STABILIZING SOILS WITH PORTLAND CEMENT, EXPERIMENTS BY SOUTH CAROLINA HIGHWAY DEPARTMENT

By W H MILLS, Jr

Testing Engineer, South Carolina Highway Department

SYNOPSIS

Initial experiments with portland cement soil mixtures led in October, 1933, to the moulding of samples in the driveway of the laboratory to learn their resistance to weather and traffic These samples, consisting of top soil and rich sand clay soil were used with varying amounts of cement Their resistance to traffic was noticeably greater than that of the raw soil The first field experiment, a 528-ft section of road in good sand clay soil was constructed in December, 1933, the soil in place being pulverized, and cement applied to the surface at the rate of one bag per linear foot of 20-ft roadway Cement and soil were mixed dry, sprinkled, mixed wet, shaped and rolled After being under traffic a year, the road was covered with a one-inch sheet asphalt wearing course A few pot-holes developed prior to application of surfacing, but there was no indication of raveling or general break-down

In the Summer of 1935 a test section known as the Johnsonville Experiment was undertaken with preliminary laboratory study of soil compaction and of the resistance of soil cement mixtures to repeated wetting and drying, freezing and thawing From the laboratory tests and experience on previous experiments it was decided to use 6 per cent of cement in most of the field work plus one per cent for loss in placing and mixing

A temporary wearing course of cut back asphalt and sand was applied soon after the base was completed An inspection during the Spring showed the surfacing in good condition, with no failures except in two small poorly constructed areas where cracking and small pot-holes had developed. Sections left unsurfaced showed the effect of traffic by shallow pot-holes and wear of the top crust

In the opinion of those associated with the project the sheeps foot roller is better for obtaining compaction than tractors and loaded trucks Tests of cores indicated that mixing of the cement was fairly uniform throughout the samples Average compressive strength at 86 days was 480 pounds per square inch, the low being 350 and the high 581 Durability tests clearly indicated the benefit of adding cement to raw soil

Continuation of this method of soil stabilization applied to 2 miles of road during the summer of 1936 (Loris Experiment) was used as a test for specifications written for this type of work, as well as for improvement in equipment At the time the wearing course was applied in July, this base appeared to be in excellent condition

No attempt is made to draw definite conclusions The action of weather and traffic will in time evaluate the worth of this method of stabilization The present indication is that treatment of soils with portland cement has appreciable merit and is possible and comparatively economical for many light traffic roads in South Carolina

EARLY EXPERIMENTS

Experiments with portland cement-soil mixtures were started in the laboratory of the South Carolina State Highway Department in 1932 at the suggestion of the late Dr Charles H Moorefield who was at that time state highway engineer

The initial laboratory work was started in 1932, the first field experiment was placed in December 1933, and four other field experiments were constructed in July 1934 In all of these early experiments cement was mixed with dry soil until it was uniformly distributed, then water sufficient to dampen the mixture was added and mixed and this mixture was tamped in place before the moisture evaporated

The preliminary investigation consisted

of molding cement-soil mixtures into small pats for observation After these tests showed that cement-soil mixtures would harden, larger specimens (about 2 ft by 2 ft x 6 in) were molded in the driveway at the laboratory to learn their resistance to weather and traffic These specimens were cast in October 1933 and are still under test Although they show the effects of weathering and traffic, they are intact and have retained their original form One set of specimens was made of top soil with one, two, three and four bags of cement per cubic yard, and the other with rich sand clay soil and these same quantities of cement The resistance of these specimens to traffic, even the one containing only one bag of cement, was noticeably greater than the raw soil

The first field experiment was built in December 1933 This section was 528 ft long, and it was constructed in a good sand clay soil The soil in place was pulverized and cement was applied to the surface at the rate of one bag per linear foot of 20-ft roadway as inspections of the laboratory specimens indicated that this quantity would be necessary to stabilize the soil The cement and soil were mixed in place until the mixture was uniform in color This mixture was then wetted by sprinkling the surface and mixing the water with the soil and cement This mixture was shaped to the approximate cross-section with a road machine and rolled with loaded trucks and a roller

The morning after construction the surface had hardened so that a road machine could not remove ruts left by the compacting equipment Cracks, in some places only six inches apart, soon appeared but these did not seem to increase after most of the moisture had evaporated The section was covered with a wearing course of one inch of sheet asphalt after it had been under traffic about one year When covered, the surface showed the effect of traffic by a few small pot-holes, but there was no indication of raveling or general breakdown This section has been under traffic continuously since it was constructed

As a result of inspections of this experiment and the laboratory specimens in March 1934 the Portland Cement Association offered to furnish cement for additional experiments With this help, four additional experiments were made in July 1934 One of them is in low grade top soil, one in red clay soil, one in good sand-clay and the other in very poor sand-clay The method of construction was similar to that used for the first experiment

The quantity of water which was added was limited by the fact that it could not be uniformly distributed for the full depth of the mixture and when the surface became "slick" no more water was applied All of the experimental sections hardened rapidly after the mixtures were compacted and in 24 hours were so hard that the surface could not be easily planed with a road machine On two of the sections where the clay content was high, above 50 per cent in one instance, there were numerous shrinkage cracks This cracking appears to vary with the quantity of clay in the soil but it did not seem to affect adversely the stability of the mix, and there is some indication that the cracks close when the mix is wet Cores drilled from these experiments showed an average thickness of from 1 2 to 4 8 in on different sections, whereas the plan was to stabilize at least 6 in

These sections were covered with a wearing course approximately three months after construction, and, although they have been under traffic continuously since they were constructed, they are in good condition at the present time A short account of this early work was published in the November 28, 1935, issue of Engineering News-Record

JOHNSONVILLE EXPERIMENT

In the spring of 1935, after these experimental sections had been under traffic for nine months, the Development Department of the Portland Cement Association offered to aid in an additional experiment to study more extensively and intensively this method of stabilization. In accepting this offer, it was decided to include a cement section approximately 1 5 miles long on Project NRM & NRH 326 & 380, located on State Route 51 and 175 between the city limits of Johnsonville and Hemingway. The project was constructed in three sections to study the practicability of three methods of stabilizing soil Tar was used on a section 5400 ft long, cement on 7850 ft and cut-back asphalt on 7166 ft. The methods of using the bituminous materials and the results obtained were briefly described in a paper presented at the January 1936 meeting of the American Road Builders' Association by J S Williamson, State Highway Engineer

The soils in the entire project are similar consisting of a natural mixture of fine sand, silt, and clay, but the clay content varies considerably and wide variations were found within a few hundred feet due to the manner in which the road was graded The soil as found in the subgrade was used in every instance and no selected material was brought in and no attempt was made to fit any of the above stabilizing materials to any particular location The physical test constants and grain size of samples of soil representing the material in the subgrade throughout the project are shown in Table 1

A short series of preliminary laboratory investigations for control of field construction and an outline for the field experiments predicated on laboratory results and including the use of a sheeps foot roller for compacting the field mixtures were submitted by the Development Department of the Portland Cement Association and adopted by the highway department for this experiment

The preliminary laboratory work was predicated on the principles of soil compaction established by R R Proctor[1] of the Los Angeles Water Board, and on the durability or resistance of soil-cement mixtures to repeated wetting and drying and freezing and thawing

Tests were conducted to determine the moisture-density relations of the raw soil and the soil-cement mixtures The cement contents are based on the oven dry weights of the soil In addition, specimens of soil-cement mixtures compacted at the optimum moisture content were prepared, cured for 7 days and subjected to durability tests to determine the desirable cement content to use in the field The unit dry weight of the compacted mixture gave the data required for computing the quantity of cement required per square yard of treatment

In general the laboratory mixtures of each soil were made with 2, 4, 6 and in some instances 8 per cent cement by oven dry weight of soil The moisture-density relations of these mixtures and similar relations for the raw soil are shown in Figures 1 to 9 inclusive It will be noted that with one exception the soil-cement mixtures have higher densities or unit dry weights than the raw soil and that there is a slight decrease in the optimum moisture content producing this maximum density

Durability tests were of two types: (1) The specimens were first subjected to repeated wetting and drying and then (2) subjected to repeated freezing and thawing which also included wetting and drying Specimens about $1\frac{1}{2}$ in in diameter and 2 in high were drilled from

[1] "Fundamental Principles of Soil Compaction" by R R Proctor, Field Engineer of Waterworks and Supply, Los Angeles, California ENGINEERING NEWS-RECORD, August 31, September 7, 21 and 28, 1933

TABLE 1

ANALYSES OF TYPICAL SOIL SAMPLES TAKEN FROM ROADWAY

Laboratory No	Section No	Analysis of Sample as a Whole: Pass No 10[1]	Analysis of Sample as a Whole: Silt	Analysis of Sample as a Whole: Clay by Elutriation	Analysis of Material Passing No 10 Sieve — Gradation of Material Above No 200—After Wash: Ret No 20	Pass No 20 Ret No 60	Pass No 60 Ret No 100	Pass No 100 Ret No. 200	Gradation of Portion of Material Passing No 200 Sieve — Elutriation Test: Silt	Elutriation Test: Clay	Hydrometer Test: Fine sand No 200–270	Hydrometer Test: Silt 05–005 mm	Hydrometer Test: Total Clay Below 005 mm	Hydrometer Test: Colloidal Clay Below 001 mm	Specific Gravity[3]	Soil Constants — Tests on Portion of Original Sample Passing No 40 Sieve: Field Moisture Equivalent	Liquid Limit	Plasticity Index	Shrinkage Limit	Volume Change
A-21510	2	99 8	16 2	22 4	2 0	10 6	27 8	21 0	16 2	22 4	4 6	17 5	17 6	10 9	2 60	11 6	19 3	6 5	12 3	11 3
A-21513	3	99 7	15 8	26 1	1 6	6 6	28 4	21 4	15 8	26 2	4 2	17 8	20 6	15 1	2 60	16 4	24 7	8 7	28 2	13 8
A-21517	4	99 8	8 6	30 5	1 4	8 8	35 2	15 4	8 6	30 6	3 1	10 6	27 3	22 3	2 60	15 7	32 9	16 4	15 1	23 9
A-21518	4	99 8	8 6	15 4	1 2	10 2	41 6	23 0	8 6	15 4	3 0	10 8	13 2	8 9	2 56	14 7	19 2	[2]	12 6	10 9
A-21710	5	99 8	7 2	22 6	0 8	10 0	32 8	26 6	7 2	22 6	2 0	11 0	16 8	13 2	2 62	15 5	20 9	4 6	14 8	13 8
A-21691	6	99 7	6 0	16 0	2 2	21 2	33 6	21 0	6 0	16 0	2 3	7 0	13 7	9 6	2 60	15 1	19 1	[2]	15 7	4 5
A-21692	6	99 8	6 2	24 8	1 8	12 0	39 8	15 4	6 2	24 8	0 9	6 5	22 7	17 7	2 66	17 1	27 8	9 3	13 3	9 3
A-21686	7	99 5	8 6	21 3	2 2	11 4	31 4	25 0	8 6	21 4	1 7	7 3	23 2	16 2	2 60	19 3	20 8	3 2	16 8	6 2
A-21689	7	99 4	8 2	13 9	2 4	6 8	45 8	22 8	8 2	14 0	2 0	8 3	11 9	8 4	2 65	14 8	17 4	[2]	13 9	7 6
A-22551	8	99 7	5 6	30 5	2 2	16 6	29 0	16 0	5 6	30 6	0 0	8 3	25 7	18 9	2 56	15 7	28 4	21 7	14 9	24 2
A-21683	8	99 4	7 3	13 9	2 4	11 8	42 4	22 0	7 4	14 0	2 0	6 4	11 9	8 8	2 60	16 5	18 2	[2]	16 1	2 9
A-21883	9	99 7	5 6	9 8	1 8	15 8	44 0	23 0	5 6	9 8	0 6	6 9	7 9	5 2	2 63	16 3	17 5	[2]	20 6	7 3
A-21888	9	99 9	5 6	15 0	2 0	11 0	44 2	22 2	5 6	15 0	0 7	7 4	13 1	7 8	2 60	17 5	18 7	[2]	15 2	6 2
A-21880	10	99 8	7 0	17 4	2 4	9 6	39 0	24 6	7 0	17 4	4 8	7 9	12 8	10 0	2 54	16 0	19 7	2 5	17 8	6 2

Notes These samples were chosen after the soil was pulverized and before cement was applied
[1] 100% Passes ⅜″ screen
[2] Not obtainable
[3] Test made on material passing No 10 sieve

the mixtures after they were compacted in the Proctor mould at the optimum moisture content All specimens were cured in air for 7 days before the durability test was started but no attempt was made to provide moisture for curing At the end of this period, the specimens were weighed and immersed in water at 70°F for 18 hours The control specimens of raw soil had slumped at the end of this initial period and only slightly resembled their original shape A picture of these specimens after the first immersion period is shown in Figure 10

Durability tests of the specimens were continued by removing the specimens from water and drying them in an oven at a temperature of 300°F for 8 hours They were then allowed to cool in air, brushed lightly with a wire brush, weighed and then immersed in water at 70°F for 16 hours After 15 such cycles, the losses were surprisingly small, and the opinion was formed that a sufficient quantity of cement properly combined with the soil would result in a stable, durable mixture

The same specimens that were used in the wetting and drying tests were next subjected to freezing and thawing tests in conjunction with wetting and drying in order to study their resistance to this more severe treatment The freezing and thawing cycle consisted of drying the specimens at 300°F for 15 hours, soaking them in water at 70°F for 8 hours, and placing them in the refrigerator in which the air temperature was 20°F for 16 hours They were then removed and allowed to thaw in air at room temperature for 8 hours, redried in the oven as before, brushed lightly with a wire brush and weighed to determine the loss The results of these tests are shown in Table 2 and Figures 1 to 9 inclusive

Based on information obtained from 15 cycles of wetting and drying and on the experiments previously conducted, it was decided to add 6 per cent cement by weight in most of the field experiment but 4 per cent of cement was considered sufficient on 2500 feet of the project Due to the absence of information as to the losses which would be incurred in placing and mixing the cement in the field, it was decided to increase the quantity of cement actually used to 7 per cent and 5 per cent respectively. According to the results of the durability tests it would have been possible to decrease the quantity of cement used but the saving in cost made possible by these reductions would have been so small that they would not have been justified in this work where so many new construction problems had to be solved

In addition to these laboratory tests, a series was conducted to determine the possibility of adding cement in the form of "slurry" The required quantity of cement and water were mixed and then this mixture was combined with the dry soil It was noted during the mixing of "slurry" and soil and again after this mixture was compacted in the mould and the top shaved that small balls of cement varying in size from $\frac{1}{8}$ to $\frac{1}{4}$ in diameter had formed Because of the formation of cement balls, it was decided not to try a

---

Figures 1–9. Density and Durability Curves of Tests on Laboratory Cores

Density specimens made by Proctor method Durability specimens cut from samples immediately after compaction in Proctor mold at optimum moisture content.

For the wetting and drying tests one cycle consists of: 8 hours wetting at room temperature, approximately 70°F , 15 hours drying at 300°F. and 1 hour cooling at room temperature (70°F. approx.).

For the freezing and thawing tests one cycle consists of. 8 hours wetting at room temperature approximately 70°F., 16 hours freezing at 20°f., 8 hours thawing at room temperature (70°F., approx.), 15 hours drying at 300°F., 1 hour cooling at room temperature (70°F , approx.).

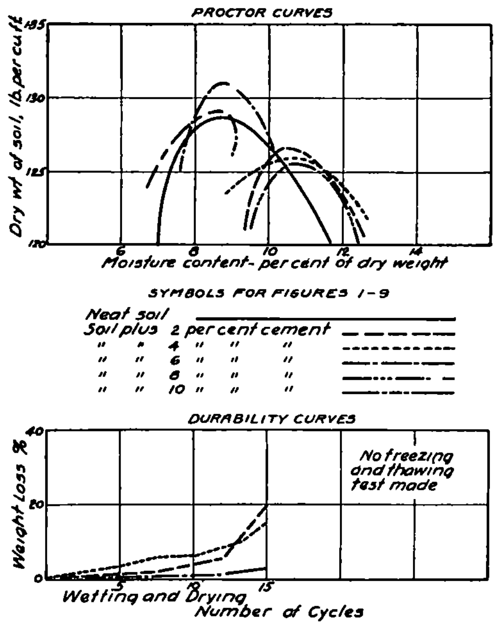


Figure 1. Density and durability of laboratory cores. No 19967, Passing No 10 sieve 98.5%, silt 14 8%, clay 24%, F.M.E. 14 2, L.L. 21.1, P.I. 10.5.

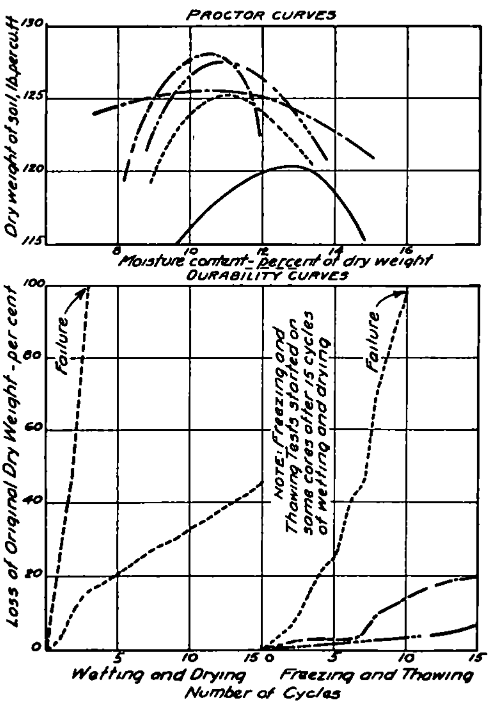


Figure 2. Density and Durability of Laboratory cores. No. 19968. Passing No. 10 sieve 99.7%, silt 12%, clay 27.3%, F.M.E. 14.4, L.L. 24.8, P.I. 14 6.

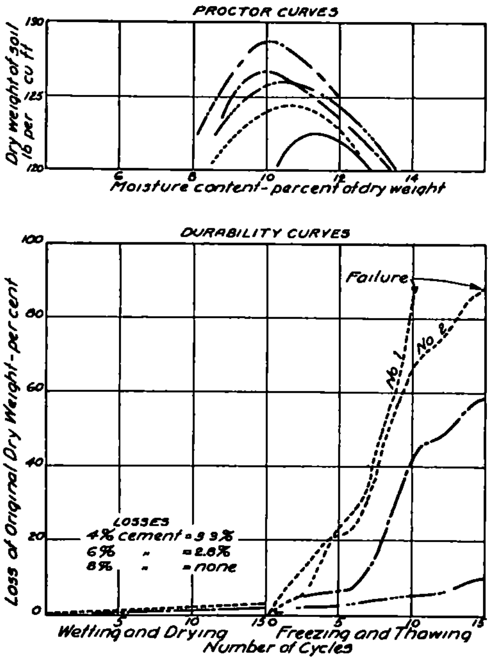


Figure 3. Density and durability of laboratory cores No. 19969, Passing No. 10 sieve 99.6%, silt 10 4%, clay 30 1%, F M E. 17 4, L L 37.8, P I 23 2.

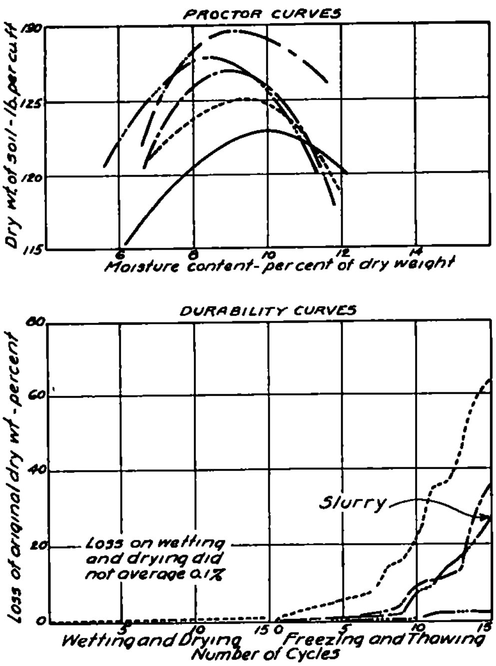


Figure 4 No. 19970, passing No. 10 sieve 99.3%, silt 6%, clay 17.5% F M E. 14.1%, L L. 17 8.

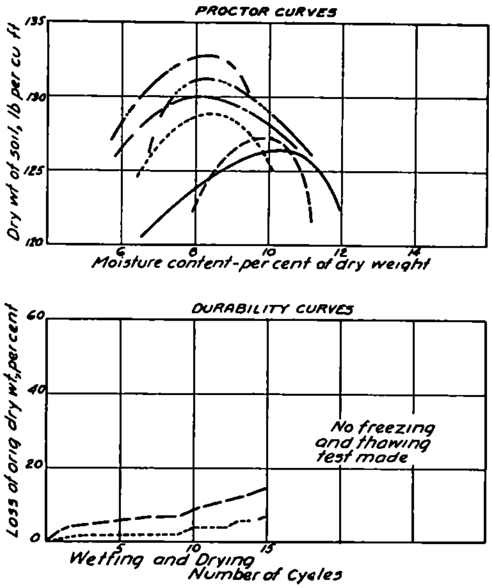


Figure 5 No 19971, Passing No 10 sieve 99 6%, silt 6 2%, clay 19 5%, F M.E 13 9, L L 19 0

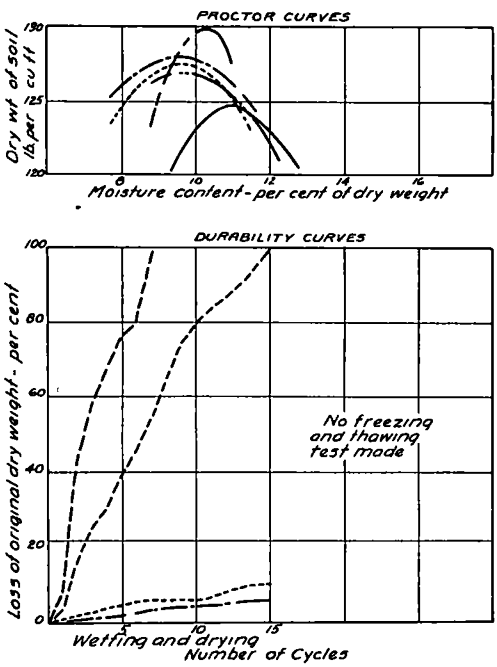


Figure 6. No 19972, Passing No 10 sieve 99.0%, silt 1.2%, clay 26 5%, F.M.E 14 0, L L. 21 0, P.I 13 2.

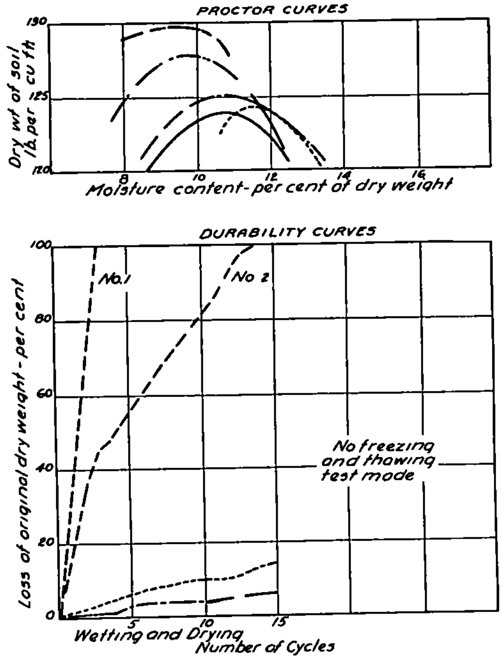


Figure 7 No. 19973, Passing No 10 sieve 99 1%, silt 2 9%, clay 23 2%, F M.E 17 8, L L. 32.1, P I 18.7.

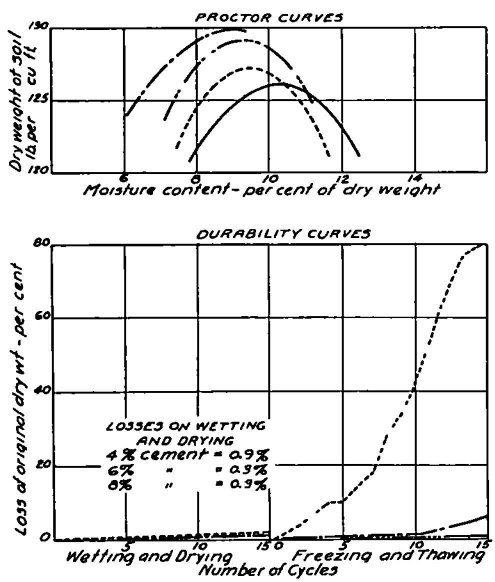


Figure 8. No. 19974, Passing No 10 sieve 99.2%, silt 8.7%, clay 16.1%, F.M.E. 15 6, L L. 18.8.

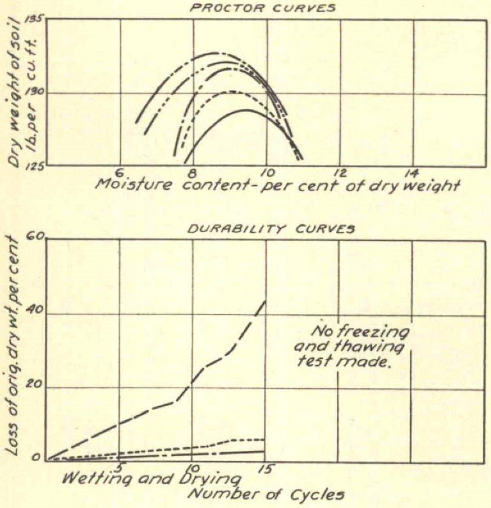


Figure 9. No. 19975, Passing No. 10 sieve 98.9%, silt 6.3%, clay 23.1%, F.M.E. 13.8, L.L. 21.8, P.I. 11.6.

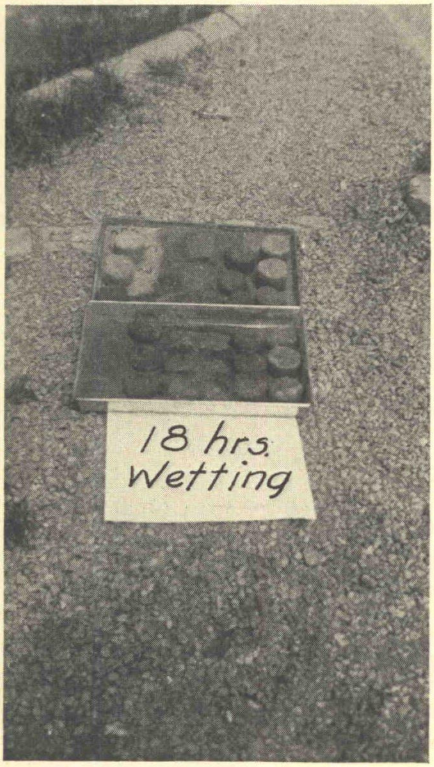


Figure 10

field experiment with the cement added to the water to form a "slurry." However, several durability specimens of the laboratory mixtures were tested along with the other specimens mentioned above and the low losses of these specimens were very surprising considering the fact that the cement in balls was probably not effective. The results obtained are shown on the curve marked "slurry," (Fig. 4). These results indicate that further investigations of "slurries" should be made.

FIELD EXPERIMENTS

The field experiments were started on September 17, 1935, but the last section was not completed until November 21 1935. Weather conditions in November contributed to delay on several sections.

Except for initial pulverizing, each section was constructed completely during one day. This procedure was necessary because of the rapidity at which the cement hardened after water was applied and the necessity for compacting the mixture at the optimum moisture content before the cement had set. The method consisted of mixing in place the cement and soil, then adding and mixing water and compacting this damp mixture.

As stated above the cement content and the thickness of the roadway were varied on some of the sections and a summary of the theoretical quantities as well as the station of each section and date are given in Table 3. .

The equipment used in constructing all sections was practically the same but many changes were made in the methods of using the different pieces of machinery. A short description of the various construction operations together with the equipment used follows:

(1) *Pulversizing:* Scarifier pulled by a 30 or 60 horse power crawler tread tractor and a 20-in. disc harrow pulled by a 30 horse power crawler tread tractor.

(2) *Applying Cement:* Sand spreader

TABLE 2

DURABILITY OF LABORATORY SPECIMENS

Section Number	Station Number	Laboratory Number	Cement %	Loss After 15 Cycles: Wetting and Drying %	Loss After 15 Cycles: Freezing and Thawing %	Cycle at which Failure Occured
1 and 2	1330	A-19987	2	20 0	b	c
			4	15 0	b	c
			6	3 0	b	c
3	1335	A-19968	2	a	b	3 W
			4	45 0	a	11 F
			6	2 0	22 0	c
			8	1 3	6 5	c
4	1345	A-19969	2	a	a	1 W
			4	3 3	88 0	17 F
			6	2 8	58 0	c
			8	g 0 1	10 5	c
5	1392	A-19974	4	0 9	80 0	c
			6	0 3	6 8	c
			8	0 3	0 5	c
5	1408	A-19975	2	44 0	b	28 W
			4	6 0	b	c
			6	4 1	b	c
6	1388	A-19973	2	a	b	11 W
			4	14 0	b	c
			6	6 0	b	c
7	1377	A-19972	2	a	b	10 W
			4	10 2	b	c
			6	6 0	b	c
8	1367	A-19971	2	15 0	b	c
			4	7 0	b	c
9 and 10	1358	A-19970	4	g 0 1	62 5	c
			6	g 0 1	5 5	c
			8	g 0 1	3 0	c

Notes a—Failure before 15th cycle
b—This series not run
c—No failure at end of plotted cycles
W—Wetting and Drying Cycle
F—Freezing and Thawing Cycle
g—Less than

Both wetting-drying and freezing-thawing tests were made on the same specimens Freezing and thawing were started after 15 cycles of wetting-drying

for spreading cement on the surface of the pulverized soil and ten $1\frac{1}{2}$-ton trucks for hauling cement

(3) *Mixing* Road machine, with 12-ft. blade and 20-in mould board, pulled by a 60 horse power crawler tread tractor, multiple blade drag with 20-in mould board pulled by a 60 or 75 horse power

crawler tread tractor and a 20-in disc harrow pulled by a 30 or 60 horse power crawler tread tractor

(4) *Applying Water* Asphalt distributor having a capacity of 1000 gal and four feeder trucks having a capacity of 600 gal each

(5) *Compacting* One sheeps foot roller filled with water so that the pressure on the feet was 100 lb per sq in Feeder trucks loaded with water were used for compacting the top mulch

(6) *Finishing* One hand operated road machine pulled by a 60 horse power crawler tread tractor

TABLE 3

Section Number*	Length	Theoretical Cement Content	Theoretical Thickness	Date Constructed
	feet	%	*inches*	
1	500	7	6	10/ 5/35
2	650	6	6	10/10/35
3	825	7	6	10/14/35
4	805	7	6	10/16/35
5	820	7	6	10/21/35
6	1000	7	4	10/22/35
7	800	7	6	10/23/35
8	800	7	6	10/25/35
9	720	5	4	11/ 1/35
9 A	530	5	4	11/14/35
10	420	9 7	4	11/21/35
10	300	5 3	4	11/21/35

* Sections are numbered in the order in which they are constructed

WEARING COURSE

Portions of the previously constructed soil-cement projects had not been surfaced so that they would be exposed to traffic The wear on these sections had shown the desirability of using a wearing course to give a smooth riding surface and prevent pot-holes and excessive wear. It had been planned, therefore, to construct a wearing course consisting of an application of tar prime followed by a mixed-in-place bituminous surface treatment of 50 lb of ½-in stone and 0 60 gal of cut-back asphalt per square yard This wearing course could not be constructed satisfactorily when Section 10 was completed due to cold weather and a temporary wearing course as described below was applied to all sections except No 10

The temporary wearing course consisted of an application of approximately 0 2 gal per sq yd of 4–8 viscosity tar which was allowed to dry for 10 days The average penetration of this prime coat into the base was ⅜ in The prime coat was followed with an application of approximately 0 3 gal per sq yd of naphtha cut-back asphalt, which was immediately covered with approximately 10 lb of sand This sand was rolled into the asphalt with a five ton roller, and the experiment was immediately opened to traffic This temporary wearing course was completed on December 7

Approximately 150 ft each of Sections 4, 5, 6 and 7 were not surfaced at the request of the Portland Cement Association so as to learn the effect of traffic on the unprotected cement soil mixture

The temporary wearing course was not applied on Section 10 due to the fact that this section had not dried sufficiently to permit the application of the bituminous materials It was applied the following April

DISCUSSION

SOILS

The soil in the road-bed was used and no selected soil was brought in nor was there any attempt to fit any stabilizing material to the soil at a certain location It so happened that the portion of the project allotted to the cement method of stabilizing contained more clay on the average than either of the other parts of the experiment

Referring to Table 1, it will be noted that wide variations in the clay content occurred The minimum clay content 5 2 per cent (Hydrometer Test) occurred in Section 9, and the maximum occurred in Section 4 where two samples contained 27 per cent clay (Hydrometer Test) Practically none of the sand particles were retained on a No 20 sieve and only about 15 per cent were retained on a No 60 sieve

PRELIMINARY LABORATORY TESTS

In making the determination for the optimum moisture content of soils in this experiment the rammer used was applied with more force than is obtained by dropping it through a distance of 12 in The operator retained the rammer in his hand and exerted some force as it descended

The cement contents required for the field experiments were determined when the laboratory specimens of cement-soil mixtures had completed 15 cycles of wetting and drying Freezing-thawing tests, which also included wetting and drying, were conducted on these same specimens As would be expected, the freezing and thawing test destroys the sample much more rapidly than the wetting-dry test but gives similar relative information No attempt has as yet been made to correlate these durability tests with actual service, but the results obtained on this project will serve as a basis for future comparison The durability tests are valuable in that they furnish a method of determining the comparative durability and stability of different raw soils and soil-cement mixtures and, therefore, supply a logical method for determining the cement contents required to meet field conditions

The durability tests, Figures 1 through 9, show quite clearly why 6 per cent cement was chosen as the theoretical cement content for most of the sections of this experiment There is a very marked decrease in the losses from specimens containing 6 per cent cement compared with similar ones containing 4 per cent cement It will be observed from reference to Table 2 and the durability curves in Figures 1 through 9 that most of these samples were intact after 15 cycles of wetting-drying and the additional 15 cycles of freezing-thawing

The results obtained in the field experiments confirm the opinion formed in the laboratory regarding the addition of cement in the form of a "slurry" Considerable trouble was experienced in Sections 1 and 9 with lumping of cement caused by too much moisture during mixing This trouble was not experienced on Section 10 apparently because the moisture in that section was uniformly distributed whereas in the other sections the moisture was added and had to be mixed

No trouble was experienced in the field due to hardening of the mix before the section was finished, but it will be necessary to control the time of mixing and compacting after water is added, and laboratory tests to determine the safe allowable time should be conducted

FIELD EXPERIMENTS

(a) *Cement Content* The theoretical quantity of cement to be applied on each section was calculated on the basis of 125 lb per cu ft, oven dry weight, of compacted soil-cement mixture Assuming a section 6 in thick, 22 ft wide and a theoretical cement content of 7 per cent, the theoretical quantity of cement to be applied was 96 lb per lin ft of roadway

(b) *Description of Operations* It was very interesting to one closely associated with the project to follow the developments in construction procedure from the awkward, uncontrolled two layer 500-ft method used on Section 1 to the smoother operation of constructing the one layer 800-ft sections placed last It was not possible with the equipment available to carry out the work so that a section could be finished during daylight, and grateful thanks must be paid to the operators of the finishing equipment for the smooth surfaces obtained Control of mixing and compaction, as well as other items, was poor on the first four sections Sections 5 to 10 were built with good control except that Section 9-A was built with soft shoulders which prevented good edge compaction and Section 10 was built with soft shoulders and subgrade which caused bad cracking in the surface since there was nothing substantial to pack against

Many improvements can undoubtedly be made in the equipment and methods of construction, but a summary of the best method developed on this project is as follows:

(1) Pulverizing: This work was accomplished effectively by first scarifying the soil to the desired depth with a scarifier and then pulverizing the lumps with a disc harrow assisted by a sheeps foot roller where dry hard lumps of soil are encountered.

(2) Spreading Cement: As the sand spreader used for this operation was only seven feet wide, it was necessary to make three trips over each section to cover the surface with cement The spreader was attached to and pulled by loaded dump trucks containing a known quantity of loose cement Considerable time was lost in spreading as each time a truck was emptied it was necessary to unfasten the spreader and attach it to the next loaded truck The moisture content of the soil should be below the optimum required for compacting, as high moisture contents cause the cement to form into balls

(3) Mixing Cement With Dry Soil: A disc harrow was first run slowly over the freshly spread cement in order to partially mix it with the loose soil The cement flows into the furrows cut by the discs and if the discs cut below the depth to be treated, the cement will flow into the bottom of the furrows and be lost as the other mixing equipment will not cut into the hard subgrade Mixing was completed by using a road machine and multiple blade drag simultaneously The drag follows the road machine and mixes the roll of material turned up by the road machine blade Mixing in this way was first performed on the edges and continued through the middle Approximately twelve trips of each machine were required for the dry mixing

(4) Application Of Water Water was applied with an asphalt distributor of 1000 gallons capacity This quantity of water was spread uniformly over the surface in one trip The distributor was filled at each end of the section by feeder trucks

(5) Mixing Water: Each application of water was partially mixed with a 20-in disc harrow pulled as rapidly as possible by a 75 horse power crawler tread tractor For most efficient mixing, it is necessary that the disc harrow be operated at a high rate of speed so that the discs will throw the material instead of merely cutting into it On sections 6 in thick, it was necessary to store approximately one-third of the dry mixture on the shoulders and apply and mix water to that remaining in the bottom layer, then bring in the stored material from the shoulders and mix water with it In order to wet the mixture efficiently on the edges, approximately 3 ft of the mixture near the edges was pulled toward the center of the road when the stored material was brought in from the shoulders After the water had been mixed with this material, the mixture was spread back to the edges before compaction was started The entire section was then loosened to the bottom with a disc harrow so that the sheeps foot roller could begin compaction at the bottom

(6) Compaction: The sheeps foot roller used for this operation was pulled with a 30 horse power tractor for the first few trips so that the feet of the roller could penetrate the mix easily, but a 75 horse power tractor was used when compaction had progressed as it could be operated

at higher speed On the average 800-ft. section, it usually required about $3\frac{1}{2}$ hours for the one roller used on this job to work itself to the surface It was found that the moisture content of the soil below the treatment and of that on the shoulders must be at the optimum or below to obtain satisfactory compaction The operation of the sheeps foot roller on soft sub-grades produces numerous fine cracks throughout the compacted surface similar to those occurring on Section 10 Usually about 1 in of loose material remained on the surface when the sheeps foot roller had compacted the mix as much as possible, and this loose material was shaped with a road machine to the correct cross-section and rolled with loaded trucks

(7) Finishing. The finishing operation consisted of blading the surface to the correct grade and cross-section with a hand operated road machine This operation determined the riding quality of the section and was done by very skillful operators This work was partly done during compaction and completed before the trucks had finished rolling the surface The road machine blade will not cut the surface of the hardened base the day after it is constructed, and therefore, it is necessary that the final surface be obtained as soon as possible after compaction

(c) *"Turn-Arounds"*: The connections between sections were a constant source of trouble on this project as the equipment, especially that used for mixing and compacting, was turned around each time the end of the section was reached On account of this turning the connections are called "Turn-Arounds "

Approximately 25 feet of a completed section was covered with 6 in of loose soil so that the discs, wheels, tracks, etc , of the machines used in constructing the adjacent section would not mar the surface when they were turned Part of the cement-soil mixture was always dragged forward into this protecting soil, and some of this soil was invariably pulled into the cement-soil mixtures as the machine started the return trip In trying to avcid these occurrences the blades of the mixing equipment were raised just before the end of the section was reached, and lowered only part of the distance at the beginning of the return trip These procedures caused thin places at the "Turn-Arounds," and it was realized that failures due to non-uniform mixing as well as insufficient depth would be likely to occur here

After the section had been compacted and finished, the soil which had been placed over the previously constructed section was removed with a road machine and the junction of the two sections was smoothed as much as possible Due to the hardness of the previously constructed section and the short distance through which the róad machine was operated, it was impossible to obtain a smooth connection

Very little time was spent on improving the method of constructing the connections between sections as it was believed that the difficulty could be satisfactorily solved on future work when more time would be available for study of this problem

(d) *Moisture Contents* The moisture contents of the different sections at the time of compaction are shown in *Table 4* These moisture determinations were made by drying samples of the full depth of the mixture in an open frying pan over a blow pot until there was no sign of moisture This process burned off vegetable matter as well as moisture and recent tests have shown that the variation between oven dried samples and those dried in this way may be considerable

Moisture contents as shown by samples were above the theoretical optimum in most of the sections This was due in part to treating depths less than theo-

TABLE 4

MOISTURE CONTENT OF SOIL BEFORE FIELD COMPACTION, CEMENT SECTION

Section	Station	Optimum Moisture %	Moisture in Soil %	Section	Station	Optimum Moisture %	Moisture in Soil %
	1321/50		Tests	6	1390	10 4	11 8
		10					
1	thru		Averaged	Average		10 4	11 6
	1326/50		9% Moist.	7	1374		11 5
2	1327		11 3		75		13 4
	28		12 5		76		12 7
	29		14 8		77		11 2
	30		16 8		78		10 9
	31		12 7		79		12 5
	32		13 5		80		14 8
	33		14 5	Average		10 0	12 4
	34		12 4	8	1367		10 1
Average		10 0	13 5		68		9 4
3	1335		15 6		69		11 1
	36		14 3		70		10 6
	37		14 9		71		9 9
	38		14 7		72		10 1
	39		14 5	Average		8.5	10 2
	40		15 3	9	1358		14 1
	41		15 4		59		14 1
Average		11.0	14 9		60		14 1
4	1342		14 0		61		15 7
	45		12 7		62		16 0
	46		13 7		63		16 9
	47		13 7		64		14 7
	48		14 4		65		14 6
	49		14 7	Average		8.8	15 0
	50		16 0	10	1352		11 1
Average		10 0	14 1		53		10 2
5	1392		12 2		56		10 5
	93		13 0		57		11 9
	94		13 6	Average		10 0	10 9
	95		14 2				
	96		13 9				
	97		12 2				
	98		11 6				
	99		12 5				
Average		9 0	12 9				
6	1382		14 3				
	83		8 5				
	84		12 4				
	85		11 2				
	86		13 6				
	87		11 1				
	88		11 1				
	89		11 4				

retical, in part to the fact that a small excess of water was applied to compensate for evaporation In one instance evaporation was more rapid than was expected, but generally little moisture was lost during the compaction period

(e) *Condition of Experimental Sections* Many inspections have been made but the results of only two are mentioned here

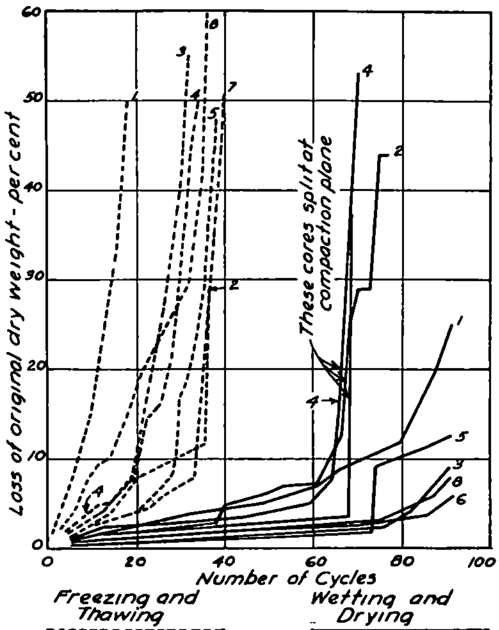


Figure 11 Durability Curves of Field Cores

Number	Station	Section
1	1325, 3 1 L.	1
2	1330, 6 3 R	2
3	1332, 6 0 R.	2
4	1338, 6 3 R	3
5	1346, 6 4 L	4, Spec 1
6	1346, 6 4 L.	4, Spec 2
7	1372, 7 6 R	8
8	1275, ctr.	7

A wetting and drying cycle consists of:
8 hours wetting at 70°F.
15 hours drying at 300°F
1 hour cooling at 70°F
A freezing and thawing cycle consists of:
8 hours wetting at 70°F
16 hours freezing at 0°F.
8 hours thawing at 70°F
15 hours drying at 300°F.
1 hour cooling at 70°F.
Cores brushed with wire brush before weighing after each cycle.

A careful inspection was made by two engineers of the department on January 9 as soon as the first extended cold spell had broken During this period the temperature was below freezing for 13 days and the ground was covered with snow for 3 days, in addition to several days of rain On this inspection, it was the opinion of both men that the sections were in good condition and that there was no failure except in the unsurfaced "Turn-Around" between Sections 6 and 7 where cracking had developed, and on the portion of Section 9 which was not reconstructed where small pot-holes were developing All of the unsurfaced sections were showing the effect of traffic by the formation of small, shallow pot-holes and some scaling of the top crust which had been compacted by trucks

On June 16, 1936, the experiment was inspected by Mr Catton of the Portland Cement Association and Mr Mills of the State Highway Department and the following observations were made.

Section 1—Surface in good condition—no failures In a few places, not larger than 8 in in diameter, the wearing surface had pulled off of the base The base was intact

Section 2—Surface in good condition—no failures

Section 3—Surface in good condition—no failures

Section 4—Surface in good condition—no failures The unsurfaced part of this section was slightly rough and uneven due to material breaking out of sheeps foot roller holes for a maximum depth of 1 in The edges were sharp See Figure 12

Section 5—Surface in good condition—no failures The part which was unsurfaced had not been seriously damaged and there was no apparent evidence of wear on small areas where the marks of the feet of the sheeps foot roller were still visible These marks were approximately 6 in on centers The crust which had been compacted by trucks had worn badly in some places and pot-holes as much as 2 in. deep had formed. Some areas were very smooth and show practically no evidence of wear. The condition of this unsurfaced area is shown in Figure 13.

Section 6—Surface in good condition—no failures except that an area approximately 2 ft. wide and 10 ft. long at a private driveway was cracked. At the "Turn-Around" connecting Sections 6 and 7, a complete failure about 10 in. in diameter developed. The damaged material, having a thickness of about 2 in., had been removed and the hole patched with a mixture of stone and asphalt. The remaining unsurfaced part showed evidence of wear, especially near the "Turn-Around." See Figure 14.

Section 7—Surface in good condition—no failures, except the "Turn-Around" previously mentioned. The part unsurfaced was showing the effect of traffic in places by pot-holes and scaling approximately 1 in. deep. Tire marks left by the loaded trucks in compacting the top crust were still visible in many places. See Figure 15.

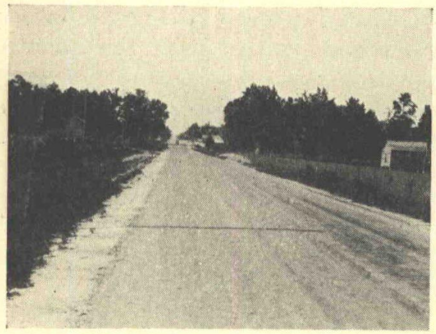


Figure 12. Finished Road, Section 4

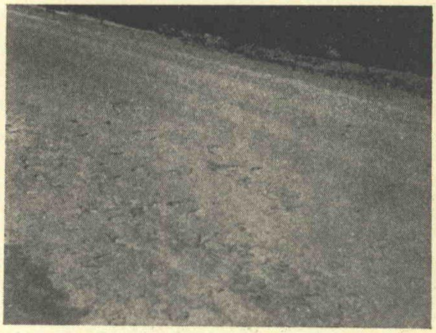


Figure 14. Turn-Around, S. End Section 6

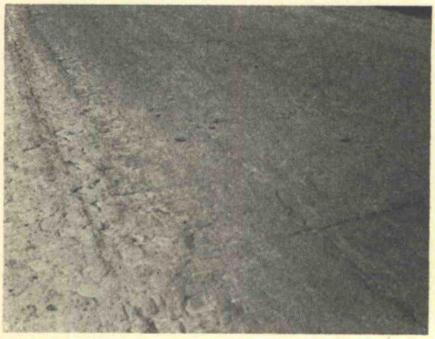


Figure 13. Turn-around, N. End Section 5

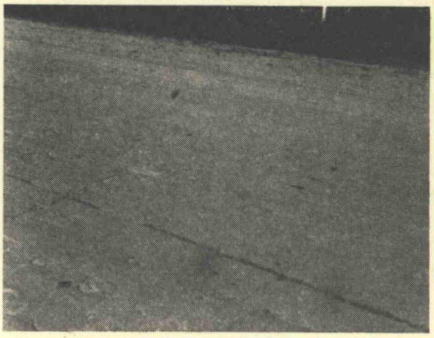


Figure 15. Turn-Around, N. End Section 7

Section 8—Surface in good condition—no failures. Figure 16, a photograph of this section shows the average condition of the surface of this experiment.

Section 9—Surface in good condition—no failures. The pot-holes which had developed during the winter had been patched with a mixture of asphalt and stone.

Section 9-A—Surface in good condition—no failures. No pot-holes.

Section 10—A wearing surface similar to that on the remainder of the experiment, except that a prime coat was not applied, was placed on this section during April. The surface was very rough and had worn badly before surfacing was applied except those areas which were patched soon after construction.

Considering the conditions under which this section was constructed, its 4 in. thickness and the cracking which occurred immediately following construction, it is somewhat surprising that it did not break up or entirely disintegrate during the winter.

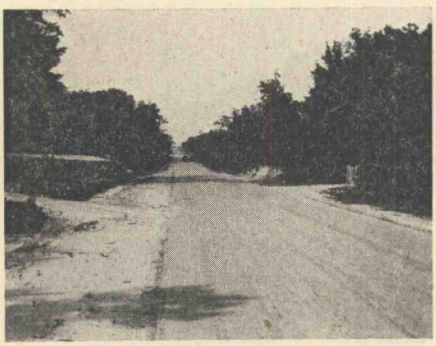


Figure 16. Finished Road, Section 8

No new defects were discovered during a recent inspection.

COST OF CONSTRUCTION

Only the actual cost of constructing the stabilized base course is included in the figures quoted below as the experiment had been cleared, graded and drained at a cost of approximately $5172 per mile several months before this work was done. No data on the cost of these items for each section were available.

The project was constructed under the regulations of the Bureau of Public Roads for NRS Projects. The wage scale was 45 cents and 60 cents per hour for semi-skilled labor such as tractor, machine and roller operators and 30 cents per hour for common labor. Most of the semi-skilled labor received 60 cents per hour.

The cost of cement is based on the current delivered price of cement to Johnsonville, S. C. which is $2.33 per barrel allowing deductions for sacks and cash payment. Naturally, the cost of cement for a section varied with the quantity applied.

No rental of equipment is included in this cost data as all the equipment used was owned by the highway department and no rent was allowed under the regulations governing this work. All repairs, which were extensive in some cases, are included however.

With the explanations mentioned above, the cost figures are presented as information:

COST OF CONSTRUCTING SOIL-CEMENT STABILIZED BASE COURSE

Labor, Equipment (Gas, Oil, Repairs Only)......	$0.168 per sq. yd.
Cement............	0.216 " " "
Total............	$0.384 per sq. yd.

SUPPLEMENTARY LABORATORY WORK

In addition to the holes frequently dug for the purpose of checking depths the morning after a section was constructed, cores were drilled at 100-ft. intervals on the entire project. Three cores, one at the center and one approximately one-quarter of the distance from each edge were obtained alternately with two cores, each at about one-third of the distance from the edge to the center.

(a) *Thickness:* The effective depth of the treatment was considered as the depth of the hole from which the core was obtained and not the thickness of the core as the cores sometimes broke as they were being drilled and frequently there were compaction planes which caused the core to split transversely There was always a very marked difference between the color and hardness of the treated base and the untreated subgrade, and these facts permitted accurate measurements of the depth of hardened base The results of thickness determinations are shown in Table 5

The thickness of all six-inch sections, except Section 1, is considerably less than the theoretical and the average thickness of the sections varies from $\frac{3}{4}$ to $1\frac{1}{2}$ in. less than theoretical thickness Better thicknesses were obtained on the four inch sections The average thickness of these sections varies from $\frac{3}{8}$ in less than the theoretical thickness to $1\frac{7}{8}$ in more than the theoretical thickness These results show the need for better methods of controlling finished thickness The "Turn-Arounds" are generally thin as would be expected with the method of construction used but the thickness can be materially improved by using improved equipment which can be more accurately controlled

(b) *Density and Cement Content.* In the laboratory, the cores were divided into two parts by sawing them parallel to the height Density was determined on one part and samples for tests of cement content and moisture were taken from the other

Density was determined as follows: The core was coated by immersing it in melted paraffin, after which it was removed and excess paraffin allowed to drain The core was weighed both before and after it was coated, then the weight in water at room temperature was obtained These tests were made as soon as possible after receipt of the cores in the laboratory to reduce moisture losses to a minimum The density per cubic foot was calculated by the formula

$$D = \frac{\frac{A}{100 + M}}{B - C - V} \times 62\,425$$

A = Weight of core in air
B = Weight of core and paraffin in air
C = Weight of core and paraffin in water
D = Density of core, pounds per cubic foot, dry weight basis
M = Moisture content in per cent of dry weight of soil
V = Volume of paraffin coating $V = \frac{\text{Weight of paraffin}}{904}$

TABLE 5

SUMMARY OF THICKNESS MEASUREMENTS

Section No	1	2	3	4	5	6	7	8	9	10
Theoretical Thickness, In	6	6	6	6	6	4	6	6	4	4
Actual Thickness, In	7⅞	5¼	4½	4¾	5	3⅝	4¾	5	4¼	5 0
Average Variation, In	+1⅞	−¾	−1½	−1¾	−1	−⅜	−1¼	−1	+¼	+1
Max Overrun in Thickness, In	+4	+2½	0	0	+¼	+¼	+¼	0	+2	+2
Max Underrun in Thickness, In	0	−2	−2¾	−2¾	−2½	−2	−2	−3¼	−1	−1

Moisture tests were made on a sample from top to bottom of the outer 2 in of the core The densities are based on oven dry weight of soil-cement mixture in accordance with the Proctor procedure Table 6 gives a summary of the densities of the cores

These figures show that the density obtained in Section 1 with compaction by tractors and loaded trucks compares favorably with that obtained by using the sheeps foot roller on the section constructed afterward, but there is no question in the minds of those associated with the project that the sheeps foot roller is better for obtaining compaction The density of the cores from Section 10 is rather surprising when the trouble encountered in construction is considered The densities throughout the experiment would probably have been increased if the moisture content of the mixtures at the time of compaction had been more accurately controlled See Table 4 for a summary of the moisture contents at the percentage of cement assuming that the cement contained 63 per cent calcium oxide This determination was made on a sample from the top inch and bottom inch in practically all cases and on a sample from the middle inch where possible A summary of these results is given in *Table 7* Except for Section 1 the average cement content as shown by these tests is above the theoretical

TABLE 6

SUMMARY OF DENSITY TESTS

Section No	1	2	3	4	5	6	7	8	9	10
Theo Proctor Density[1]		130 8	125 0	128 5	130 0	125 0	127 0	128 0	127 0	127 0
Avg Density, lb per cu ft	115 4	119 9	115 7	115 4	114 9	116 4	116 5	118 5	118 0	118 0
Max Density, lb per cu ft	120 1	130 2	124 2	122 0	120 9	125 2	121 5	125 2	124 5	127 8
Min Density, lb per cu ft	109 6	113 4	110 5	108 3	107 4	111 3	109 0	108 3	110 6	103 6

[1] The Theoretical Proctor Density was obtained from laboratory tests on mixtures of soil from each section with 6 per cent cement by weight

TABLE 7

SUMMARY OF THICKNESSES AND CEMENT CONTENTS

Section Number	Theoretical Thickness	Actual Thickness	Theoretical Cement Content	Minimum Cement Content	Average Cement Content		
					Top	Middle	Bottom
	in	*in*					
1	6	7⅞	7	1 7	5 7	5 6	6 0
2	6	5¼	6	0 4	6 1	6 5	5 8
3	6	4½	7	4 0	7 7	8 5	7 7
4	6	4¾	7	3 8	8 0	7 9	7 2
5	6	5	7	2 3	8 3	8 4	7 7
6	4	3⅝	7	6 5	7 6	8 1	7 6
7	6	4¾	7	5 4	7 9	8 1	7 9
8	6	5	7	4 6	7 3	7 1	7 4
9	4	4¼	5	3 2	7 0	5 8	7 0
10	4	5	9 7 & 5 3	0 2	9 5 & 7 1	7 9 & 7 0	7 7 & 3 8

Note All cement contents are expressed as percentage by weight

time of compaction. Proctor's tests show that field density should be equal to that obtained in the laboratory and this lack of proper moisture control is probably responsible for the failure to obtain maximum density

The cement contents of samples of the field cores was determined by obtaining the percentage by weight of calcium oxide present and calculating this to quantity placed This can be explained by referring to the thickness report *Table 5*, which shows that most of the sections are thin Where a certain quantity of cement is applied, a decrease in depth to which it is mixed naturally increases the proportion of cement This conclusion is supported by the evidence from Section 1, in which the tests show that extra depth was obtained and the cement contents are less than the theoretical quantities placed

The mixin of cement appears from these tests to be fairly uniform for the entire stabilized depth The variation in cement content of the same core is usually small but at different stations it is often considerable However, the samples from the top inch do not contain any more cement than those from the middle or bottom inch except in Section 10 where the mixing was not satisfactory

(c) *Compressive Strength* The compressive strength of eight cores was determined merely for information and these results are shown in Table 8 After the cores were obtained they were stored in the laboratory at room temperature then capped with a mixture of Lumnite and portland cement which was allowed to cure for 48 hours The cores were then broken in a dry condition in a 200, 000 pound testing machine The average compressive strength at 86 days is 480 lb per sq in The lowest compressive strength shown was 350 lb per sq in and the highest 581 lb per sq in A comparison of the strength of the cores with the average density for the section does not show any relation between the compressive strength and density

(d) *Durability Test of Field Cores:* Durability tests of the field cores were conducted as a check on the weathering of the field experiments and the results of these tests are shown in Figure 11 The tests were made on the same part of the core that was used for density determination This part of the core was sawed parallel to the height into two approximately equal parts The coating of paraffin was carefully removed and one of the specimens was subjected to wetting-drying by soaking it in water at room temperature for 8 hours and then drying it in an oven at 350°F for 15 hours It was allowed to cool for approximately one hour during which time it was brushed, weighed and then immersed in water and the cycle repeated The other portion of the core was subjected to freezing-thawing tests which also included wetting and drying by immersing it in water for 8 hours at room temperature, and immediately upon removal from the water, placing it in a cooling cabinet at a temperature of 0°F for 16 hours, removing and allowing it to thaw in air at room temperature for 8 hours, drying it in an oven at a temperature of 350°F for 15 hours and cooling it for approximately one hour during which time it was brushed, weighed and re-immersed to begin the cycle again

TABLE 8

COMPRESSIVE STRENGTH OF FIELD CORES, CEMENT SECTION

Section	Section No	Ordinate	Theo Cement %	Theo Thickness in	Diameter Core in	Capped Height in	Age At Test (days)	Density lb per cu ft	Comp St lb per sq in
1	1322	7 2 ft L	7	6	6 00	6 75	98	115 4	360
2	1329	3 0 ft R	6	6	6 34	6 63	93	119 9	550
3	1337	3 4 ft R	7	6	6 34	5 00	89	115 7	550
4	1344	6 9 ft L	7	6	6 25	6 00	87	115 4	534
5	1396	7 3 ft R	7	6	6 25	5 88	82	114 9	581
6	1385	2 5 ft L	7	4	6 25	5 00	81	116 4	389
7	1376	7 6 ft L	7	6	6 25	4 50	80	116 5	350
8	1371	1 7 ft L	7	6	6 25	5 50	78	118 5	529
Grand average							86	116 6	480

Note Average Density for Section All Cores Tested Dry

Tests were run to determine the cycles required to produce loss of approximately 50 per cent

Eight cores representing each type of soil were tested in this way The freezing-thawing cycle is far more severe in its action than the wetting-drying, and it will be observed that the cores withstood a maximum of 40 cycles of freezing-thawing before a loss of 50 per cent was obtained In the wetting-drying tests the majority of the cores withstood more than 90 cycles of wetting-drying before a loss of 50 per cent was obtained In most instances the cores withstood 20 cycles of freezing-thawing with very little loss When the fact is considered that raw soil specimens do not withstand one alternation of either of these cycles, the benefit of the addition of cement is clearly indicated by the results obtained here The practical value of these tests in predicting the resistance to weather of the field experiments will evolve through time

LORIS EXPERIMENT

Study of the cement method of soil stabilization was continued by the department with the construction early this summer (1936) of the Loris experiment, NRH Project No 350-C This project is two miles long and it is located on State Route No 9 approximately six miles northwest of Loris An attempt had been made to write a specification for this type of work, and it was desirable to test this specification, as well as improved equipment, under field conditions

As no soil suitable as a base for bituminous surfacing was available locally, it was necessary to stabilize the soil in the roadway or bring in material from a distance at considerable expense Although the soils in the project contained on the average 30 per cent more coarse sand than those on the Johnsonville project, they are very unstable in wet weather due to the very plastic clay they contain The results of the grading test and soil constants for samples from this project are shown in Table 9 These tests show that the minimum clay content (by Hydrometer Method) of 7 3 per cent occurs at Station 105, and that the maximum of 19 3 per cent occurs at Station 59 Approximately 0 1 per cent of the soil particles are retained on the 10 mesh sieve and 44 0 per cent on the 60 mesh sieve

The cement content was determined by the same methods used for the Johnsonville experiment with slight modifications Durability specimens of the soil-cement mixtures were tested both by repeated wetting and drying and freezing and thawing The specimens were obtained from Proctor specimens of soil-cement mixtures compacted at the optimum moisture content The durability tests on this series were more severe in their action on the specimens than those used for the Johnsonville experiment due to the fact that the temperature for drying was 400°F as compared with 300°F , and the temperature in the freezing cabinet was 0°F as compared with 20°F

It was observed that the losses on specimens made with the sandy soil are more rapid than from specimens made with soil containing a relatively high percentage of clay For comparison, the durability curves for two samples of the soil are shown in Figure 17 The cement content for the field work was chosen after the durability specimens had completed 30 cycles of wetting and drying and 15 cycles of freezing and thawing As a factor of safety, the quantities chosen from the results of the durability tests were increased by 25 per cent

Plans for this project were to construct a base course consisting of 6 in of compacted soil-cement mixture using the soil in the road-bed and then cover this base before it was exposed to traffic

TABLE 9

ANALYSES OF DIFFERENT TYPES OF SOILS

Laboratory Number	Section Number	Analysis of Sample as a Whole: Passing No 10[a]	Analysis of Sample as a Whole: Silt	Analysis of Sample as a Whole: Clay by Elutriation	Analysis of Material Passing No 10 Sieve — Gradation of Material Above No 200 Sieve After Washing: Ret No 20	Pass No 20 Ret No 60	Pass No 60 Ret No 100	Pass No 100 Ret No 200	Gradation of Material Passing No 200 Sieve — Elutriation Test: Silt	Elutriation Test: Clay	Fine Sand No 200-270	Silt 05-005 mm	Total Clay below 005 mm	Colloidal Clay below 001 mm	Specific Gravity[b]	Soil Constants: Field Moisture Equivalent	Tests on Portion of Original Sample Passing No 40 Sieve: Liquid Limit	Plasticity Index	Shrinkage Limit	Volume Change
A23079	2	99 9	9 8	16 0	3 6	54 2	11 0	5 4	9 8	16 0	2 1	9 5	10 8	7 2	2 65	14 8	17 7	[c]	10 7	12 0
A23081	3	99 9	11 0	15 6	1 2	39 0	25 6	7 6	11 0	15 6	3 4	12 6	9 5	5 8	2 63	13 8	15 8	[c]	13 3	6 3
A23082	4	99 9	10 0	20 6	1 4	26 8	25 2	10 0	16 0	20 6	3 8	22 3	16 3	11 2	2 69	15 6	19 4	4 9	11 1	14 2
A23084	6	99 8	8 4	12 8	6 0	49 4	18 0	5 4	8 4	12 8	5 1	11 3	7 8	3 8	2 62	14 9	15 6	[c]	18 1	2 2
A23086	7	99 8	6 6	12 6	3 8	61 8	11 2	4 0	6 6	12 6	0 8	2 7	9 6	6 3	2 60	19 9	16 3	[c]	12 7	6 9
A23088	8	99 9	7 8	16 6	1 6	47 6	19 6	6 8	7 8	16 6	0 2	10 0	12 7	8 1	2 56	17 6	19 6	[c]	12 4	12 7
A23090	9	100 0	11 4	17 8	1 0	21 4	39 6	8 8	11 4	17 8	1 4	13 1	13 1	8 8	2 58	16 0	17 5	[c]	13 8	4 7
A23092	10	100 0	5 4	12 2	3 4	50 0	21 4	7 6	5 4	12 2	0 1	5 3	7 5	5 0	2 60	16 0	17 6	[c]	16 2	0 0
A23094	11	99 9	5 6	14 0	2 6	38 2	27 6	12 0	5 6	14 0	0 9	8 1	10 1	7 6	2 60	14 1	18 5	[c]	23 0	9 4
A23096	12	99 9	7 6	14 2	1 6	41 8	27 6	7 2	7 6	14 2	0 7	5 5	10 2	7 1	2 58	17 6	19 2	[c]	14 0	9 3
A23097	13	99 9	3 2	10 8	1 2	45 4	30 2	9 2	3 2	10 8	0 0	4 2	7 8	4 9	2 63	20 7	19 1	[c]	18 1	5 1
A23099	14	100 0	5 0	11 8	1 4	40 8	28 8	12 2	5 0	11 8	0 2	7 3	9 4	6 9	2 60	17 0	17 9	[c]	18 1	3 1

[a] 100 per cent passing ⅜-in screen.
[b] Test made on portion of sample passing No 10 sieve
[c] Not obtainable

with a wearing course of 50 lb of ½-in stone and 0 65 gal of cut-back asphalt per sq yd Construction of the base course was started on May 28 and the last section was placed on June 19 A total of 66 calendar days elapsed from the beginning to the completion of 7850 ft of base on the Johnsonville experiment compared with 22 days for the construction of 10930 linear feet on this project This increase in the rate of construction was the result of the success-

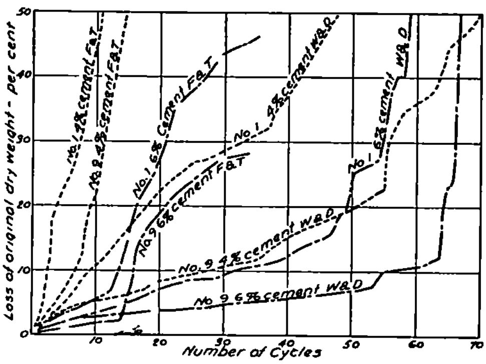


Figure 17 Durability curves of soil-cement mix Specimens obtained from cores compacted at optimum moisture content.

	Passing No 10 sieve	Silt	Clay	F M E	L.L	P I.
No 1	99 9	10 7	16 5	14 5	16 5	0
No 9	99 9	16 4	27 2	19 5	28 9	12 1

Wetting and Drying Cycle—8 hr wetting at 70°F , 16 hr drying at 400°F.

Freezing and Thawing Cycle—8 hr. wetting at 70°F , 16 hr. freezing at 0°F., 8 hr thawing at 70°F , 16 hr drying at 400°F.

ful routine developed by key men on the Johnsonville work, better coordination of the different operations, better equipment for spreading cement, and more powerful equipment for mixing operations Each section was approximately 1000 ft long, and all sections, except one, were finished in less than 12 hours Several changes were made in the routine methods of mixing to secure better distribution of the ingredients more uniform depth and a smoother surface, but there were no radical departures from the basic procedures and principles used in the Johnsonville experiment

Soon after the completion of the last section, cores were obtained from the entire project at intervals of 200 ft Three cores, one at the center and one at each quarter point, were obtained alternately with two cores each at the third point The thickness of the base as measured by the depth of the hole after the core was drilled and the density of the cores are shown in *Table 10* These tests show that the average thickness of all sections is practically equal to that specified and that the thickness is, also, very uniform The densities of the cores are reasonably uniform and compare favorably with the theoretical density as obtained in the laboratory in the Proctor cylinder

Several of the sections comprising a total of 2500 ft were wetted by rain during construction to slightly above the optimum moisture, but each one was compacted even though the moisture content was slightly high Cracks appeared in the surface of these sections within 24 hours Figures 18 and 19 show typical areas of these cracks These pictures were made of different sections and show the worst and the average conditions Cracking in any one section was reasonably uniform and it appears to be primarily caused by compacting the mixture when the moisture content is above the optimum It was the opinion of the engineers, however, that there was much less cracking of this type in this project than on the Johnsonville project The mixture in one section, which was compacted during a light rain, was practically dry for one inch at the bottom due to inadequate mixing of the water but, approximately 16 hours later, tests holes in this same section showed that this dry mixture had become damp and had hardened, although it was not as

TABLE 10

SUMMARY OF BASE THICKNESSES AND CORE DENSITIES, LORIS EXPERIMENT

Section Number	1	2	3	4	5	6	7	8	9	10	11	12	13
Thickness, Inches:													
Theoretical	6″	6″	6″	6″	6″	6″	6″	6″	6″	6″	6″	6″	6″
Average	6¼″	6½″	5½″	5¼″	5¾″	5¾″	6″	6″	6¼″	5½″	5¾″	5¾″	*
Maximum Overrun	2″	2″		¼″	1″	1¾″	1″	1½″	1½″	½″	1″	½″	
Maximum Underrun	1½″	¼″	1″	2″	1½″	1½″	½″	1¼″	1″	3″	2″	1½″	
Average Variation	+¼″	+½″	−½″	−¾″	−¼″	−¼″	0	0	+¼″	−½″	−¼″	−¼″	
Density, #/Cu. Ft.:													
Theoretical Proctor	135.0	127.5		133.0	135.0	133.0	131.0	131.0	131.0	129.0	130.0	130.0	
Avg. Cores From Rdway	120.4	123.2	124.0	124.0	125.7	122.6	121.5	123.3	121.4	120.1	118.0	119.4	
Max. Cores From Rdway	125.6	126.3	125.3	130.9	128.8	129.3	125.3	127.3	124.1	125.2	120.5	124.1	
Min. Cores From Rdway	116.2	179.1	120.2	117.8	122.0	117.9	118.4	117.6	118.8	113.9	116.0	112.5	

* Not sufficient cores.

The Theoretical Proctor Density shown above was obtained from laboratory tests on mixtures of soil from each section with 6% cement by weight.

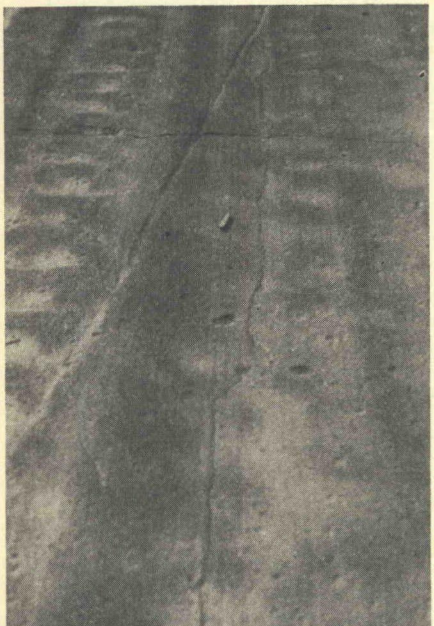


Figure 18

Figure 19

hard as the top portion which had been compacted with the sheeps foot roller

In order to finish one of these "wet" sections, the protecting earth was scraped off on the adjacent section which was completed only 16 hours earlier Rain water had collected in puddles on this section but when tractors and road machines were turned around on it, the surface was not broken and only slightly scarred This fact is mentioned merely as an illustration of the rapidity with which the mix hardened and of its stability when wet

In one section, where the subsoil was unstable on account of excess moisture, cracks appeared during the rolling of the top mulch by trucks These cracks were undoubtedly caused by movement of the subsoil It was necessary to patch approximately 15 sq yd on account of raveling of the mixture due to this type of cracking Shrinkage cracks were also numerous in this section as the mixture was compacted during a light rain which caused an excess of moisture in the top inch Reconstruction of this section was considered but this idea was abandoned and it was surfaced after the above minor repairs, in order to learn the effect of the combination of cracks on the durability of the base

The wearing course was applied on July 7 and 8 At that time the base appeared to be in excellent condition throughout the project and no defects have been discovered on subsequent inspections

Both this and the Johnsonville project were constructed under labor provisions which prevented the organization of an efficient corps of workmen The cost of constructing the base course was 36 8 cents per square yard, of which amount 4 9 cents was spent for labor, 6 0 cents for gas, oil and equipment repairs, and 25 9 cents for cement No rent for equipment is included in these figures, but for the equipment used this cost would amount to approximately 0 7 cents more per square yard Due to greater losses of the laboratory durability specimens, the proportion of cement used in this experiment was slightly higher than had been used on the Johnsonville experiment

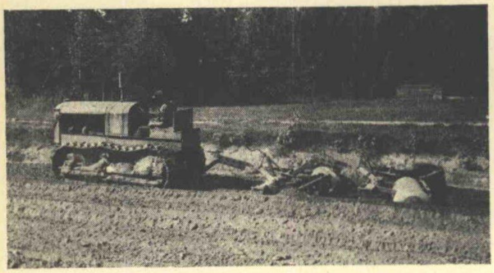
CONCLUSIONS

No attempt will be made to draw definite, long range conclusions from this work at the present time The action of the weather and traffic will, in time, prove the merits of this method of stabilization. However, the present indication is that treatment of soils by the method described herein has appreciable merit and is possible and comparatively economical for many lightly travelled roads in South Carolina

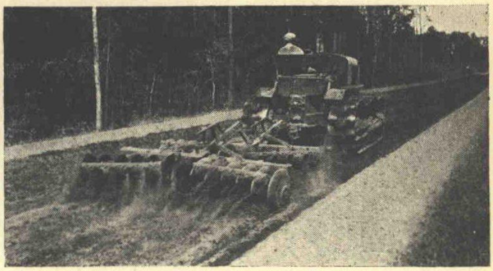
There is need for much additional laboratory investigations as well as field experimentation before work of this kind could be performed on a large scale Construction methods and machinery can undoubtedly be vastly improved Further, as the control of this new construction material develops, it will be possible to determine depth of treatment required by various classes of traffic on various soils

Acknowledgments Acknowledgment is gratefully made of the spirit shown by the key men, especially Mr A P Bolton, during the construction of these field experiments These men were always ready when extra work was necessary

The author also wishes to express appreciation of the efforts of Mr Raven I McDavid, State Representative, and Mr M D Catton of the Development Department of the Portland Cement Association

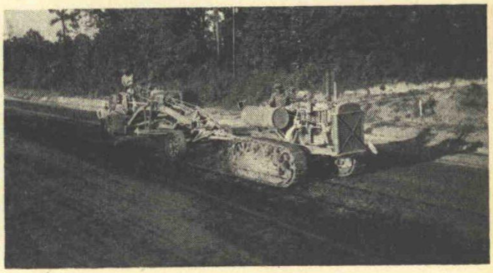


Pulverizing Soil

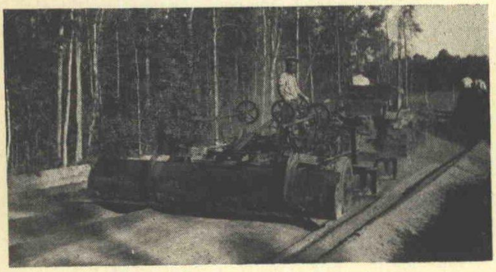


Mixing Water

Cutting in Cement

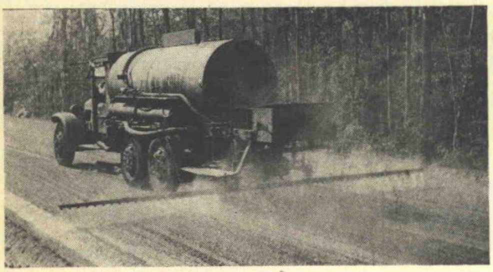


Finishing

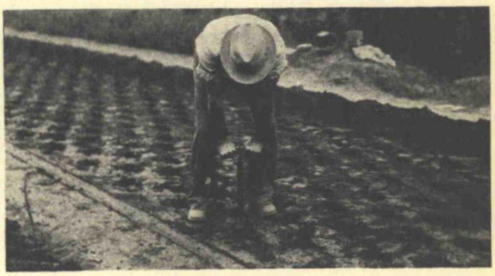


Mixing Cement and Soil

Determining Moisture Content



Applying Water



Testing Compaction

Figure 20. Construction Operations

DISCUSSION ON STABILIZING WITH CEMENT

MR C N CONNER, *U S. Bureau of Public Roads* What provisions were made for curing the concrete after it had been placed and finished, and what method was used in constructing joints?

MR MILLS. No provision was made for curing The section was left open to the sun No joints were constructed. There have been some shrinkage cracks and perhaps some others but they do not seem to affect the stability or durability of the base

MR M H ULMAN, *Pennsylvania Department of Highways*· What are the maximum and minimum temperatures in that part of South Carolina during your study of durability?

MR MILLS: Minimum air temperature 110°—maximum air temperature 125°F

MR M. D CATTON, *Portland Cement Association*· Mr Mills has described the details of laboratory and field work on the Johnsonville project The work is unusual in that it was possible to follow a laboratory investigation of new basic concepts of soil-cement mixtures immediately with a field project to determine if these concepts and laboratory results could be applied in the field Perhaps some of the basic thinking back of the laboratory concepts which we set up for South Carolina would be of interest

You have heard several people say during the last few days that most any soil had some moisture content at which it had considerable stability However, we know that most soils only have this stability for short periods as they occur in roadways and often nature does not provide this desirable moisture for good stability at any time

In our study of soils and their possible relations to various cement contents, which were started two years ago, these factors were encountered frequently However, not until the very progressive work of R R Proctor of the Los Angeles Water Board was studied in detail, did any avenues open up for a scientific approach to soil-cement mixtures The work of Proctor showed how to determine the moisture content of a soil which would give maximum density and stability with a predetermined degree of compaction. These tests made it possible to determine in the laboratory the moisture content of each soil which would give maximum density and also, a very important point in soil work, they would permit the investigator to reproduce many specimens of soil having the same characteristics

Two questions regarding soil-cement mixtures presented themselves in the light of the relations which were known to exist between compaction, moisture content and density of a soil First, did these same relations hold for soil-cement mixtures and second, would the mixtures of soil-cement when compacted at optimum moisture to maximum density, maintain these characteristics under natural weathering conditions

Our knowledge of soil and cement led to the conclusion that these relations of compaction, moisture content and density should hold for many soil-cement mixtures and further that these mixtures should have stabilities which would not change readily under natural weathering conditions

Our laboratory work was started the first part of 1935 and Mr Mill's paper has described similar laboratory work on soil for a field project His paper describes how these concepts and laboratory results were applied very successfully in the field Our exploratory research has now been completed on all major soil types and the results show that every soil-cement mixture investigated has a desirable moisture content which will give maximum stability with a fixed amount of compaction Our durability tests on soil-cement mixtures have given results which have materially exceeded our hopes

The laboratory and field results are checking each other closely All major construction problems encountered in the field were effectively solved on the Johnsonville project Details of equipment and control are changing rapidly as these new basic concepts are applied on other jobs Each job built during 1936 has simplified construction procedure and equipment and resulted in improved control and reduced costs Experience has given ample demonstration that by applying the basic principles of density, compaction and moisture together with severe durability tests to determine cement contents in the laboratory, a soil-cement mixture can be produced in the field which will have marked resistance to natural weathering agencies