ft Grade stakes were set at 50-ft intervals in order to check the depth of processing at all stages of the work After the existing roadbed was scarified to a depth of six inches further pulverizing, due to the clay encountered, developed into an extended operation requiring the use of 24-in farm disks, spike tooth cultivators and unique field cultivators, called "quack grass diggers" This implement also proved useful later in mixing the cement and the water Preparation of the roadbed required a full day's work per section On the next day the water was applied, the water and cement mixed with the soil in the amounts prescribed and the final mixture spread and compacted to

TABLE 2

Cement Recommended for Each Soil Covered in Table 1

P C A Soil No	Cement Content by Volume, Per Cent	Optimum Moisture Content, Per Cent	Maximum Density, lb per cu ft
27	12	15 5	111
29	10	13 2	114
33	13	16 5	103

grade. Due to uncertain weather conditions and the realization that rainfall following the preparation would result in loss of all the work done in pulverizing the roadbed materials, the work was protected by covering the section with Sisalkraft paper This detail proved to be successful and almost essential for the time of the year in question which was from October 30 to November 28, 1936

Cement was spotted along the road at the rate of four sacks equally spaced across the road at three foot intervals along the road The cement was spread by hand rakes Dry mixing of the cement with the pulverized roadbed materials followed and was continued until no concentration or segregation of the cement could be observed The equipment for this mixing consisted of the 24-in disks and field cultivators with spike tooth harrows in tandem Ordinary bituminous distributors were used for the several applications of water required to bring the moisture to or slightly above the optimum moisture content as predetermined One or more round trips of the cultivator and disks were made between applications of water After all of the required water had been added, wet mixing was continued until a uniform dispersion of the moisture to the depth of the loosened material was obtained

The material was then compacted with sheepsfoot tampers loaded so as to apply pressure of 100 lb per sq in This method of compaction resulted in a rough dented surface with one-half to one inch of loose mulch on top A motor blade finished off the irregularities and final compaction and smoothness were obtained by use of a three-wheel ten-ton roller A straw cover was spread over the completed surface as a protection from freezing and to reduce moisture loss during the curing period

The foregoing procedure required completion of individual sections on separate days so that in working a new section the turning of the equipment on a previously completed section was unavoidable In order not to mar the finished section approximately 25 ft adjacent to the new section were covered with 6 in of loose soil This protecting soil was later removed by hand However, these "turn arounds" are markedly rough and unsightly as compared to the rest of the road.

Fourteen sections comprising 1 52 miles were completed before the inclement weather and lateness of the season stopped the work

The prevailing weather conditions were unfavorable The average daily maximum temperature during the entire construction period was 56°F, and the average daily minimum was 27°F Below freezing temperatures were recorded during the night following construction on 12 of the 14 sections Rainy weather also delayed the work and the 14 daily sections were spread over 28 working days

Cement was applied so as to give 12 per cent by volume for the designed 6 in compacted thickness It soon developed that the processing was loosening the roadbed to a greater depth than anticipated and the final compacted thickness varied from 6 to 10 in, averaging 7¾ in with a corresponding variation in cement content of from 12 to 7 2 per cent, averaging 9 3 per cent

The optimum moisture content of 16 per cent as recommended from laboratory tests was increased, after field trial and observation to 19 per cent and with slight variation was held at that point Moisture tests were made at the completion of the dry mixing for determining the amount of water to be added Additional moisture tests were made during wet mixing in order to secure the optimum moisture content At this stage density determinations on samples were made by the Proctor method A split mold was used and the cylinders were cured and saved for further study and durability tests

In order to obtain accurate measurements of compacted thickness the wet mixed material was removed from selected points and an 18-in square of heavy wrapping paper was placed on the undisturbed subbase and buried After compaction the depth to the paper could be definitely measured

The density of the finished roadbed was also determined by sounding with a 4-in posthole auger The material removed was carefully retained and weighed and the moisture content determined The quantity of dry standard Ottawa sand required to backfill the hole was used to determine the volume of the compact material recovered From these data the dry weight per cubic foot obtained was determined The Proctor test gave an average result of 103 2 lbs, the roadbed measurements averaged 102 4 lbs

This was a new type of construction which of course necessitated breaking in a crew Operations were also hindered by rainy weather during the first part of the construction period As a result, the cost on the first two sections was 75 cents per square yard As the crew became more proficient costs decreased until on the last two sections the cost was 41 cents per square yard

The total cost of the project was $9,214 52 or $0 457 per square yard This covers only time and material used in construction and does not include the cost of moving in equipment, preparing and maintaining detour, moving out equipment, shouldering and engineering Cost data are given in Table 3

The total cost of the project, including moving in equipment, preparing and maintaining detour, moving out equipment, shouldering and engineering was $12,870 23, making the cost per square yard $0 639

This section was allowed to stand without surface treatment until the middle of the summer of 1937 During this time no base weakness developed; however, considerable surface scaling occurred, approaching pot-holes in some spots particularly at "turn-arounds" These holes were fairly successfully hand-patched with soil-cement mixtures However, a light surface treatment was not effective in correcting the surface defects that developed and a later bituminous drag treatment was necessary to give the section good riding quality

In evaluating the results of this section it should be noted that the work was seriously handicapped by the lateness of the season and the accompanying inclement weather A substantial part of the cost can be charged to long delays as well as to inexperience with this type of construction

TABLE 3

COST DATA—MONITEAU COUNTY

Pulverizing	$1,055 99
Cement (including hauling and spreading)	6,145 33
Mixing (Dry)	239 51
Mixing (Wet)	837 00
Packing	185 47
Final Finish	92 92
Turn-around	97 06
Curing, Moist Straw	271 32
Supervision (not including engineering)	289 92
Total	$9,214 52

ROUTE 100TR, WASHINGTON—NEW HAVEN, FRANKLIN COUNTY

In connection with an extensive field study of variations in materials and methods in base construction and soil stabilization on Route 100TR, Franklin County, two miles of soil-cement stabilization were built These sections were constructed to obtain definite cost and manipulation data as well as to determine the service values of the various suggested types of stabilization under uniform field conditions The subgrade consisted almost entirely of the Union Silt Loam, a loessial type soil of the A-4 group The original wearing surface consisted of approximately one inch of mixed stone and gravel rather poorly bonded Samples representing a six-inch depth were taken in duplicate and submitted to the Highway Materials laboratory and to the Portland Cement Association for tests and recommendations Typical test results showing the character of the material are given in Figures 1 and 2 and Table 4 On one section, with two variations in cement content, namely, six and eight per cent by volume, the preparation, mixing and spreading was carried on in practically the same manner as on the previous work on Route 5, Moniteau This method is referred to as the "Road-mix" method On the other section, with the same variations in cement content, the "Traveling plant" method, consisting of a Barber-Greene traveling plant and an attached Barber-Greene finisher for mixing and spreading, was used

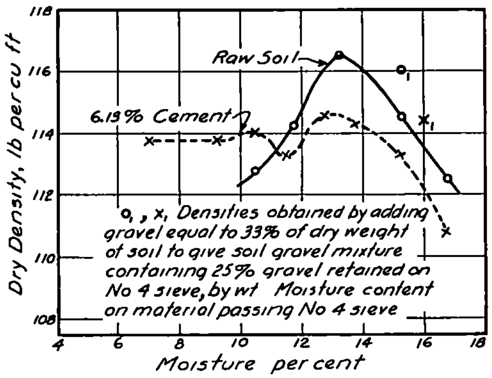

Figure 1. Moisture-Density Relations. The raw soil is that part passing the No. 4 sieve The cement mixture contains 7 05 per cent cement by volume of soil, 6 13 per cent by weight of dry soil Franklin County, Station 970 Route 100, Sample No 151.

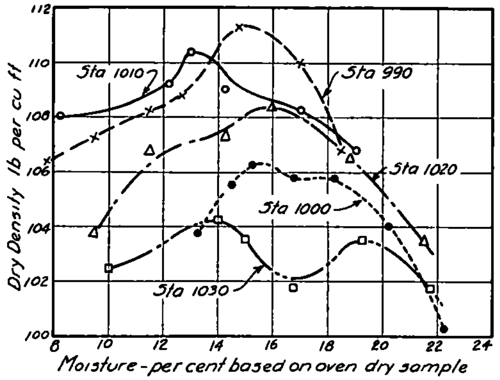

Figure 2. Moisture-Density Relations The curves are for that fraction of the soil sample which passed the ¼-in. sieve, with enough cement added to give approximately 7 per cent by volume of the mixture at maximum density.

TABLE 4

ROUTE 100TR, FRANKLIN COUNTY

Typical gradation and soil analyses of original materials

Screen or Sieve	Per Cent Passing
1-in round	100
¾-in round	98
½-in round	95
No 4	89
No 20	84
No 40	81

Clods retained on ½-in round = 24%

Materials passing No 40 mesh sieve

Lower liquid limit—35

Lower plastic limit—17

Plasticity index—18

Silt—Diameter 0 5 to 0 005 mm —56%

Clay—Diameter smaller than 0 005 mm —30%

Colloids—Diameter smaller than 0 001 mm —17%

Road-Mix.

This work benefited by the previous experience on Route 5, Moniteau and progressed smoothly with good organization in both equipment and procedure This section was divided in two subsections, No 44 having 6 percent cement and No 45 having 8 percent cement The following is a list of the equipment used

Preliminary scarifying and pulverizing
- 1—60 Crawler type tractor
- 1—35 " " "
- 1—Block Scarifier
- 1—Double 24-inch disc
- 1—Motor patrol

Cement Processing and Compaction
- 2—two-ton trucks
- 3—35 Crawler type tractors
- 2—Double 24-inch discs
- 1—Cultivator (quack-grass digger)
- 3—Distributors
- 2—Motor patrols
- 2—Sheepsfoot tampers (double units)
- 1—Spike tooth harrow
- 1—10-ton, three-wheel roller

A section one-quarter mile long was cement processed each day This required an average total working time of 15 hr and 38 min

This time, by operations was divided as follows

Distributing and spreading cement	2 hr 41 min
Dry mixing	2 " 49 "
Applying water and wet mixing	4 " 19 "
Constructing joint	0 " 38 "
Compacting and shaping	3 " 41 "
Smooth rolling	1 " 30 "

The average miles for the various types of equipment in order to process one mile are as follows

DRY MIX			WET MIX		
Disc	Cultivator	Motor Patrol	Disc	Cultivator	Motor Patrol
40	34	18	92	58	32

COMPACTING AND SHAPING

Sheepsfoot Tamper	Spike Harrow	Motor Patrol
50	*18	12

* The spike tooth harrow was attached behind the sheepsfoot tamper in order to eliminate the tamper marks preliminary to rolling with the flat wheel roller

Two rollings were necessary with the smooth roller in order to finish the surface

The average gradation of the material at completion of dry mixing and start of wet mixing is given in Table 5

TABLE 5

Openings	Percentage Passing Sec No 44	Percentage Passing Sec No 45
1¼-in round	100 0	100 0
1-in round	100 0	98 3
¾-in round	98 7	94 8
½-in round	95 6	90 3
No 4 Sieve	90 6	84 5
⅛-in Sieve	89 0	82 4
No 20 Sieve	84 0	76 9
No 40 Sieve	81 2	75 1
Soil clods retained on ½-in round	26 9	24 6

The averages of the field test results are shown in Table 6 Density and weight per cubic foot were determined by the Proctor method

The use of straw for curing was abandoned on this section Sisalkraft paper was used for curing a section approximately 150 ft in length The balance of the surface was primed with 0 15 of a gallon of TC-2 tar on the day following construction

Developments in construction procedure produced some interesting features The main criticism of former work concerned the unsatisfactory condition resulting from the "turn-arounds" incident to each day's run. On these sections the material to be treated, next to the header dividing it from the completed previous day's run, was bladed forward for all the processing. Just previous to compaction the header was removed and the material was bladed back, shaped and compacted to conform with the previous work. Finishing with the flat-wheel roller removed practically every evidence of the joint.

TABLE 6

Sec. No.	Cem. Design	Cem. Actual	Average Compacted Thick.-in.	Moisture		Density at final Moisture	Roadbed Density	Optimum Moisture	Maximum Density
				Initial	Final				
	%	%		%	%			%	
44	6.0	6.36	5.66	8.3	16.2	101	100	14.5	104
45	8.0	7.04	6.82	9.2	15.2	99	98	15.9	103

Figure 3. Close-up of surface of 8 per cent cement soil-cement mixed-in-place base after 7 days of cover with Sisalkraft paper. Note only very slight incipient cracking of surface.

Construction cost data are shown in Table 7. The cost of armor coating was approximately $1,500.00 per mile.

Traveling-Plant Mix:

The efficiency of the traveling plant in mixing soil, cement and water was tested on another one mile section. This section was sub-divided into equal sections of six and eight percent cement but the construction of the mile followed a uniform procedure.

The existing road surface was scarified to an approximate depth of six inches with a block scarifier, after which the materials were disked and cultivated with double sets of 24-in. farm discs and "quack grass diggers". After the material was well pulverized, it was placed in two similar windrows along each edge of the road and a final check taken on the depth. The windrows were joined again along the centerline of the road. Usually one-quarter of a mile of pulverized windrow was kept in advance of the machine and Sisalkraft paper was on hand to cover the pulverized windrow in case rain fell. Sacks of cement were placed at the specified rate per station and were emptied on top of the windrowed material. The pulverized material and cement were partially mixed before entering into the pugmill by the action of the spiral feeders to the bucket elevator and by dumping into the closed storage hopper above the apron feeder. The amount of water added to the pugmill was slightly higher than the optimum required as allowance was made for evaporation before final compaction was completed.

The pugmill discharged the mixed materials directly into a hopper on the finishing machine which spread the materials over the undisturbed subgrade. Immediately behind the finishing machine the mixed material was sheepsfooted in short stretches until the tamper feet did not penetrate more than one to two inches from the top of the unconsolidated surface. Final shaping of the

TABLE 7

Final Cost Data—Route 100TR Franklin County

Sections 44–45, Road Mix, Net Length 5185 ft.

	Labor	Equip. Rental
Reshaping Roadbed	$12.46	$18.22
Scarifying & Pulverizing	70.88	91.51
Hauling & Spreading Cement	267.75	43.55
Dry Mixing	40.30	105.39
Wet Mixing	52.80	120.20
Compaction	14.60	63.55
Final Shaping & Rolling	44.05	44.40
Water (72590 Gal.)	54.30	248.20
Total	$557.14	$735.02

Total Cost of Manipulation for Section	$1,292.16
Total Cost of Manipulation per Station	24.90

Section 44, 6 per cent Cement, Net Length 2636 ft.

Manipulation—26.36 Sta. @ 24.90	$656.36
Cement	877.14
Tarpaulins for Covering Cement	64.07
Other Equipment, Gas, Oil, and Grease	45.95
Engineering	80.70
Supplies, Tools, & Repairs	30.90
Signs & Barricades	6.66
Supervision	128.09
Supply Truck, Freight, etc.	67.88
Total	$1,957.75
Cost Per Mile	$3,923.35

Section 45, 8 per cent Cement, Net Length 2549 ft.

Manipulation—25.49 Sta. @ 24.90	$635.80
Cost of Cement	1,142.46
Tarpaulins for Covering Cement	64.07
Other Equipment, Gas, Oil, and Grease	44.50
Engineering	78.20
Supplies, Tools, & Repairs	29.95
Signs and Barricades	6.45
Supervision	123.98
Supply Truck, Freight, etc.	65.71
Total	$2,191.12
Cost Per Mile	$4,536.48

surface was done with a motor grader. It was necessary to add a small amount of water to the surface at this stage of the operation as the mix on the surface was usually fairly dry. After the final shaping was done, a 7-ton roller made two complete passes over the width of the road.

Straw was used for curing, although a bituminous curing agent called "Curcrete" was used at the rate of 0.10 gallon per square yard in one place for experimental purposes. The straw was wetted occasionally with water. Due to hot weather and heavy local traffic this method of curing did not prove very effective. Where "Curcrete" was used there was slightly less early checking and cracking but after several weeks there was no apparent difference between the surfaces having straw or "Curcrete" curing. Both are probably good methods of curing, provided the straw is kept well dampened and covered over the entire surface and the application of "Curcrete" is sufficient to form a continuous film over the entire surface. The straw was raked onto the shoulders after 7 days and burned. Several weeks after the placing of the mix, one-half of the surface was primed with MC-1 and the other half with TC-2, each approximately 0.20 gal. per sq. yd.

Figure 4. Incipient cracking of surface on 6 per cent cement soil-cement machine mix base. The cracks were of surface nature and approximately one inch deep. This surface later developed into a pitting and ravelling stage and a drag treatment was placed over it before sealing.

It was found necessary to place a drag treatment on the surfaces of the two machine mix sections because of the bad raveling which occurred before the seal coat work began. The riding surface was also wavy. This condition can be explained plausibly by the fact that the continuous operation of the machine required finishing and compaction in very short stretches. The stone for the surface treatment consisted of 60 lb. per sq. yd. of $\frac{3}{4}$-in. to $\frac{1}{4}$-in. limestone chats, 16 lb. per sq. yd. of $\frac{3}{8}$-in. to $\frac{1}{8}$-in. limestone screenings, and 0.65 gal. per sq. yd. of RC-3. This treatment filled in the raveled areas and corrected most of the waviness of the surface. The seal coat consisted of 0.25 gal. of 250 penetration asphalt and 25 lb. of $\frac{1}{2}$-in. to No. 10 pea gravel.

TABLE 8

Section	Initial Moisture	Final Moisture	Density at Final Moisture	Final Density of Roadway
	%	%	*lb. per cu. ft.*	*lb. per cu. ft.*
6% Cement	9.1	18.8	99	97
8% Cement	11.2	19.6	100	96½

Section	Maximum Density	Optimum Moisture	Depths	
			Loose	Compacted
	lb. per cu. ft.	%	*in.*	*in.*
6% Cement	106	18.1	8.5	5.4
8% Cement	108	18.0	7.1	4.9

Average field test results are given in Table 8. Density and weight per cubic foot were determined by the Proctor method.

Construction cost data for the 6 and 8 per cent cement sections by the Barber-Greene traveling plant are shown in Table 9. The cost of drag treatment was $1,708.35 per mile and of armor coating was approximately $1,500.00 per mile.

ROUTE 13, ST. CLAIR COUNTY, OSCEOLA NORTH

This section of road-mix soil-cement stabilization is of interest in that it is the only Missouri section constructed under contract. The project, which is 4.975 miles long, was commenced September 18 and completed October 15, 1937. The cement processing was done in 20 working days. The longest section processed in one day was 1600 ft., and the average length processed per day for the entire project was 1313 ft. The soils encountered varied in character as is indicated by the typical test results in Table 10.

TABLE 9

FINAL COST DATA—ROUTE 100 TR—FRANKLIN COUNTY

Sections 41, 42, 43, Traveling Plant, Net Length 5276.35 ft.

	Labor	Equip. Rental	Materials	
			Straw	Curcrete
Scarifying & Pulverizing	$124.08	$297.48		
Hauling & Spreading Cement	162.75	85.15		
Spreading	40.15	216.94		
Compaction	30.50	85.29		
Final Shaping & Rolling	41.50	86.29		
Curing (49700 Gal.)	63.99	128.00	$10.80	
Total	$462.97	$899.15	$10.80	

Total for Section Manipulation	$1,372.92
Cost of Manipulation Per Station	26.02

Section 41, 6% Cement, 5 in. Thick, Net Length 1256.35 ft.

Manipulation—12.56 Sta. @ 26.02	$326.81
Mixing—458 Cu. Yds. @ 30¢	137.40
Water—16506 Gal. @ 40¢ per 100	66.02
Cement—214½ bbls. @ 1.98	424.71
Curcrete	25.92
Cost of Pumping Water	14.85
Labor for Mixing	54.40
Freight and Unloading on B. G. Finisher	54.98
Freight and Unloading B. G.	11.97
Windrow Cover	21.11
Other Equipment, Gas, Oil, & Grease	21.92
Engineering	38.50
Supplies, Tools, & Repairs	14.73
Signs & Barricades	3.18
Supervision	61.09
Supply Truck, Freight, etc.	32.38
Total	$1,309.97
Cost Per Mile	$5,504.07

TABLE 9—*Concluded*

Section 42—8% Cement, 6 in. Thick, Net Length 1350 ft.

Manipulation—13.5 Sta. @ 26.02	$351.27
Mixing—543 Cu. Yds. @ 30¢	162.90
Water—17755 Gal. @ 40¢ per 100	71.02
Cement—303½ bbls. @ 1.98	600.93
Cost of Pumping Water	17.62
Labor for Mixing	64.40
Freight and Unloading on B. G. Finisher	59.14
Freight and Unloading B. G.	12.88
Windrow Cover	22.71
Other Equipment, Gas, Oil, & Grease	23.58
Engineering	41.45
Supplies, Tools, & Repairs	15.85
Signs and Barricades	3.42
Supervision	65.71
Supply Truck, Freight, etc.	34.83
Total	$1,547.61
Cost Per Mile	$6,045.35

Section 43—6% Cement, 6 in. Thick, Net Length 2670 ft.

Manipulation—26.7 Sta. @ 26.02	$694.73
Mixing—887 Cu. Yds. @ 30¢	266.10
Water—35094 Gal. @ 40¢ per 100	140.38
Cement—453½ bbls. @ 1.98	897.93
Cost of Pumping Water	28.71
Labor for Mixing	104.80
Freight and Unloading on B. G. Finisher	116.88
Freight and Unloading B. G.	25.40
Windrow Cover	44.80
Other Equipment, Gas, Oil, & Grease	46.49
Engineering	81.70
Supplies, Tools, & Repairs	31.25
Signs and Barricades	6.75
Supervision	129.63
Supply Truck, Freight, etc.	68.70
Total	$2,684.25
Cost Per Mile	$5,315.35

In addition to the variations in soil another new condition was introduced by the fact that a considerable portion of the road consisted of the remains of a failed oil mat surface which could not be entirely removed. In some portions of the section bituminous treated materials were found in the mix.

The contract specified 8 percent cement by compacted volume of the finished road, 6 in. thick. However, during the course of construction an exceptionally heavy clay soil (Lab. No. 77) was encountered on 1.12 miles and the cement on this portion of the project was increased to 10 percent.

Field test methods recommended by the Portland Cement Association were used to control moisture-density relationships during construction The average results obtained are as follows.

Percent Moisture		Dry weight at Optimum Moisture	Finished Base	Thickness of Base
Initial	Final			
		lb per cu ft	*lb per cu ft*	*inches*
8 6	14 1	113	105	7 5

The outstanding feature on this project was the trial and adoption of a different piece of equipment for loosening the roadbed, dry mixing and wet mixing. Considerable difficulty had been experienced in the past, in controlling the depth and uniformity of scarification This same difficulty was encountered at the beginning of this job and it was suggested that a gang plow be given a trial Two 14-in plows in gang were tried out on the fifth section constructed The roadbed on this section was first scarified with a Duoclaw scarifier and then plowed The plow was pulled by a R D 4 Diesel caterpillar tractor Subsequent investigations showed that the scarified depth could be controlled more accurately and a more uniform subgrade cross-section obtained by this method The plow was used very effectively from time to time during the pulverizing operations to turn the cloddy material to the surface, where it was broken down more readily by the discs

The plow was later tried in combination with the discs in the dry and wet mixing operations The results were very satisfactory and the plow was used in place of the orchard cultivator, for these operations, on the remainder of the project The plow was definitely effective in turning over the material and in that way both moisture and cement could be brought to the same percentage in top and bottom so that no variation in set with depth could be noted This weakness had been observed on other sections. The total cost of the soil-cement stabilization section was $26,818 90 or $5,396 16 per mile, exclusive of surface treatment

TABLE 10

GRAIN SIZE

Lab No	Pass 1 in Ret ½ in	Pass ½ in Ret No 4	Pass No 4 Ret No 10	Coarse Sand 2 00–25 mm	Fine Sand 0 25–0 05 mm	Silt 0 05–0 005 mm	Clay less than 0 005 mm	Colloids less than 0 001 mm
75	8 7	6 3	5 9	9 1	23	33	14	7
76	0 7	1 5	0 7	4 1	12	56	25	15
77	6 6	7 8	3 4	5 2	16	33	28	19

TEST CONSTANTS

Lab No	L L	P L	P I	F M E	S L	S R	Group
75	25 5	18 8	6 7	22 1	15 6	1.82	A-2
76	28 5	20 1	8 4	25 3	16 6	1 75	A-4
77	41 7	18 6	23 1	31 2	12 3	1 94	A-6

SUMMARY OF PROJECTS IN THIS REPORT

(1) In examining the cost data of the various sections it was found that the cement cost, together with the handling charge, could be considered a fixed charge and can be closely approximated by the figure 2 5 cents per square yard for each percentage of cement used On this

basis, the other costs of the various sections can be compared by deducting the cost of the cement.

COST MINUS CEMENT

	Per Sq Yd	Per Mile
Route 5, Moniteau County	$0 34	$4,350 00
Route 100, Franklin		
Road Mix	0 15	1,950 00
Machine Mix	0 27	3,450 00
Route 13, St Clair County	0 20	2,550 00

Part of the excess cost on Route 5, Moniteau, has already been explained, however, another item is the character of the soil, the proper preparation of A-6 clay for treatment requiring considerable more manipulation than the readily friable A-4.

(2) The costs as given are reasonable and in the range of what one can expect to pay for a reliable base in the low cost program

(3) Some surface treatment to provide a wearing course is required before putting the road under traffic

(4) The results obtained do not appear to justify the extra cost of the machine mixing as carried on in this case

(5) In the processing it developed that by proper care and provision the objectionable conditions that develop on "turn-arounds" could be eliminated Another development in processing indicates that the use of gang plows in turning over the material during the disking and mixing operations is more effective in preparation of the material and in uniform mixing than the "Orchard Cultivators"

(6) With good organization it appears that a complete crew of men and equipment will complete, as an average, one quarter mile per working day

SOIL-CEMENT BASE, WAYNE COUNTY, IOWA

By FRANK L DAVIS

Resident Engineer, Iowa State Highway Commission

During 1937, 1 64 miles of soil-cement stabilization base were built in Wayne County, Iowa by the State Highway Commission The section had been maintained with a traffic bound gravel surface since 1923

The new base course was built 26-ft wide, 4-in deep and with a finished crown of 5-in The material for the base was secured by scarifying the surface to the depth necessary to produce the required yardage of material About 60 per cent of the original gravel surfacing material was recovered and used

To make the final 4-in depth, 2127 cu yd. of material per mile were required from the road bed

Cement was mixed with the base material in the ratio of 1 to 10 by weight The optimum moisture content was found to be 11 per cent, which required the application of 5 09 gal of water per sq yd less the moisture contained in the material

The characteristics of the material in the base are given in Table 1

The job was done on contract by the road mix method

The base material was taken from the road bed with two No 11 auto patrols with scarifier attachments By removing half of the scarifier teeth and setting the rest to the correct depth below the scarifier block, it was possible to scarify to the full depth by running the scarifier block tight to the road surface The operation followed a heavy rain and by using one patrol to pull the other machine with the scarifier, the material was loosened to the full depth in one operation The material was then bladed into a windrow until all scarifier marks were removed from the sub-grade.

Pulverization was accomplished by two No 30 AC caterpillar tractors pulling a tandem and spring tooth harrow and a quack grass digger Some rolling was done to help flatten out the lumpy material.

After the material was pulverized it was placed into a windrow at one side of the road so that the water distributors would not travel too near the edge and cause settlements in the sub-grade.

TABLE 1

BASE MATERIAL

Sieve Size	Percentage Passing	Material Passing No 40 Sieve	
1 in	100 0	Liquid Limit	30 0
¾ in	98 0	Plastic Limit	14 8
⅜ in	91 3	Plasticity Index	15 2
No 4	82 1		
No 8	71 1		
No 10	68 8		
No 40	49 0		
No 60	42 6		
No 100	38 6		
No 270	35 3		
No 005	14 8		
No 001	7 6		

MIXING AND LAYING

Mat for Turning Equipment·

The first operation each day was to place a mat of 3 by 12-in fir plank over the end of the last day's run long enough for the mixing and rolling equipment

Spreading:

Following the placing of the mat, the header board from the last day's run was removed and the material between the header and windrow loosened from the sub-grade The windrow was then knocked down and spread uniformly over the sub-grade for the distance of the day's run The windrow was flattened for about 50 ft beyond this point to enable the equipment to be turned beyond the end of the run

A red flag was placed on each side of the road at the end of the day's run so that the point was clearly marked where each operation was to stop for the day

Applying Cement·

After the spreading of the material in the windrow the cement was placed

The cement was distributed with a Buckeye spreader attached to the rear end of a flat bottomed truck used for hauling the cement in bags The cement was applied in three widths of the spreader and in two layers After a few adjustments, on the first day's run, the machine was able to spread the cement uniformly at the required rate per square yard Considerable difficulty was encountered the first day as the contractor started dry mixing at the time he applied the cement which caused the mixture to become very loose and fluffy The Buckeye spreader, being traction driven, would sink deep into the loose material and cause trouble by stones and gravel getting into the drive chain and sticking the machine After the first day, the cement was spread on top of the material before dry mixing was started

Dry Mixing

Following application of cement, the material was uniformly dry mixed by the use of the quack grass digger, tandem disc and spring tooth harrow The quack grass digger which was a 10-ft McCormick Deering solid arm with large type open back shovels did an excellent job of mixing Shields should be used on the outside shovels of the quack grass digger to keep the mixed material from spreading beyond the trench in the sub-grade An extra set of shovels should be provided for this type of digger so that they can be replaced and sharpened when dull Upon completion of the dry mixing the water was added

Watering:

Water was obtained from a railroad reservoir two miles from the south end of the project A supply of 200-gal per min was provided by means of a portable pumping unit Gravity type distributors of 1040-gal capacity were mounted on Ford or Chevrolet truck chassis

The water was distributed over the dry mixed material as evenly as possible until 2 per cent above the optimum content had been added

Wet Mixing·

Mixing was continued as the water was added, until sufficient moisture showed uniformly distributed through the depth of the material It was often necessary to operate the mixing equipment in a zig-zag line of travel from one side of the road to the other to disperse wet streaks left by over-laps in the trips of the water distributors The same equipment was used for wet as for dry mixing It was often necessary during both the dry and wet mixing to blade the material in from the outside edges to prevent loss

In turning during the mixing and the rolling that followed, all equipment, as much as possible, was pulled upon the mat on the one end and past the red flags at the other Very little turning of the equipment should take place in the mixed material.

Preliminary Packing and Shaping·

Following the wet mixing, the mixture was rolled with a sheepsfoot roller until it was up to about 1½-in from the surface at which time the motor patrols shaped the road to the proper width and crown The rolling continued after the shaping until the roller was about ¾-in. from the surface On account of the heat and large evaporation it was necessary to sprinkle with considerable water during this operation in order to keep sufficient moisture in the material

Final Packing and Shaping.

The final shaping was done with the auto patrols The material was bladed back and fourth over the surface of the base and to such depth that all compaction planes of the sheepsfoot were removed During this operation, a spike tooth farm harrow was used to help roughen any compaction planes missed by the blading When the final shaping was completed, a uniform mulch of the loose material was left over the base and compacted by a pneumatic roller It was often necessary to wet this mulch to provide enough moisture to bond it to the balance of the base The pneumatic rolling was continued until all material was rolled tightly into the base

Joining New Work to Completed Base·

After the header had been removed in the morning, the material was cleaned to the sub-grade for about 2-ft back from the joint During the wet mixing the material used for the joint was shoveled by hand against the end of the last day's run and hand tamped in place

The base usually thickens at this point, due to accumulation from the equipment pulling upon the mat in turning On final shaping, the mat was removed and blading operations carried over the joint When pneumatic rolling was about completed, the joint was given a final blading with the blade over the joint at an angle of about 60° with just enough pressure to clean the completed base and to cut the new base to the same level During the pneumatic rolling, the roller passed over the joint and turned on the section previously completed

Final Rolling and Finishing

Finally the base was given a smooth even surface with a smooth steel roller This roller had to be used with considerable caution if the surface was too wet, it picked up on the roller and if too dry, the best results could not be obtained

Header at End of Day's Run

The header was placed by hand after the steel roller left the base A line was struck across the base between the red flags, placed at the end of the section, and a trench about five to six inches in width was cut across the base to the subgrade Care was used to make the completed side vertical and straight and a 2 by 4-in header board was placed in the trench and staked in place against the completed base A small amount of mixed material which had been saved was wetted and tamped into the narrow space between the header board and the mixed base This completed the day's operations

CURING

The completed base was cured by priming with a TC-2 bitumen on the morning of the day following the completion of each day's run at the rate of 0 2-gal per sq yd

The first and second day's runs were not primed on the following day as intended The car of bitumen arrived three days late and the two day's base was kept wet by sprinkling with water five times each day until primed This delay in priming did not seem to cause any serious defects in the base

Upon completion of the soil-cement base, the shoulders of the roadway were treated by priming with SC-1 bitumen

PROGRESS

Operations on the soil-cement section was started July 25th, and completed Aug 10th, 1937

The removal of the material from the road bed and processing required three days

The mixing and laying of the base was completed in eight working days

Some rainy weather was encountered between the starting and completion dates However, only a few light showers were had on the days of operation

The temperature ranged from 90 to 102 deg F

The schedule of a typical day's operations is given in Table 2

TABLE 2

Construction Operations, One 14-hour Day, 1100 Ft

Operation	Time, hr
Spreading Windrow	0 50
Spreading Cement	2 75
Dry Mixing	1 25
Watering	2 50
Wet Mixing	4 25
Preliminary Packing	2 50
Preliminary Shaping	0 50
Final Packing	1 00
Final Shaping	0 50
Smooth Rolling	1 50
Header and Turning Mat	0 75

COSTS

The Contract prices were as follows

Item 1 Portland cement for base stabilization in place on road	$2 66 per bbl
Item 3 Water for wetting base mixture	$3 00 per 1000 gal
Item 4 Constructing soil-cement base	$0 68 per cu yd
Item 6 Primer bitumen TC-2 for base furnished and applied	$0 1413 per gal
Item 7 Primer bitumen MC-1 for shoulders and approaches, furnished and applied	$0 087 per gal.

The cost data for the project are given in Table 3

THE FINISHED BASE

Measurements of density, thickness and water content were made on each day's run at 100-ft intervals before the prime coat was applied Table 4 gives the typical results

Two Proctor density tests were made on composite samples taken at the time of completion of wet mixing as follows

(1) Density 110 0 at 13 6 per cent water
(2) Density 123 8 at 11 5 per cent water

TABLE 4

	Thickness of Base, in	Density, lb per cu ft	Water %
Minimum	4 25	92 0	9 4
Average	5 04	105 8	14 5
Maximum	6 50	117 2	23 8

RECOMMENDATIONS

As this project was the first soil-cement base to be laid in the state very little information was available as to what type of equipment should be used and how many units of each type would be necessary to do the work in a satisfactory manner

The contractor accordingly furnished such equipment as was recommended and the project was completed without any changes in the set-up

It became apparent that with additional equipment and different methods for cement spreading better progress could have been made, better results would have been obtained and operation costs reduced

Recommendations for operations and equipment on soil-cement base stabilization are as follows

1 The mat for turning on completed base should be full width of base and 30 to 35 ft in length with a covering of dirt over the planks to prevent breakage and hold them in place All equipment should turn entirely upon the mat

2 The handling of cement in bulk with proper facilities for weighing and hauling with end dump trucks to feed the cement spreader This should save labor and expense and speed up the operation

3 As wet and dry mixing time seems to be the largest factor in the day's operation plenty of equipment should be used for this operation At least two quack grass diggers equipped with large type shovels should be used as this machine is fast and gives a very thorough mixture

4 The tandem farm disc should be replaced with quack grass diggers or their equivalent as it has a tendency to ride

TABLE 3

COST FOR SOIL-CEMENT STABILIZED BASE

Items	Costs for Project	Costs Per Mile	Cost Per Sq Yd of 4" Base	Cost of Sq Yd Per Inch of Base Depth
Cement in Place	$6,315 51	$3,848 79	$0 2523	$0 0631
Water for Mixture	450 30	274 42	0 0180	0 0045
Constructing Base	2,372 52	1,445 86	0 0948	0 0237
Prime TC-2 Curing	707 33	431 06	0 0282	0 0070
Prime MC-1 Shoulders	308 05	187 73	0 0123	0 0031
Total All Items	$10,153 71	$6,187 86	$0 4056	$0 1014

out of the material and does not mix to the bottom of the base

5 Water should be applied with power driven distributors properly tachometered whenever possible At least all water distributors should have spray bar length control and adjustable valves so that the spread of water can be controlled at all times and under all conditions

6. Rolling with sheepsfoot rollers should be completed while the base mixture is at the optimum moisture content

Enough rollers should be used so that the required density is reached in 2 to 2½ hours

7 During the initial compacting, or sheepsfoot rolling, only tractors of the track laying type should be used for operating the rollers Pneumatic tires should not be used at this stage as they compact the base unevenly

8 For final compaction the pneumatic roller should be operated by pneumatic tired tractors as a uniform surface, free from tracks, is desired Where track laying tractors are used, track marks are left in the base and extra rolling and blading are required to remove them

One pneumatic roller will take care of about 1500 ft per day The job should be equipped with two rollers of this type as this final compaction is important to the finish of the base In case of extra footage or breakdown of roller, the additional machine would be available to complete the day's run

9 For removing compaction planes on final shaping and packing, a fine spike tooth harrow should be used This type of harrow should have more and finer teeth than the common farm harrow so as not to leave too large ridges in the top mixture

10 Where bitumen is used for curing, it appears advisable to give the completed base one or two light applications of water before priming The first application should be about five hours after the base has been completed and the second 5 hours later, with about the same lapse of time before the prime coat is applied

FINISHED ROAD

The soil-cement stabilized base was surfaced with a bituminous wearing mat of inverted penetration type, 22 ft wide applied in two courses The binder was SC-7 bitumen applied at 0 3 gal. per sq yd for each course Crushed lime stone was applied at 30 lb per sq yd for each of the two courses

EXPERIMENTAL SOIL-CEMENT ROAD IN WISCONSIN

By Guy H Larson

Senior Assistant Engineer of Materials

An experimental soil-cement stabilization project was undertaken in Wisconsin during the fall of 1936, and early summer of 1937 The project consisted of a 3 3-mile section, located on State Highway 13, immediately north of Friendship in Adams County, 1 65 miles were built in 1936 and the project was completed in 1937. The work was done by county forces at the expense and under the supervision of the State Highway Commission of Wisconsin, working in cooperation with the Portland Cement Association, who also conducted the preliminary tests and designed the proportions.

The region is an old glacial lake bed and while the sandy soil deposited by the lake waters lent itself to some easy manipulation during construction, it also presented some unexpected problems during the preliminary tests The soil was graded largely between the 30 and 100-mesh sieves and appeared very uniform throughout the project A limited number of representative samples of the soil occurring on the road were obtained for preliminary tests Determination of grain size distribution and physical test constants showed the soil in these samples to be very similar Because of this similarity and the uniformity of the soil, one of the samples (No 36) was selected for the preliminary tests of strength and durability of the sand in combination with various percentages of cement

Durability tests consisted of wetting and drying, and freezing and thawing, conducted on specimens molded at the optimum moisture content The specimens were cured for 7 days in a covered container having free water in the bottom, before the tests were started. Wetting and drying tests were conducted by placing the specimens in an oven at a temperature of 160°F for 42 hr, after which they were removed, wire brushed and weighed, then placed in individual cans containing tap water After soaking for 5 hr the specimens were removed and weighed, then replaced in the oven Freezing and thawing tests were conducted by setting the specimens on blotters in the carriers so as to insure maximum capillary absorption of water during thawing They were then placed in the refrigerator where they were frozen in 3 hr. and reached a temperature of −15°F. in 20 hr Upon removal from the refrigerator the specimens were weighed and then placed in the moist room in containers holding sufficient water to submerge the blotters beneath the specimens, where they were permitted to thaw and absorb water for 24 hr After this, the specimens were brushed with a wire brush, re-weighed and again placed in the refrigerator The specimens thus brushed and weighed in each test gave data on the soil loss Twelve cycles constituted a complete test in either the wetting and drying or freezing and thawing tests unless the material slaked to its angle of repose before the twelve cycles were finished Compressive strength tests were made on 2 by 2-inch cylinders molded with a sand-molding machine regulated so that the density of the specimens approximated that obtained in the durability specimens

These preliminary tests showed unsatisfactory results with pure sand and cement mixtures Table 1 shows results of strength tests of various mixtures of sand and cement

Chemical tests revealed that the soil contained 11,000 parts of organic matter per million, and study of the grain size distribution indicated a shortage of fine material It was concluded that these factors were largely responsible for the unsatisfactory test results Fines could be provided by adding clay to the sand, and it was felt the clay might react to overcome somewhat the effects of the organic matter

TABLE 1

EFFECT OF ADDING INCREASED AMOUNTS OF CEMENT TO WISCONSIN SOIL No 36, SAND

Cement Content, Percent By Dry Weight	Compressive Strengths of 2-in Cylinders, lbs per sq in Average of Two Cylinders	
	2 days	7 days
12	25	38
14	25	43
16	29	40
18	33	46
20	37	57

Additional samples of the sand (No 66) and two clays (Nos 75 and 76, and No 77) were obtained for further tests Soils 75 and 76 came from the same deposit, one superimposed upon the other, so they would be mixed in approximately equal parts, and they were used in combination as one soil Table 2 gives the grain size distribution and physical test constants of these new samples and those of the original sample of soil, No 36

A comparison of the grain size distribution and test constants of soils 36 and 66 shows them to be very similar Chemical tests showed the organic content of soil No. 66 to be approximately 11,000 parts per million, which checks that of soil No 36

Strength and durability tests of mixes using varying proportions of clay and cement showed very beneficial effects from the addition of clay The general effect on strength of various additions of clay, and using varying cement contents is shown very clearly in the Table 3

Moisture-density relations were determined as shown in Figure 1, and the data in Table 5 were calculated from the curves

Durability specimens were molded using these data The tests gave satisfactory results and the mixture recommended for construction of the project was as follows

20 per cent by dry wt of either clay Nos 75 and 76, or No 77 to be added to the sand,

TABLE 2

GRAIN SIZE DISTRIBUTION

P C A Laboratory Sample No	Smaller than 2 00 mm , %	Coarse Sand, 2 00-0 25 mm , %	Fine Sand, 0 25-0 05 mm , %	Silt, 0 05-0 005 mm , %	Clay, 0 005-0 000 mm , %	Colloids,* 0 001-0 000 mm , %	Classification
36	100	52 0	36 0	7 0	5 0	2 5	Sand
66	100	54 0	40 0	3 0	3 0	1 0	Sand
75 & 76 (50-50 mix)	100	1 0	28 0	48 0	23 0	8 0	Clay-loam
77	100	4 0	8 0	50 0	38 0	12 0	Clay

* Also included in clay fraction

PHYSICAL TEST CONSTANTS

P C A Laboratory Sample No	L L	P I	F M E	S L	S R	Classification
36	15 3	0	14 8	16 6	1 80	Sand
66	13 0	0	18 2	18 2	1 66	Sand
75 & 76 (50-50 mix)	24 5	7 1	20 0	17 5	1 78	Clay-loam
77	30 6	13 9	18 9	17 2	1 85	Clay

These strengths were high in comparison with those obtained with sand and cement alone and compared very favorably with those obtained with soils encountered on similar projects which gave satisfactory results It was noted during the series of tests that mixes in which the clay was pulverized to pass a No 10 sieve gave better results than those in which the clay passed the one-fourth-inch sieve

The mixtures (Nos 5 and 6) shown in Table 4 were then made up, using 10 percent cement by weight

10 per cent by dry wt of cement to be added to the sand-clay mixtures

The optimum moisture content and maximum density of this mixture were given as 9 5 percent and 126 lbs per cubic foot, respectively

EQUIPMENT

Since equipment had not been developed especially for this type of construction, it was necessary to select such units as were available and appeared likely to function satisfactorily That

TABLE 3

EFFECT OF ADDING VARIABLE PERCENTAGES OF SOILS 75 AND 76 (50-50 MIX), CLAY-LOAM, AND NO 77, CLAY, TO WISCONSIN SOIL NO 66, SAND

(Admixed soils pulverized approximately to pass No 10 sieve)

P C A Lab Sample No of Soil Admixed to No 66 Sand	Parts of Soil by Dry Wt Admixed to to 100 parts of Soil No 66, Sand	Cement Content Percent by Wt	Compressive Strength, lbs per sq in Av of Two Specimens	
			3 days	7 days
75 & 76 (50-50 mix)	15	8	120*	226
		10	115*	231
		12	99*	278
	20	8	184	274
		10	216	368
		12	280	609
	25	8	213	380
		10	312	571
		12	330	565
77	15	8	204	362
		10	198	420
		12	268	567
	20	8	257	410
		10	345	615
		12	377	716
	25	8	256	391
		10	360	584
		12	403	664

* These strengths are low due to an accident while handling the specimens

TABLE 4

MIXTURES OF SOIL 66, SAND, WITH NOS 75 AND 76 (50-50 MIX), CLAY-LOAM, PASSING ¼-INCH SIEVE AND WITH NO 77, CLAY, PASSING NO 10 SIEVE

P C A Laboratory Mixture Designation	Parts by Dry Wt of Soil No 66, Sand, in Mixture	Parts of Soil Nos 75 and 76 (50-50 mix), Clay-loam, in Mixture	Parts of Soil No 77, Clay, in Mixture
Mixture No 5	100	20	—
Mixture No 6	100	—	20

used on the Wisconsin project consisted of four tractors, 60, 40, 35, and 20, the lighter ones being used with the pulverizing and rolling equipment and the heavier ones with the mixing and grading equipment, two small 16-in tractor discs and spike-tooth harrows for pulverizing and breaking down the clay; four quack grass diggers, ranging from 7 to 10 ft. in width, for mixing operations, one large grader, one motor grader, two sheepsfoot rollers for compacting soil, one single and one double unit, four trucks for hauling cement and clay, and also for compacting, one 8-ton three-wheeled smooth roller, one 1,000-gal oil distributor for distribut-

TABLE 5

DATA CALCULATED FROM PROCTOR CURVES USED FOR MOLDING DURABILITY SPECIMENS HAVING PREDETERMINED CEMENT CONTENTS BY VOLUME

Admixed soil passed No 10 sieve

P C A Laboratory Mixture Designation	Percent Cement by Weight	Optimum Moisture, Percent	Maximum Density Lbs per cu ft
Mixture No 5	10	9 0	127 4
Mixture No 6	10	9 5	125 5

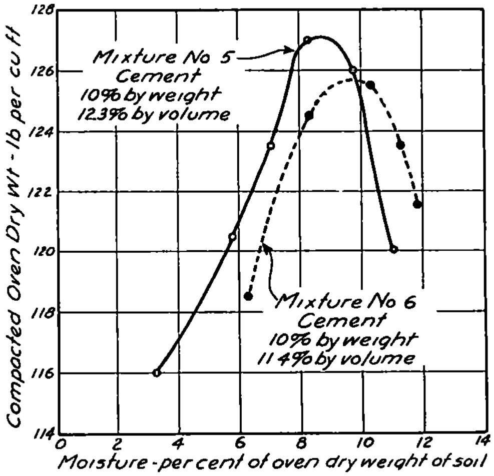

Figure 1 Moisture-Density Relations. Adams County, Wisconsin.

ing water, one pump and pipe line for supplying water to the project, and field laboratory and testing equipment

SUBBASE

It was decided to place clay over a width of 24 ft, and to add cement over a 22-foot width and process to a compacted depth of 6 inches This required approximately 780 cubic yards of clay and 2,000 barrels of cement per mile

Since this project was built on a new roadbed consisting of loose sand which had been brought as nearly as possible to the desired shape and grade, no scarifying was necessary The clay was hauled and spread by means of trucks, supplemented by hand spreading when necessary The clay was pulverized and partially mixed with the sand by means of discs and spike-tooth harrows, after which it was mixed to the full depth by means of quack grass diggers traveling back and forth over the length of the section being worked. The quack grass digger is similar to a spring-tooth harrow mounted on wheels, and can be set to work at various desired depths

These quack grass diggers were an innovation in mixing equipment for this work They eliminated the necessity for blading the entire mass of material back and forth over the grade and replaced the large discs and blade graders used for mixing on previous projects of this character

APPLICATION OF CEMENT

Construction began each day with the application of cement on a section of road which the engineer estimated could be finished during the day Cement sacks were spotted at regular intervals so as to provide the required amount for a compacted depth of 6 in The sacks were opened and dumped, and the cement spread by hand labor using shovels and rakes As soon as the cement was spread uniformly over the surface of the road, mixing was started with the quack grass diggers, drawn by crawler tractors, and continued until the cement and soil were thoroughly mixed to the full depth as indicated by uniform color of the mixture The depth of mixing was controlled by means of reference stakes placed along the shoulder. It was necessary to maintain the edges of the road during processing by shoveling material back as the diggers worked it out

When the dry cement was thoroughly mixed with the soil, tests were made of the moisture content of the mixture, and the amount of water necessary to bring it up to the optimum determined The necessary water was added in several "shots", each at the rate of about two gal per sq yd with a 1,000-gal oil distributor. Water was brought to the work by means of a pump and pipeline, from which the distributor was filled at the side of the road Mixing with the diggers was continued until the mixture was again of uniform color, indicating that the water had been thoroughly and uniformly dispersed throughout the mass The mixture was then such that when squeezed firmly in the hand it could just be compressed into a ball which would withstand very light handling

COMPACTING AND FINISHING

Having brought the sand, clay, and cement into an intimate mixture and provided the proper moisture content, the mass was compacted with sheepsfoot rollers The bearing surfaces or "feet" of the roller were 3 by 4 in, and were so loaded as to exert a pressure of 100 lb. per sq in when the feet were in full contact with the soil This type of roller was used because its compaction had been correlated with the laboratory compaction At first the "feet" settled to their full depth in the soil, but as compaction proceeded they gradually worked out until they were riding near the surface

At this point it may be of interest to mention two factors, the moisture content and the clay, which had very noticeable effects on the success of the compacting operation. The importance of the proper moisture content may be illustrated by the comparative compaction of spots having moisture contents different from the "optimum." A moisture content of 9.3 percent gave poor compaction, the soil being dry and crumbly, 10.5 to 11.5 percent gave good compaction, while a moisture content of 12.3 percent resulted in sponginess and a tendency of the soil to peel and stick to the smooth roller. A short section of road processed with the same cement content but without the addition of clay could not be compacted with the sheepsfoot roller and the usual equipment. It was necessary to resort to a cleatless crawler tractor and lighter equipment.

The finishing procedure varied somewhat from that used on previous projects in other states. When the sheepsfoot roller began to ride well up in the mass, shaping of the road was started by blading material from the sides toward the center so as to obtain some crown, the compaction process being continued as this blading was done. When the roller ceased to "pack out" rolling was stopped, and the road dragged with a spike-tooth harrow to remove roller marks and to loosen and level the surface. Compaction was then continued with a cleatless crawler tractor, followed with trucks and the distributor, starting at one side and working over the entire width of the road. The reason for finishing compaction with the tractor and trucks was that the sheepsfoot roller could not be followed directly by the smooth roller because of its tendency to pick up the loose material.

Immediately after compaction with the tractor and trucks, the surface was bladed and "shaved" with a motor grader to bring the road to final crown and shape. This blading was started at the center, and continued toward either side. Excess material was bladed off the road and wasted. It was found more satisfactory to cut high spots completely down, with consequent waste of the excess material, than to attempt to cut them partially and fill in low spots. Any material placed and compacted on the smooth and near-finished surface was almost certain to loosen and peel off. The final shaping with the grader was followed by ironing and smoothing irregularities in the surface with an 8-ton three-wheeled smooth roller. The finished surface was covered with damp sand to a depth of approximately one inch as a curing measure. The usual curing time was from 7 to 10 days.

PREPARATION FOR NEXT DAY'S WORK

At the end of the day, preparations were made for the following day's work. This included the construction of a "turn around" on the end of the completed section, the preparation of the end of the processed material for making the joint with the following day's work, and loosening up the soil in the section next to be processed. The "turn around" consisted of a board mat 4 to 6 ft. wide at the end of the completed section with wings about 3 ft. wide extending back and covering the edges of the road. This mat and the entire road was covered with sand or soil to a depth of 6 to 8 in. for a distance of approximately 50 ft. This protected the surface from the wheels of the equipment as it was turned around on the following day. There was a certain amount of "dragging out" of the cement mixture at the end of the section processed and preparation for the joint consisted of cutting this back to sound, dense material and beveling off the end. The joint was of the feather-edged or beveled type. This joint was not satisfactory because the thin edge of the "overlap" would chip and spall off. Several vertical butt joints were tried. Certain difficulties in mixing and compacting the material right up to the vertical end of the previous day's work made this joint difficult to construct.

The average length of section processed per day in 1936 was 513 feet, with a maximum of 660 feet. On the portion completed in 1937 the average was 728 feet, with a maximum of 900 feet. There naturally was considerable experimentation with equipment and procedure, particularly on the section processed in the fall. Of those available and tried, the ones described gave best results; they are not, however, to be taken as entirely satisfactory.

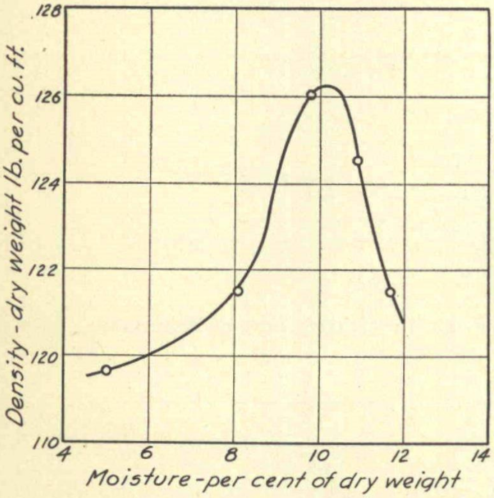

Figure 2. Moisture-Density Relations. Field Test. Station 153, Project 4758.

TABLE 6

Typical Sieve Analyses of Field Mixtures

Sieve No.	Percent by Weight Retained		
	Sand	Sand-clay	Sand-clay-cement
4	0	10.7	10.6
10	0.3	25.0	22.1
16	1.2	32.8	28.8
50	45.5	80.1	65.4
100	92.7	97.8	90.8
200	99.0	99.7	94.7
Pan	100.0	100.0	100.0

PROTECTIVE SURFACING

There was some shrinkage after final compaction, as evidenced by the formation of cracks noticed at intervals of approximately 25 ft. upon the removal of the sand covering. Also, there was some scaling and spalling of the surface attributed to improper finishing and attempting to patch or fill low spots. The clay could not be completely pulverized with the equipment available, and small clay balls were apparent in the surface. It was, therefore, deemed advisable to protect the surface from abrasion with a light wear-

Figure 3. Drilling hole for determining density of hardened road.

ing surface, or armor coat This consisted of an application of one-third gallon of a heavy tar, T H -4, and 20 lb of stone chips per sq yd

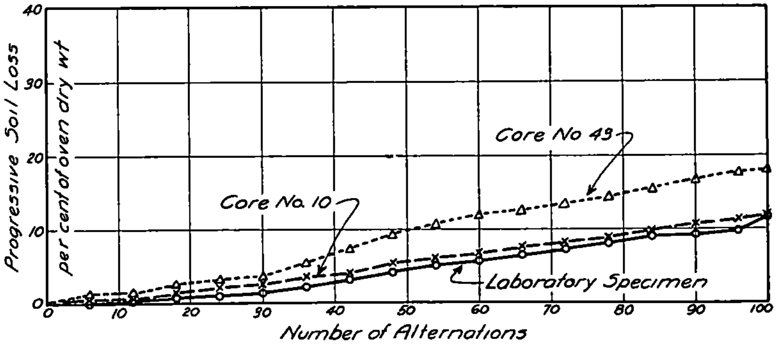

Figure 4. Wetting and Drying Tests. Progressive Loss of Material

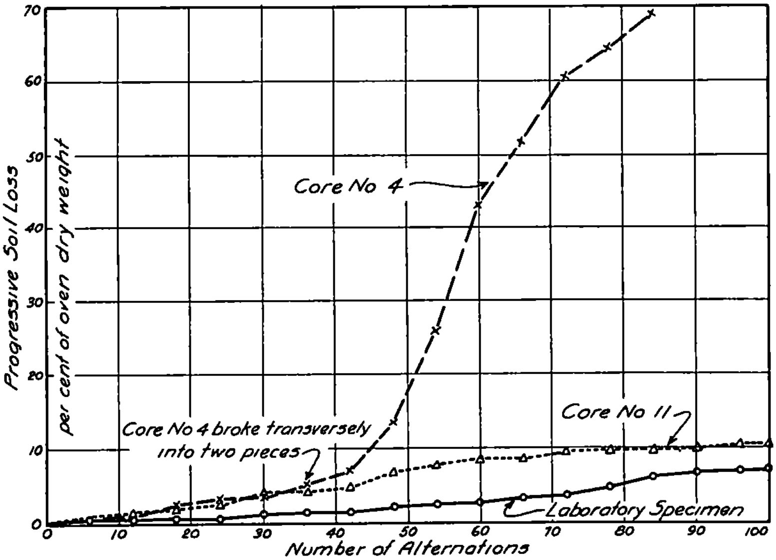

Figure 5. Freezing and Thawing Tests. Progressive Loss of Material

TEST RESULTS

In order to check the effectiveness of the field operations, certain tests of the field mixture and of the compacted and hardened material in the road were made, and the results compared with laboratory test results.

Typical sieve analyses of the sand, sand-clay, and sand-clay-cement mixtures are shown in Table 6.

The material retained on the Nos 10

and 4 sieves consisted of a clay core to which cement and fine sand were adhering; material between these sieves and the No. 100 was a mixture of sand, clay, and cement; that between the 100 and 200 mesh sieves consisted of fine sand, clay, and cement; and below the 200 mesh it was entirely clay and cement. Typical results of Proctor moisture-density relations obtained in tests on the field mixture are shown in Figure 2. The average moisture content of the mixture when compaction was started on the portion completed in 1936 was 10.3 percent, and the average of 48 field density tests made on the compacted material showed a dry weight per cu. ft. of 120 lb. Later a number of cores were taken from the road, and density tests made in the laboratory on them showed a weight of 123 lb. per cu. ft. These results compare favorably with the density of 126 lb. per cu. ft. obtained in the laboratory tests. Field density tests on the section processed without the addition of clay showed a weight per cu. ft. of 116.4 lb. Measurements of the thickness of the compacted material taken when field density tests were made showed an average of 6.3 in. for the middle of the road and 5.7 in. two to four feet from the edges. The cement content was reduced to 8 percent by weight on the portion built in 1937. The average moisture content at the beginning of compaction was 10.2 percent, and the density averaged 117 lb. per cu. ft.

Durability tests were conducted on certain of the cores taken from the road in parallel with companion laboratory specimens. The progressive soil losses in 100 cycles of wetting and drying, and 100 cycles of freezing and thawing, are shown graphically in Figures 4 and 5. Figures 6 to 9 show the condition of these cores at the end of 12, 48, 72 and 100 cycles. The agreement in results between laboratory specimens and field cores should be noted.

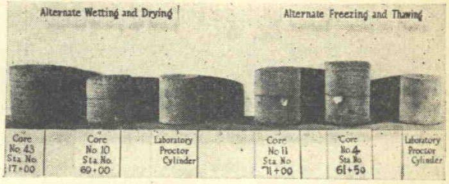

Figure 6. Condition of cores and cylinders after 12 cycles of durability tests.

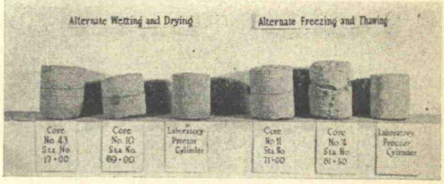

Figure 7. Condition of cores and cylinders after 48 cycles of durability tests.

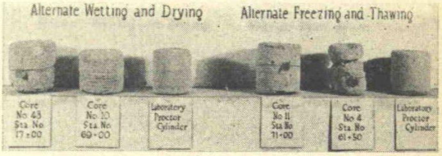

Figure 8. Condition of cores and cylinders after 72 cycles of durability tests.

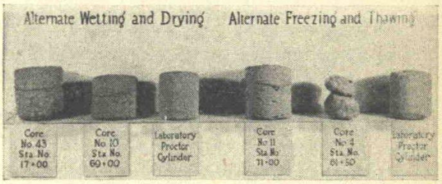

Figure 9. Condition of cores and cylinders after 100 cycles of durability tests.

The section built in the fall of 1936 came through the winter in good shape. It is rather early, however, to make any comment as to ultimate service behavior.

LABORATORY INVESTIGATION OF SOIL-CEMENT MIXTURES FOR SUBGRADE TREATMENT IN KANSAS

By M D Catton

Cement can be added to soils for other purposes than the achievement of a hardened road surface for light traffic use. It may also be used to change the characteristics of unsatisfactory soils in subgrades under substantial load carrying pavements, such as concrete, so that these soils will function satisfactorily as subgrades.

The Kansas State Highway Commission has made extensive laboratory and field studies of very bad soils which produce distortion of concrete pavements at cracks and joints as a result of volume increases and moisture gradients in the soil which accompany infiltration of water As a result of these investigations a comprehensive field project was started in the fall of 1935 on a soil which would produce pavement distortion with a view to applying the laboratory and field studies in construction procedures in such a manner that the tendencies of very bad soils to produce pavement distortions would be overcome The work is in Douglas County and is identified as Project 10-13-PWS$_2$ Several methods of subgrade preparation and construction make up this project One section, (No 10) was to be treated with about 5.3 per cent cement by volume (45 lbs per sq yd) for a depth of 12 in

A typical sample of the soil was shipped to the Portland Cement Association in the winter of 1935–36 for analysis and suggestions for the treatment of the section with cement The following report covers the investigation of this soil mixed with various quantities of cement and covers data and analysis of data by the soil-cement Laboratory of the Development Department of the Portland Cement Association

Since the problem involved is one of reducing volume changes in the soil enough to overcome pavement distortion due to moisture changes or moisture gradients, two possible methods of treating the soil with cement were presented With one method, a soil-cement mixture would be used containing sufficient cement to give a cement hardened soil or subgrade when moisture content and compaction are properly controlled during construction This cement hardened soil would have very small volume changes and moisture gradients in comparison to the raw soil and would control pavement distortion very effectively

With the other method, a soil-cement mixture would be used containing enough cement to give a modified soil when hydration of the cement and manipulation of the mixture is properly controlled during construction This modified soil would have much lower volume change characteristics than the raw soil and would be similar in character to soils which do not produce pavement distortion In the case of this particular soil, the cement content required to change the character of the soil to that of one having small volume changes and moisture gradients is less than that required to give a permanently hardened soil. Therefore, in the course of time, weathering agencies would slowly granulate a hardened mixture to produce a modified soil similar to one obtained by pulverizing the same soil-cement mixture in the laboratory after the cement has hydrated In this case also, construction procedure similar to that used for the first method can be followed

CEMENT MODIFIED SOIL

Previous work in the soil-cement laboratory has indicated that the characteristics of soils are changed by the addition of cement, particularly volume changes accompanying moisture changes In this particular problem it is not necessary to strive for practically complete elimination of volume changes but only to change the soil characteristics to make the soils comparable with those which experience has shown do not cause pavement distortion

seven days in order to conserve time The soil-cement mixtures were dried, pulverized and the physical test constants determined at the ages indicated The results are given in Table 1, with the physical test constants of the raw soil The mechanical and hydrometer analysis of the grain size of the raw soil is shown in Figure 1 A few tests of physical constants on pulverized soil-cement mixtures one and two days old gave about the same physical test constants as those obtained on pulverized soil-cement mixtures seven days old and indicated very early influence of cement hydration on soil characteristics.

TABLE 1

TEST RESULTS ON RAW SOIL AND SOIL-CEMENT MIXTURES

	Raw Soil	Soil-Cement Mixtures (1) Containing						
		½% Cement (2)	1% Cement (2)	2% Cement (2)	3% Cement (2)	4% Cement (2)	5% Cement (3)	8% Cement (3)
Liquid Limit	54	51	48	46	45	45	45	41
Plastic Limit	24	24	24	25	27	28	34	33
Plasticity Index	30	27	24	21	18	17	11	8
Field Moisture Equivalent	31	31	31	33	32	31	37	34
$\frac{\text{Vol at S L}}{\text{Vol at F M E}} \times 100$	80 2	80 4	83 3	81 8	85 9	95 2	89 6	91 6
Shrinkage Limit	17	17	20	20	22	28	29	28
Shrinkage Ratio	1 8	1 8	1 8	1 7	1 6	1 5	1 5	1 5
$\frac{\text{Vol at S L}}{\text{Vol at L L}} \times 100$	60 5	62 5	65 8	69 0	73 2	79 2	80 1	83 6
U S B P R Soil Group	A-7	A-7	A-7	A-7	A-7-5	A-7-5	A-5-7	A-5-7

(1) Cement content based on volumes when compacted at optimum moisture by standard Proctor procedure

(2) Constants determined on pulverized soil-cement mixture by U S B P R standard procedure after cement has hydrated for seven days

(3) Constants determined on pulverized soil-cement mixture by U S B P R standard procedure after cement has hydrated for 43 days

In order to determine the influence of cement on soil characteristics, cement was added in quantities of ½, 1, 2, 3, 4, 5 and 8 per cent of the volume of the mixture when compacted at optimum moisture by the Proctor procedure The soil-cement mixtures containing 5 and 8 per cent cement were permitted to hydrate for 43 days The soil-cement mixtures containing ½, 1, 2, 3, and 4 per cent cement by volume were permitted to hydrate for

The specimens remaining from the shrinkage limit determinations are shown in Figure 2

The following discussion is based on a

comparison of raw soil with various soil-cement mixtures in which the cement has hydrated and the mixture pulverized. Pulverization of the soil-cement mixtures permits determination of physical test constants in the same manner as they are determined for a raw soil.

By referring to the physical test constants of the raw soil and soil-cement mixtures in Table 1, it will be seen that adding cement to soil and allowing time for it to hydrate, changes most of the physical test constants.

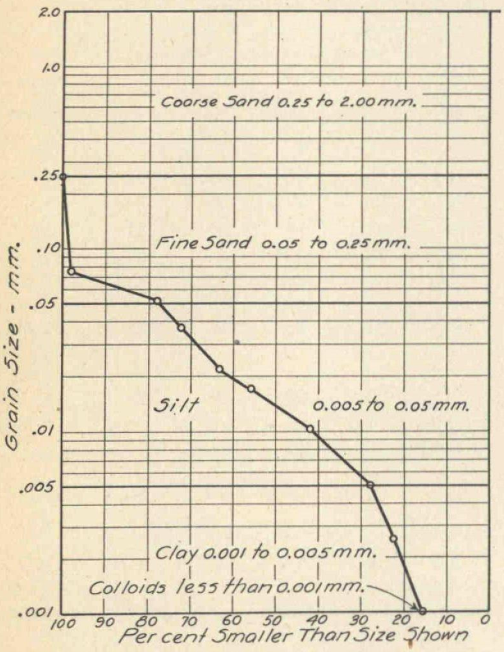

Figure 1. Mechanical and Hydrometer Analysis. Laboratory Soil Sample No. 1, Clay Loam Subsoil, Group A-7.

The liquid limit of the raw soil is 54, and, as increasing amounts of cement are added, it is lowered to 41 for the soil-cement mixture containing 8 per cent cement. In this particular soil it is probable that the cement exerts its greatest influence in reducing cohesion of the soil particles in the pulverized material.

The plastic limit of the raw soil is 24 and, with increasing amounts of cement, it is increased to a maximum of about 33 or 34 with 5 to 8 per cent cement. Moisture evaporates very much slower from soils when the moisture content is below the plastic limit than when it is above the plastic limit. Therefore, the raising of the plastic limit will be effective in reducing the rate of moisture change and the rate of volume change of the soil under similar drying conditions, which will be helpful in reducing pavement distortion.

The plasticity index of the raw soil is 30 and, with increasing amounts of cement, is reduced to a minimum of 8. This reduction in plasticity index is definite evidence that the cohesion of the soil particles in the pulverized mixture is materially reduced and approaches the values found in sandy, silty soils.

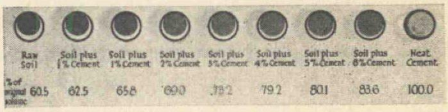

Figure 2. Relation of Shrinkage Limit Pats to Liquid Limit Volumes. Relative Shrinkage, Kansas Subgrade Soil Sample No. 1 showing effect of added cement. The cement treated soils were moist cured, then dried and pulverized for the test. The inside diameters of the circles show the original volumes of the pats molded at the liquid limit condition.

The field moisture equivalent of the raw soil and the soil-cement mixtures are essentially the same. There is a tendency for the field moisture equivalent to be raised. However, in this problem, the significance of this moisture condition lies in the fact that it is the probable maximum volume and moisture content which will be found in the field without manipulation of the soil.

The relation of volumes at the shrinkage limit to volumes at the field moisture equivalent have been computed to show the maximum probable volume change which will occur in the field. As previously mentioned, the maximum probable moisture content will be near the field moisture equivalent and it can be presumed that a long period of hot, dry weather might reduce the moisture content of the subgrade to the shrinkage limit. Subsequent rains would tend to raise the moisture content of the subgrade at cracks, joints and edges, to the field moisture equivalent and, in case a steep moisture gradient is established in the subgrade soil, would produce pavement distortion

By referring to the ratios of the volumes at the shrinkage limit to the volumes at the field moisture equivalent it will be noted that the raw soil may undergo a 20 per cent volume change As the cement contents are increased, the possible volume change is decreased one-half or more to less than 10 per cent for the higher cement contents

The shrinkage limit of the raw soil is 17 and, with increasing amounts of cement, is raised to about 28 This is of particular interest in connection with soils having large volume changes producing pavement distortion for three particular reasons Since the shrinkage limit represents the moisture content at minimum volume

1 An increase in the shrinkage limit raises the permissible moisture content which will not produce volume changes In the raw soil, any increase in moisture content above 17 will produce corresponding volume increases In the modified soils containing 4, 5 and 8 per cent cement, the moisture content must exceed 28 per cent before corresponding volume increases occur

2 An increase in the shrinkage limit without a corresponding increase in the field moisture equivalent reduces the possible volume range between a dry condition (shrinkage limit) and a probable maximum field moisture content In the case of the raw soil the difference between the shrinkage limit and field moisture equivalent is 14 This difference is progressively reduced in the modified soils, as the cement content increases, to 10 for 3 per cent cement, 8 for 5 per cent cement and 6 for 8 per cent cement The probable maximum volume change due to a change from minimum volume (shrinkage limit) to probable maximum field volume (F M.E) is reduced very materially, one-half or more, in the mixtures of higher cement content.

3 An increase in the shrinkage limit when accompanied with less of an increase in the liquid limit will result in a decrease in the total maximum volume change which can occur between the driest (shrinkage limit) and wettest (liquid limit) conditions of soil in the field The raw soil has a difference of 37 for these conditions and, as the cement content increases, the difference is progressively reduced to about 17 for the higher cement contents.

The relation of soil volumes at the shrinkage limit to soil volumes at the liquid limit are given in detail in Table 1 It will be noted that the volume of raw soil at the shrinkage limit is 60 per cent of the volume at the liquid limit This volume change is successively reduced, as the cement content increases, to about 80 per cent for the mixtures containing 4, 5 and 8 per cent cement These soil-cement mixtures have only one-half the possible maximum volume change possessed by the raw soil These data and photographs of the shrinkage limit pats are given in Figure 2

The lower column of Table 1, shows the U S B P R soil group according to the physical test constants of the soil It will be noted that the characteristics of the raw soil, an A-7, are gradually changed by the addition of cement to give an A-5-7 soil

SUMMARY OF CEMENT MODIFIED SOIL RESULTS

The foregoing discussion brings out the appreciable decrease, in probable volume changes which will occur in the Kansas soil after 4 per cent cement or more, has been added and this mixture considered as a modified soil and not a cement hardened earth subgrade. It was also pointed out that the modified soil has some of the characteristics of sandy, silty soils.

In considering the causes of pavement distortion due to volume changes in the subgrade, the possible moisture gradients in the soil are of importance It was noted in working with the soil-cement mixtures that they were more mellow and granular than the raw soil which would tend to produce a subgrade condition of uniform moisture content While tests of permeability and capillarity were not made, the changes in the physical test constants indicate that pulverized soil-cement mixtures would tend to maintain more uniform moisture contents throughout than the raw soil as moisture contents increased or decreased

Test constants determined on soil-cement mixtures at one and two days were found to agree closely with those given in Table 1 and indicate a very early influence of cement hydration on soil characteristics

The discussion and analysis of data from Table 1 indicates that cement contents of 3, 4 and 5 per cent will change the soil characteristics about a maximum amount These cement contents, by volume, are approximately equal to 27, 36, and 45 pounds of cement per square yard of surface on a basis of a 12-in treated depth

The use of cement contents around 5 per cent would produce a cement hardened soil for a time which would slowly change from a hardened cake condition to a granular condition in proportion to the severity of weather conditions So long as the hardened condition predominates, the possible volume changes are very small. As the hardened condition changes to a granular condition, the characteristics of the granular soil-cement mixture would prevail

The analysis of data pertaining to such pulverized soil-cement mixtures shows that volume change characteristics are materially reduced by cement contents of 3 to 5 per cent. The volume change characteristics of these modified soils are similar to those of soils which should not produce pavement distortion

In view of the benefits to be derived from a construction procedure which will produce a cement hardened subgrade at no extra cost, it is worth while to take full advantage of these benefits as long as they prevail, after which the subgrade will function as a cement modified soil Since the primary objective of this field research project was the production of a subgrade which would not undergo such volume changes that pavement distortion is produced, it was unnecessary to produce a hardened subgrade since the cement modified soil will accomplish satisfactory results. The cement modified soil treatment therefore becomes the preferred method because of lower material costs At the same time, the beneficial influence of the hardened soil, so long as it prevails, can be obtained at no extra cost A cement content of 5 per cent by volume (42 3 lb per sq yd) for a depth of 12 in was suggested for this initial installation as a result of these tests

Construction methods similar to those used in building hardened soil-cement roads were used Due to last minute changes in construction plans in the field the subgrade treatment incorporated 10 6 per cent cement by volume (90 lb per sq yd) for a depth of 12 in instead of 5 3 per cent originally specified by the State Highway Commission This was followed with standard concrete surfacing

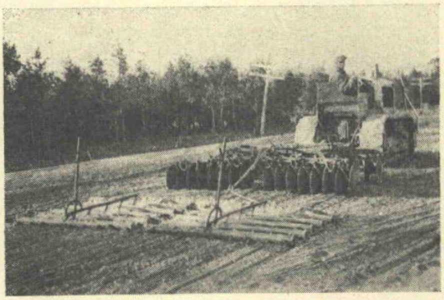

Figure 1. Disc and Spike-tooth Harrow Used for Pulverizing Clay, Wisconsin photo.

Figure 2. Quack grass diggers used in combination with disc cultivators in pulverizing scarified surfaces. Missouri photo.

Figure 3. Cement sacks were placed at a specified rate and emptied prior to spreading with a motor grader. Missouri photo.

Figure 4. Mixing cement with the soil. Illinois photo

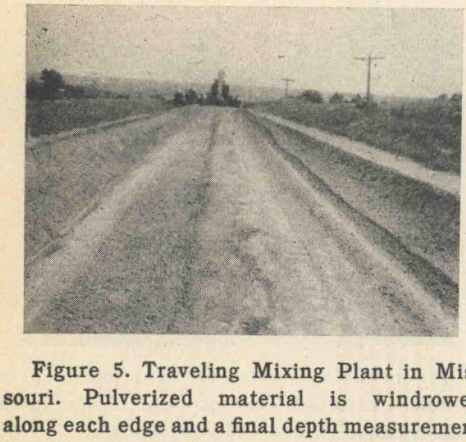

Figure 5. Traveling Mixing Plant in Missouri. Pulverized material is windrowed along each edge and a final depth measurement is taken. Note offset grade stakes along the shoulders. Windrows are joined along the centerline for the traveling plant. Missouri photo.

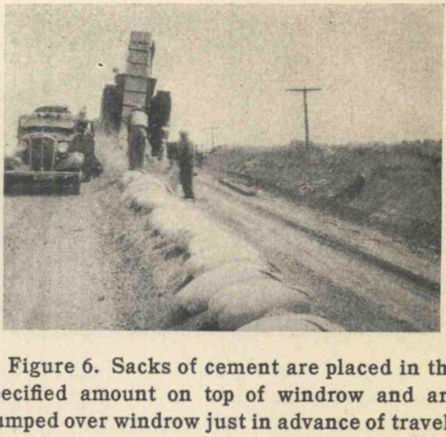

Figure 6. Sacks of cement are placed in the specified amount on top of windrow and are dumped over windrow just in advance of traveling mixing plant to prevent loss of cement by wind. Note some dusting at spiral feeders on machine. Supply truck is furnishing water for mix. Missouri photo.

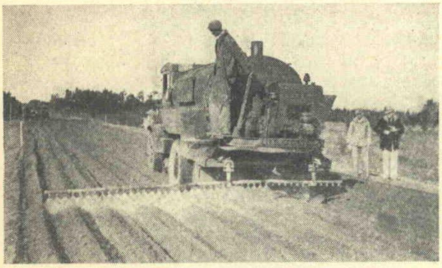

Figure 7. Oil distributor applying water. Wisconsin photo.

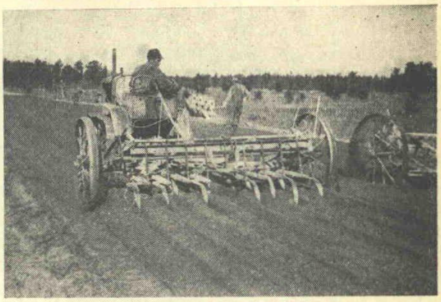

Figure 8. Quack grass digger used for all mixing operations. Wisconsin photo.

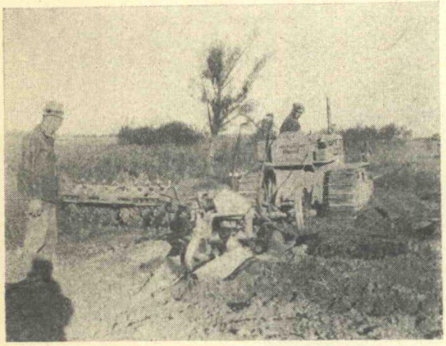

Figure 9. Fourteen-inch gang plow used in place of orchard cultivators during wet mixing. Note dry soil-cement mixture which is being turned up by the plow. Missouri photo.

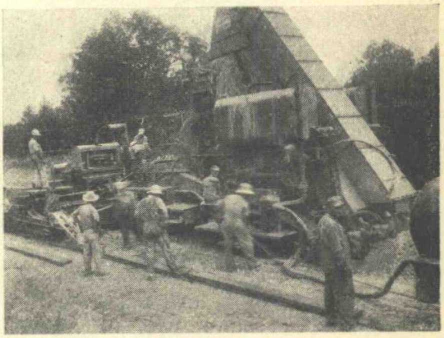

Figure 10. General view of traveling plant and finishing machine in operation. Missouri photo.

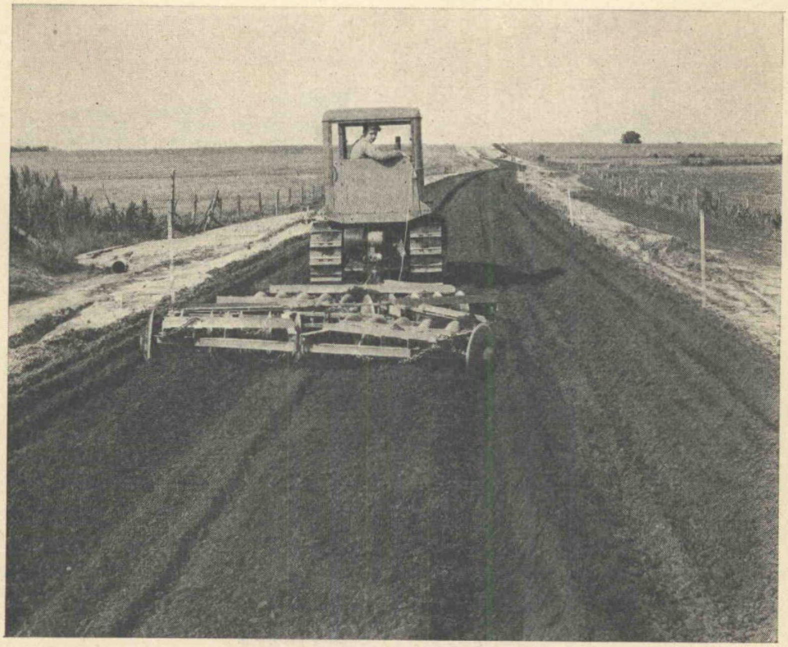

Figure 11. Surfacing material being loosened before being brought to line and grade and compacted. Illinois photo.

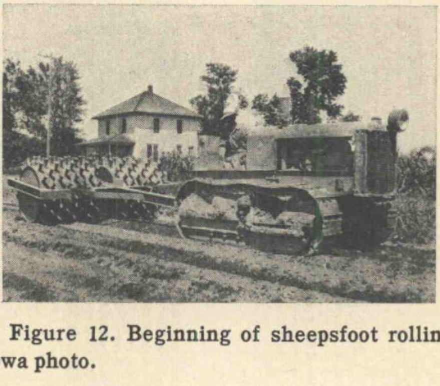

Figure 12. Beginning of sheepsfoot rolling. Iowa photo.

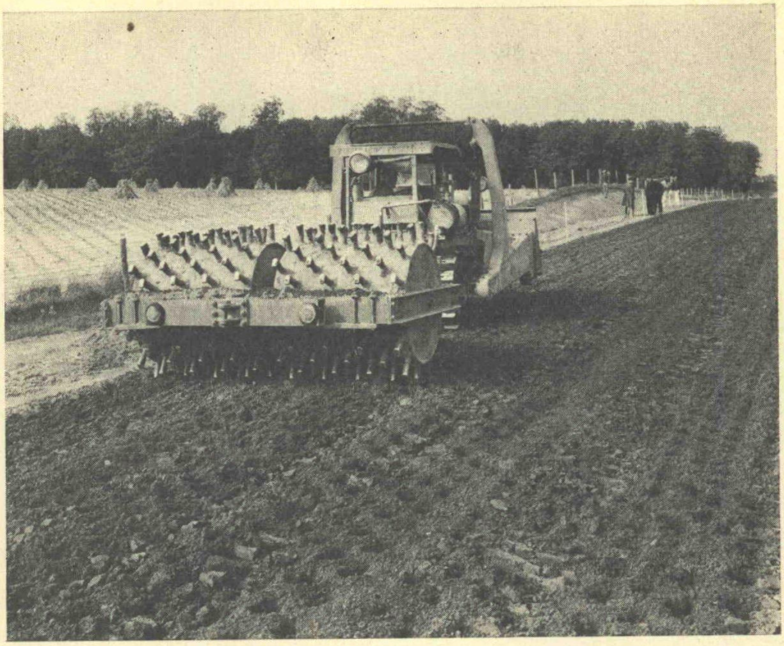

Figure 13. Compaction by sheepsfoot roller. Note drag bar placed in front of the roller to smooth and fill the roller marks made during the previous round. Illinois photo.

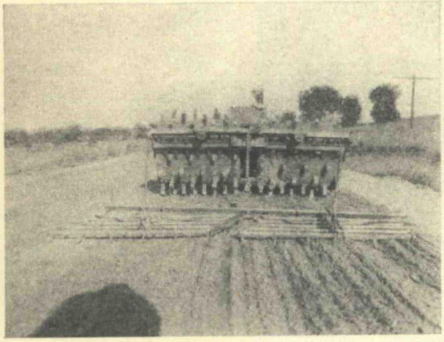

Figure 14. Final sheepsfoot rolling with small harrow attached to form a surface mulch for final smooth rolling. The surface was usually treated twice with this arrangement before smooth rolling. Missouri photo.

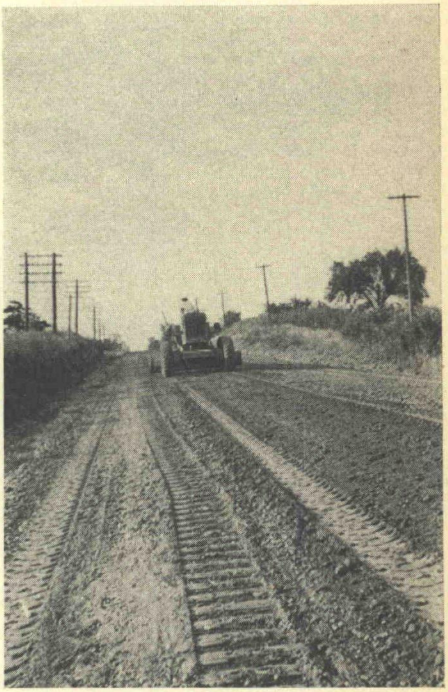

Figure 15. Preliminary shaping. Iowa photo.

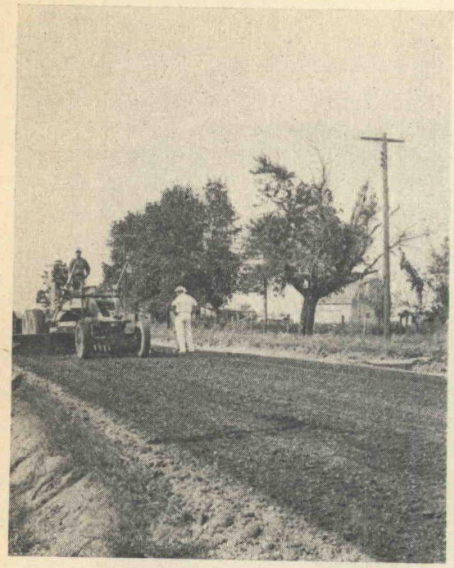

Figure 16. Final shaping with Auto Patrols. Iowa photo.

Figure 17. Pneumatic Roller. Iowa photo.

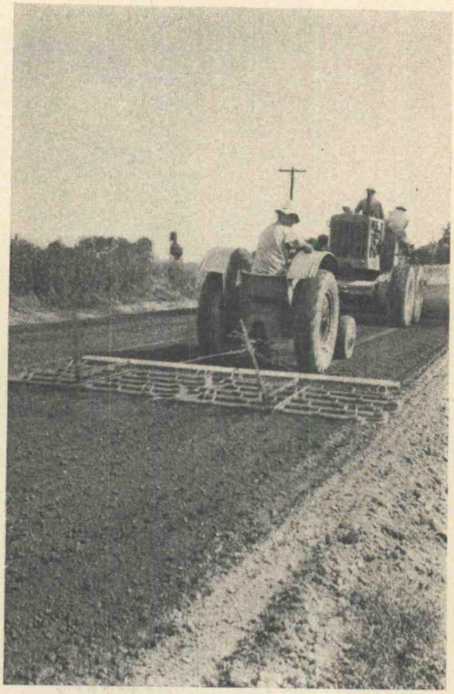

Figure 18. Removing compaction planes and preparing mulch for final packing. Iowa photo.

Figure 19. Final compaction with an 8-ton three wheel roller. Illinois photo.

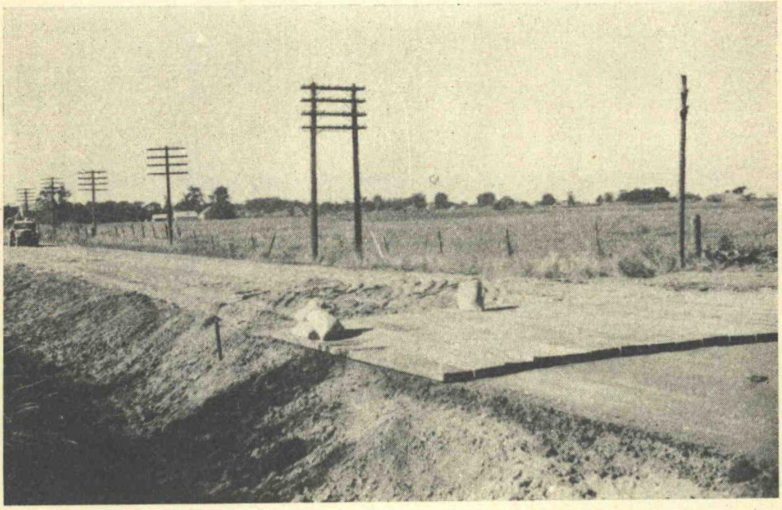

Figure 20. Spreading cement, and mat for turning. The truck and cement spreader is at the left; completed base at right. Iowa photo.

Figure 21. View showing straw placed on finished surface and covered with approximately six inches of dirt for turn-around for mixing equipment. Missouri photo.

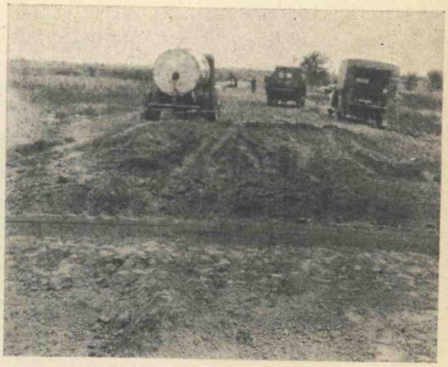

Figure 22. General view of turn-around and temporary wooden joint to be removed, after which the wet-mixed materials are pushed back into place. The length of the turn-around is about 30 ft. Missouri photo.

Figure 23. A typical turn-around, the mixed material windrowed on either side of the next increment, and the cement ready to be placed. Illinois photo.

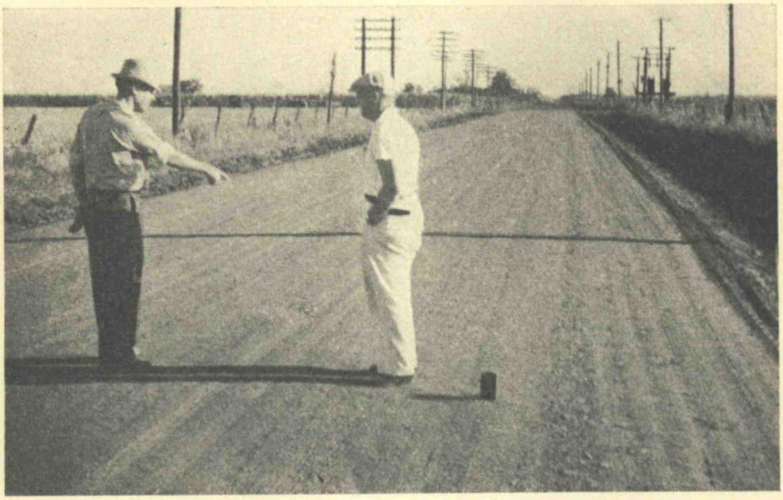

Figure 24. Completed base. Early morning inspection of previous day's run before application of prime. Iowa photo.

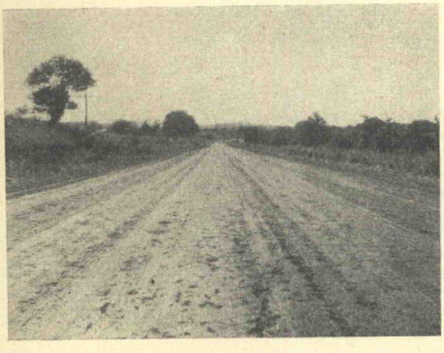

Figure 25. General surface appearance of 8 per cent cement soil-cement mixed-in-place base. Surface was primed with TC-2. Note some slight traffic pickup. Missouri photo.

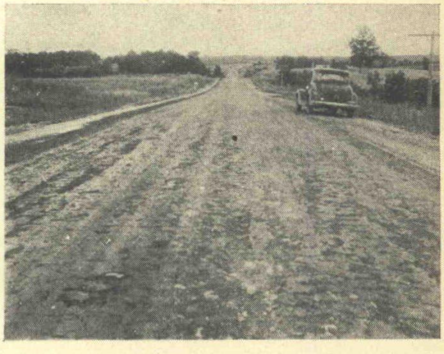

Figure 26. General view of surface on 8 per cent soil-cement machine mix base. Ravelling occurred after priming but the prime coat kept it from becoming excessive. Several weeks later the left half was primed with TC-2 and the right half with MC-1. Missouri photo.

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