Performance of Cement-Modified Soils: A Follow-Up Report

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In 1938 the Oklahoma Highway Department investigated the use of cement-modified subgrades by constructing 7 mi of test sections on US-62. Much of the subgrade consisted of expansive clay. A total of 38 test sections with 11 different cement contents was used to modify the subgrade soils. Cement contents varied from 4 to 16 percent by volume with an average cement content of 6 percent. At the time of construction the plasticity index of the subgrade was reduced from an average of 29 to 13 through cement modification. In 1983 an investigative program was conducted to determine the plasticity characteristics of the cement-modified subgrade following 45 years of service. Samples were obtained from each of the 11 different cement-content sections. The plasticity indexes ranged from nonplastic to a maximum of 13 with an average of 6. Results from these tests show that the effectiveness of cement modification of the fine-grained soils was permanent. Information on the original cement-modification work is presented and the 1983 investigative program is described in detail.

The investigation of an Oklahoma highway project constructed in 1938 where expansive clay subgrade soils were modified by the addition of portland cement is described. The purpose of a 1983 investigation was to sample the cement-modified subgrade and perform laboratory tests to determine the current characteristics of the cement-modified subgrade. Results of the investigation reveal that changes in the physical and plastic characteristics of the cement-modified subgrade have remained constant or improved in the half-century of weathering and continued service.

The technical data contained in this paper have been tabulated to provide the engineer with background information as to portland cement's long-term performance in modifying the plastic and physical characteristics of fine-grained soils. This does not imply that such modification will or should perform as well as treatments meeting the more rigid standards of soil-cement.

TERMINOLOGY

Various terms are used to describe the products made when soil and cement are mixed together. These terms are often misunderstood or used incorrectly. In this paper, the term "cement modification" or "cement-modified soil" is used to describe an unhardened or semihardened soil material with improved properties of plasticity, volume change, and bearing strength. Cement-modified soil contains less cement than that required to produce hardened soil-cement. For fine-grained soils, the degree of modification is usually judged by changes in the plasticity properties, and the normal use of the material is for subgrade modification.

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BACKGROUND OF 1938 PROJECT

A report by Ried *(1)*, published in the 1939 *Proceedings of the Highway Research Board,* describes preliminary soils survey and testing, design, construction, specifications, and field testing. Some of this information is condensed here. The 1939 report documents the physical properties of the soils both before and after the cement modificatin.

In early 1938 the Oklahoma State Highway Commission, now the Oklahoma Deparmtent of Transportation (ODOT), conducted a preliminary soil survey on an already constructed grading and drainage project. The project was located in Comanche County, southwestern Oklahoma, on US-62, in and next to the town of Indiahoma. The soil survey indicated a large portion of the subgrade to be A-4, A-6, and A-7 soils by the AASHTO Soil Classification System.

After reviewing several other types of improvements relative to costs and the long-time service value of the finished construction, ODOT authorized a research project using a cement-modified subgrade 6 in. thick and 22 ft wide. The surface pavement would be portland cement concrete 20 ft wide. Construction of the modified subgrade was to follow procedures similar to those for soil-cement.

The subgrade modification was completed during the late fall of 1938 and the concrete paving in 1939, and the project was opened to traffic.

Testing and Design

The amounts of cement required for proper reduction of the volume-change characteristics of the various soil types encountered on the project were determined by preliminary laboratory tests. The liquid limit, plastic limit, plasticity index, field moisture equivalent, shrinkage limit, and shrinkage ratio were determined on the raw soils and the cement-soil mixtures.

The guiding values recommended as desirable to obtain a subgrade with small volume changes due to moisture changes were that the "cement-modified" subgrade have a ratio of the volume at shrinkage limit to volume at field moisture equivalent of about 0.90 and a ratio of the volume at shrinkage limit to volume at liquid limit of about 0.80. The lowest percent of cement required to obtain these desired results as indicated by the tests was selected as the design mix.

On the basis of the results of the soil survey and the testing program, it was decided that the project would consist of 38 different sections using 11 different cement contents. The cement contents ranged from 4 to 16 percent by volume. The average was approximately 6 percent by volume.

Records of Construction

To determine the compliance with pulverization specifications composite samples of the material being processed were taken from at least three points across the roadway at not greater than 300-ft intervls, or more often as appeared desirable. These samples were usually taken as pulverizing was being completed.

The original mix design requirements were reviewed as to the station limits for quantity of cement required, and the spacing of cement bags was established for spreading the cement.

As dry mixing of the cement and the soil progressed, the mixture was inspected from time to time to adjust the operation of equipment as necessary to secure a uniform mix. As dry mixing was being completed, moisture samples were taken throughout the area. From these, the amount of water to bring the mix to optimum requirement was estimated. Additional moisture tests were made during damp mixing to assure uniformity and to ascertain that the optimum requirement had been reached throughout the mixture, at which time compaction could be started.

As the rolling appeared to be completed, density tests were made at selected points at intervals not greater than 300 ft. The sand density method was used for this determination, which was compared with the standard density previously obtained for this particular mixture.

At least 7 days after processing, four samples were obtained from each day's mix for comparative information, for check tests against the original design, and for further tests for information on the effect of aging. In addition, moisture samples were taken just ahead of paving opertions in order to complete records of the project as paving was placed.

Pulverization

The first section to be processed contained some of the heavier soils on the project. It was found practically impossible to pulverize this soil to the requirement that 80 percent pass the No. 4 sieve. Much time was spent with the different pieces of equipment and special methods of manipulation in an effort to secure specification requirements under the cool weather conditions prevailing (late October). The work moved on into somewhat lighter soils and when no appreciable improvement in gradation was found, prewetting and sprinkling during pulverizing was resorted to. Gradation samples were taken before and after premoistening, during dry mixing with cement, and after final mix was at or near optimum moisture requirement with the result that no appreciable improvement was effected. However, the test data show that additional pulverization was obtained during both dry and damp mixing after cement application.

It was quite evident that in these types of soil the machinery and methods commonly used for this work could not produce a pulverization of much more than 60 percent. It was therefore found desirable and practical to change the specifications as follows: "That the gradation of the raw soil prior to addition of cement be such that 95% pass the 1-in. sieve and at least 60% pass the No. 4 sieve." The average condition, as recorded during the construction of the project, indicates 98 percent passing the 1-in. sieve and 67 percent passing the No. 4.

Soils analyses of completed cement mixtures of both coarse and fine gradings of soil were made, which showed no appreciable variation or difference. Further comparative tests were made on soil-cement cylinders with soil of the coarser or revised pulverization requirement and also of soil, all of which passed the No. 4 sieve. These were measured for volume change and absorption, one each during 26½ days and one each for 77½ days exposed to capillary moisture, and at the end of that time complete soil analysis was made. None of these results showed any apparent difference to be reflected in either the coarse or the fine-graded or pulverized soil. It appears, therefore, that the change to the requirement of only 60 percent passing the No. 4 sieve will have no detrimental effect on this subgrade treatment.

Density

In the early mixes completed and immediately compacted after the sample was mixed, it was found that densities in place were not comparable with the (regular) moisture-density curves (AASHTO T-99) determined in the laboratory. All the methods were checked for errors or discrepancies, with no results. Samples of the mixture in place compacted in Proctor molds showed lower densities, indicating that the change, or modification, of the moisture-density relation of the soil was effected over a period of several hours during wetting and mixing. A series of moisture-density tests, delayed for a period of several hours after mixing, developed the fact that the principal change in density wa attained in approximately 5 hr.

These 5-hr delayed tests were made during the remainder of the work. The mixture of soil-cement for test was slightly moistened and placed in tight buckets and stirred or agitated at intervals through a period of 5 to 6 hr, after which moisture-density tests were made by using the standard procedure. Such 5-hr delayed determinations or comparisons of density with the compacted sample of the finished road mixture should be specified for control of construction of this type.

Conclusions, 1938 Work

Grading must be accurately finished to elevation and section of subgrade before construction of the treated subgrade. Scarifying this grade to the true section and elevation at the required depth for the treatment is of the utmost importance. A scarifier or gang plow, or both, of proper design and manned by skilled operators should be used throughout so that this initial work will be carefully controlled to provide a true subbase section, or "work table," for the control of all subsequent pulverization, mixing, processing, and compacting.

The loosening of 6 in. of soil in the completed roadway provided an excess thickness of finished mix sufficient for any normal irregularities or adjustments in grade or section and permitted the paving planer to trim surplus from the grade rather than to level or fill with untreated soil. As work progressed, this surplus was available for the few low areas that occurred in the grade. Proper care at this stage of construction is of great importance.

During the initial stages of compaction, no rubber-tired equipment or traffic was allowed and the offset tandem disk was used behind the roller to prevent surface crusting. After about an hour of rolling, the disk was replaced with a spiketooth harrow. Particularly during dry weather, it was found necessary to sprinkle the surface two or three times during the rolling operation. As rolling neared completion, the road was shaped frequently with motor patrol and final compaction was completed with a pneumatic-tired roller.

The final shaping of the completed subgrade was not difficult. The contractor had provided and used two extra sets of cutting bits for both his subgrade machine and the planer; because new bits were changed as necessary, very little delay developed on account of the hard subgrade. In general, the finished subgrade was practically perfect, as indicated by records of the yield of concrete (which averaged 99.28 percent), thickness tests, and measurements of cores in the completed concrete pavement.

It is highly desirable that proper and sufficient pieces of equipment for pulverization and processing be available on the job. There is no substitute for a gang plow (2 to 4 bottom), a regulated-depth scarifier, springtooth harrow (power lift and depth regulated), offset tandem disk harrow with at least 18- to 20-in. disks, double spiketooth drag harrow, and one-way disk plow.

An ample water supply must be available and it is recommended that application be provided by two or more pressure distributors. On this project, a protable water storage tank enabled the distributor trucks to load more quickly than would have been possible from pipeline and thus deliver water at a satisfactory rate.

All sheepsfoot rollers to be used should be of same general design as to spacing and area of feet and weight.

Results of tests during construction and the final characteristics of the modified soils indicate that the revised grading or pulverization requirement (95 percent passing 1-in. sieve and 60 percent passing No. 4 sieve) was generally satisfactory. It is recommended that such specifications be used in future pulverization projects on which modified soils are to be produced or that practical grading limits for the soil be predetermined and wider limits provided if necessary.

It is recommended that the density of the completed work be specified as the percentage of the density of 5-hr delayed compaction.

No protection or curing was specified for this work. It is believed, however, that some provision for protection of the cement mix in progress should be provided. On one section heavy rain fell on the finished mix just as rolling started. Subsequent tests indicated that the volume-change values were not as designed. Two percent additional cement was reprocessed in a portion of the section and 5 percent in the remainder.

1983 INVESTIGATION

After 34 years of service as a primary U.S. highway, this section was transferred in 1973 to Comanche County when a new alignment of US-62 was opened about 1 mi to the north. In 1983 the old project was still performing very well as a county road.

The 1983 investigation included field sampling and laboratory testing from each of the 11 different cement-content sec-

FIGURE 1 CME 750 coring the concrete pavement.

FIGURE 2 Thin-walled tube sampling the soil.

TABLE 1 SUMMARY OF FIELD INVESTIGATION: PART 1

Soil Description Soil Classification	Brown Silty Clay A-6			Brown Silty Sand A-1-b			Brown Silty Sand A-2-4			Brown Silty Clay A-6		
Station to Station	1044+00 1068+00			1087+50 1098+00			1098+00 1110+00			1110+00 1120+00		
Cement Content (percent by volume)	8.0			11.0			10.0			9.0		
	Raw Soil	1938 CMS	198[a] CMS	Raw Soil	1938 CMS	1983 CMS	Raw Soil	1938 CMS	1983 CMS	Raw Soil	1938 CMS	1983 CMS
Coarse Sand	7.1	7.0	7	7.0	9.6	53	9.7	10.0	26	7.0	6.8	13
Fine Sand	23.9	36.2	26	27.5	43.5	27	28.7	39.4	35	22.4	51.4	25
Silt	45.2	54.9	60	45.5	45.4	19	41.0	49.0	37	47.4	41.2	54
Clay	23.8	1.9	2	20.0	1.5	0	20.6	1.6	2	23.2	0.6	5
Colloids	10.3	1.4	5	1.2	1.5	0	7.3	1.6	0	9.8	0.6	3
Plasticity Index	24.9	13.8	13	32.4	11.8	N.P.	25.2	14.1	1	29.6	12.7	11
Shrinkage Limit	13.5	25.0	20.0	11.4	32.9	NVC	12.6	26.7	21.0	12.1	28.9	19.3
Shrinkage Ratio	1.96	1.6	1.55	2.06	1.45	NVC	2.00	1.56	1.45	2.01	1.50	1.57

Note: CMS = cement-modified soil.
[a]Average of three samples for all except 5.5 percent cement content where two samples were averaged.

tions. The 11 test sections were randomly selected to gather representative subgrade samples.

Initially the investigation was to include one sample in each of the 11 test sections. However, to avoid inconclusive results due to a nonrepresentative sample, a series of three tests was taken in each section. The center sample location was chosen at random and the other two samples were taken 50 ft on each side of the initial location. All samples were located approximately 5 ft left of the centerline.

The pavement was cored and the subgrade sampled by using a CME 750 multiuse core and auger rig (Figure 1). Cores of the asphaltic concrete patches, concrete pavement, and, in some samples, a portion of the cement-modified subgrade were cut with a 4-in.-diameter diamond-bit core barrel. Subgrade samples were obtained by thin-walled tube sampling procedures in accordance with AASHTO T207-81 (Figure 2). Following sampling, the pavement was returned to its original condition by filling the core holes with ready-mixed concrete.

The subgrade samples were wrapped to prevent moisture loss and returned to the laboratory. All samples wer visually inspected and classified. The samples first were logged and described as to color and texture; then the Atterberg limits and gradations were determined and the soils were classified.

A summary of results is given in Tables 1–3. Included are the

TABLE 2 SUMMARY OF FIELD INVESTIGATION: PART 2

Soil Description Soil Classification	Brown Silty Sand A-2-4			Brown Clayey Silt A-4			Reddish Brown Clayey Soil A-4			Brown Clayey Silt A-4		
Station to Station	1126+00 1144+50			1181+00 1189+00			1189+00 1197+25			1222+50 1236+50		
Cement Content (percent by volume)	9.5			7.0			6.0			5.5		
	Raw Soil	1938 CMS	1983 CMS	Raw Soil	1938 CMS	1983 CMS	Raw Soil	1938 CMS	1983 CMS	Raw Soil	1938 CMS	1983 CMS
Coarse Sand	7.7	9.0	42	14.4	16.5	16	20.1	15.4	29	17.0	16.3	15
Fine Sand	16.1	39.2	31	20.9	40.0	25	22.5	11.3	29	30.4	31.0	30
Silt	44.1	51.3	26	35.8	30.7	55	34.2	72.1	40	30.4	50.4	54
Clay	32.1	0.5	0	28.9	12.8	2	23.2	1.2	1	22.2	2.3	1
Colloids	11.7	0.5	0	11.9	9.7	3	11.0	0.8	1	9.7	2.3	0
Plasticity Index	40.8	18.0	3	25.5	12.1	8	21.5	6.6	3	18.0	14.0	6
Shrinkage Limit	10.2	27.4	21.1	14.0	29.0	22.6	15.0	28.2	15.9	14.5	21.8	20.3
Shrinkage Ratio	2.12	1.55	1.40	2.00	1.53	1.51	1.90	1.50	1.61	2.00	1.68	1.52

Note: CMS = cement-modified soil.

TABLE 3 SUMMARY OF FIELD INVESTIGATION: PART 3

Soil Description / Soil Classification	Brown Sandy Silty Clay A-2-4			Brown Sandy Silty Clay A-2-4			Brown Sandy Silty Clay A-2-4		
Station to Station	1236+50 1246+00			1269+00 1272+00			1301+50 1307+65		
Cement Content (percent by volume)	5.0			4.0			16.0		
	Raw Soil	1938 CMS	1983 CMS	Raw Soil	1938 CMS	1983 CMS	Raw Soil	1938 CMS	1983 CMS
Coarse Sand	18.6	16.5	32	16.2	19.9	29.0	2.0	11.6	40
Fine Sand	29.2	34.2	37	40.7	44.3	32.0	17.1	45.4	31
Silt	26.6	47.2	25	29.1	33.5	31.0	42.6	38.4	27
Clay	25.6	2.1	2	14.0	2.3	3	38.3	4.6	1
Colloids	12.8	1.3	4	1.7	1.3	5	14.5	1.6	0
Plasticity Index	26.0	13.2	6	20.8	12.8	8	50.5	15.0	4
Shrinkage Limit	13.0	23.0	13.8	15.6	24.2	18.2	10.5	34.7	22.3
Shrinkage Ratio	2.0	1.66	1.68	1.90	1.65	1.70	2.1	1.42	1.42

Note: CMS = cement-modified soil.

average plasticity indexes, shrinkage limits, shrinkage ratios, and gradations of each group of three samples. Also shown are original raw soil data and cement-modified soil tests made in 1938. A comparison of the 1938 and 1983 plasticity index data is shown in Figure 3.

SUMMARY AND CONCLUSIONS

A cement-modified soil project was built in southwestern Oklahoma in the fall and winter of 1938; 11 different cement contents were used in 38 different test sections along 7 mi of roadway. The average cement content for the total project was 6 percent by volume. Tested in 1983, the plasticity indexes ranged from nonplastic to a maximum of 17 on those sections included. The average plasticity index for these tests was 6 compared with a 1938 average of 12 for identical sections. In each section tested in 1983, the average plasticity index was less than the plasticity indexes measured in 1938. These test results show the long-term effectiveness of portland cement in reducing the plasticity indexes of fine-grained soils.

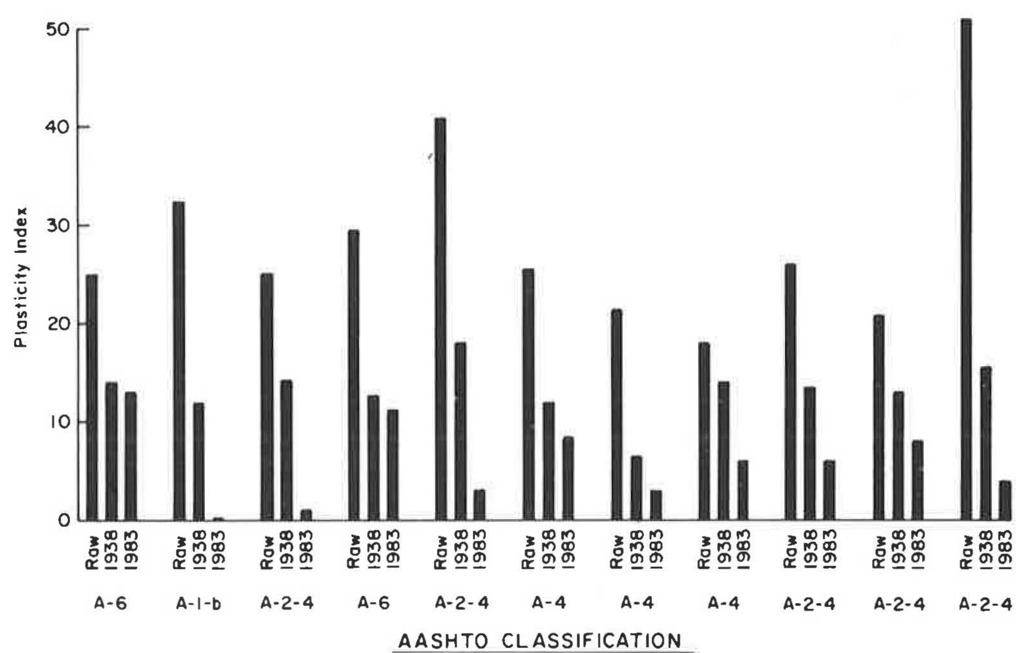

FIGURE 3 Comparison of plasticity index data for raw soil and cement-modified soil.

ACKNOWLEDGMENTS

The author wishes to thank Frank Hawthorne and the other commissioners of Comanche County for permission to core and sample their county road; Mayor Bailey and the citizens of Indiahoma for authorizing the Portland Cement Association to core and sample their street; Atlas-Truck Concrete, Inc., Duncan, for supplying the concrete and assisting in repairing the cored holes; and Shepherd Engineering and Testing Company, Norman, Oklahoma, for conducting the field and laboratory investigations.

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Publication of this paper sponsored by Committee on Soil-Portland Cement Stabilization.

Flexural Fatigue Strength of Lime-Laterite Soil Mixtures

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Laterite soils, which are the products of tropical or subtropical weathering, have been stabilized with lime to evaluate the dynamic modulus and the flexural fatigue strengths of the lime-soil mixtures. Tests have been carried out on four types of laterite soils compacted at three dry density ranges—light, medium, and heavy. Least-squares regression analysis was used to establish relationships between stress ratio and the logarithm of the number of stress cycles to failure. Heavily compacted lime-soil specimens were found to have considerably higher dynamic modulus and fatigue life than those having standard Proctor compaction. Increased values of dynamic flexural modulus and strength at the higher dry density favor the use of lime-laterite soil as a road base.

Highway pavements need good quality paving materials with adequate strength and durability characteristics. With petroleum prices rising sharply, bitumen is no longer a cheap material, particularly in India, and therefore asphalt-bound pavement layers cannot be considered economical road bases now. Highway activities, on the other hand, have increased manyfold and as a result quality paving materials have become scarce and costly. Under the circumstances, utilization of locally available indigenous materials may provide a solution to reduce construction costs if the characteristics of the in situ soils, otherwise unsuitable, are modified by appropriate treatment. This study is an attempt to evaluate the suitability of lime-treated laterite loams available in India.

Laterites are apparently very complex and controversial materials that defy any satisfactory geological, chemical, or pedological definition (*1*, p. 5). Essentially, they are products of tropical or subtropical weathering that includes all stages from parent rock to the surface and in which iron or aluminum content or both are higher and silicon content is lower than in merely kaolinized parent rock (*2*, pp. 1–10). Though they frequently occur in the humid tropical areas of South America, Africa, India, Indonesia, and Australia (*3*), there is an absence of adequate engineering data for highway and runway construction.

Areas of laterite soil occur in coastal India and the adjoining interior. The present study area at Kharagpur is on the east coast. These reddish-brown fine-grained laterite soils are evaluated for their suitability as a lime-bound base. Tests were carried out on four laterite soils treated with an optimum lime content of 5 percent.

The changes that take place on addition of lime to certain laterite soils are rapid amelioration effects and strength development due to hydration and increased degree of crystallinity of the reaction products formed during the first 5 to 7 days (*4*). The strength of a stabilized soil has been quantitatively assessed by unconfined and confined compressive strength tests (*5*; *6*, p. 290; *7–9*) and also by the split tensile strength test (*10*). But the shear and compressive strengths of lime-soil mixtures are not the limiting factors in their application as subbase or base-course materials (*11*). The lime-soil

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