Experimental Stabilization of Pierre Shale

E. B. McDONALD, South Dakota Department of Highways

The experimental study of stabilization of the Pierre shale was initiated with a threefold purpose in mind: (a) to determine if it is possible to achieve the degree of stability necessary to prevent warping of road surfacing materials by the addition of chemicals or other additives to the highly expansive in-place soils over which these surfacing materials are placed; (b) to determine if the use of additives in the in-place soils is more effective in reducing warping than replacing with nonexpansive materials; and (c) to determine, to a certain degree, the economy of using stabilizing agents in the in-place soil as compared to hauling in nonexpansive material. The experimental road includes the following types of stabilization in the upper 6 or 9 in. of soil subgrade: lime stabilization, lime-asphalt stabilization, phosphoric acid plus ferric sulphate, and PDC formula (4 parts lime, 2 parts cement, and 1 part soy flour). Control sections are composed of standard design methods, including select soil, or nonexpansive soil, varying in thickness from 6 to 18 in. in conjunction with a 3- to 6-in. thickness of standard type B subbase, 5 in. of standard type II base course, and a 2-in. class F mat. One special control section has 30 in. of select soil. Two other control sections have the earth subgrade undercut to a depth of 36 in. The undercut soil was replaced and recompacted prior to placement of surfacing materials.

At the end of the 4-year study period, all of the stabilizing agents have altered the physical characteristics of the Pierre shale to some degree. Lime appears to have the more permanent effect. The serviceability index ratings indicate that all of the stabilized sections except phosphoric acid are better than in the standard design sections. All of the treated soils have a higher CBR value after a 4-year period than the raw soil. The phosphoric acid section is only slightly higher than the raw soil. Lime-treated soils, and additives in combination with lime, apparently recover some bearing strength after suffering a loss of strength due to freezing. Serviceability index ratings indicate that treated soils tend to be more effective in reducing surface warping than the use of nonexpansive soils over the Pierre shale. It appears that the use of stabilizing agents capable of maintaining a permanent change in the physical characteristics of the soil would be more economical than the use of nontreated soils by reducing the long-range maintenance costs. Stabilizing agents capable of maintaining higher stability and bearing capacity in the treated layers throughout the year will allow the design of thinner surfacing components.

•WESTERN SOUTH DAKOTA and a portion of the state east of the Missouri River lie within the Great Plains Physiographic Province. The portion of the state within the James Basin and eastward lies in the Central Lowlands Province. The western portion of the state is divided into 3 general landforms, composed of the following:

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1. The Black Hills, a large domal uplift area that extends northwestward across the southwestern part of the state with elevations up to 7,200 ft;

2. The High Plains area in the south-central part of the state, extending along the South Dakota-Nebraska boundary at an elevation of 3,000 ft; and

3. The Missouri Plateau, a region of relatively low undulating grasslands that surrounds the Black Hills and the High Plains. This area contains the Badlands of South Dakota and the Pierre shale deposits.

The eastern portion of the state is also divided into 3 general landforms as follows:

1. Missouri Hills, in the central portion of the state;
2. James Basin, principally a low-lying, prehistoric lake bed in the north; and
3. The Prairie Hills, an area extending from the east central Minnesota border to the James Basin.

These physiographic divisions are shown in Figure 1.

Much of the soil in the Missouri Plateau in the western portion of the state is composed of Pierre shale, which exhibits highly expansive properties. This expansion causes considerable problems in building and maintaining smooth road surfaces. Our test road was built with the primary purpose of determining how effective any of several known chemical stabilizations would be in reducing surfacing roughness that develops soon after hard surface roads are placed on the expansive shale.

Because of the extremely high liquid limits of the Pierre shale, we were skeptical that any type of stabilizing agents could be adequately mixed in the field to provide any degree of uniformity. Although we were quite successful in achieving a good mixture of the high liquid limit shale-clay with various additives in the laboratory, we were not certain that this degree of uniformity could be duplicated in the field. However, warping of surfacing materials is so acute, in the expansive soil areas, that we felt that we had to try some remedial measures.

Experimental laboratory testing was completed in 1960, and we made plans to go ahead with a test road project. Shortage of state funds delayed the construction of the project, and it was not until 1963 that we were able to let a contract. All phases of the construction work were completed in September 1964.

It is the intent of this report to make rational, valid conclusions based on results of test data representing the various types of stabilization as they relate to the field conditions in South Dakota.

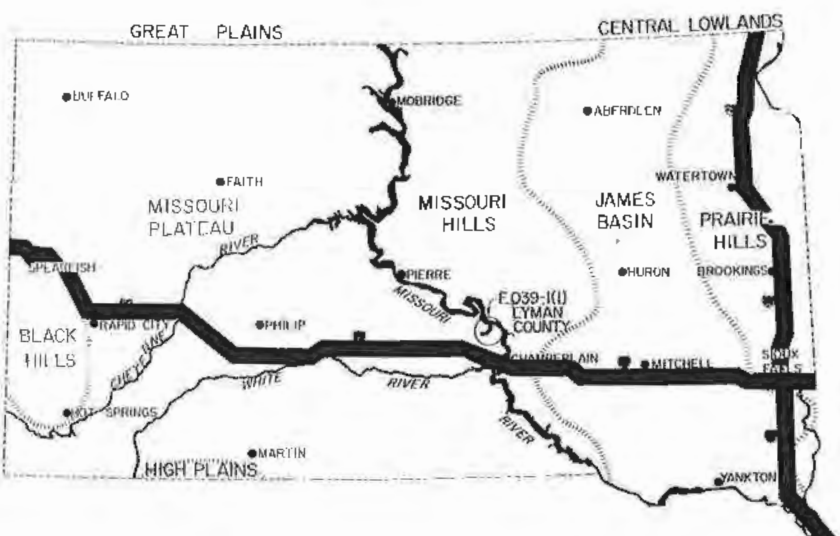

Figure 1. Physiographic divisions of South Dakota.

OBJECTIVES

The primary objectives of the test road are as follows:

1. To determine if it is possible to achieve the degree of stability necessary to prevent warping of road surfacing materials by the addition of chemicals or other additives to the highly expansive in-place soils;
2. To determine if the use of additives in the in-place soils is more effective than replacing with nonexpansive materials; and
3. To determine, to a certain degree, the economy of using stabilizing agents for the in-place soils, as compared to hauling in nonexpansive material.

In order to determine if it was possible to obtain results that would achieve these objectives the following stabilizing agents were introduced into the subgrade: lime stabilization, lime-asphalt stabilization, phosphoric acid plus ferric sulphate, and PDC formula (4 parts lime, 2 parts cement, and 1 part soy flour).

Control sections used for comparison purposes are composed of a 2-in. class F mat and a 5-in. base course, in conjunction with 3 to 6 in. of standard subbase. Several of these sections also had a layer of select soil varying in thickness from 6 to 18 in. placed below the subbase.

It is difficult to make an economic study of the cost of the individual types of stabilization on a project of this nature because relatively small quantities of some agents were used. However, maintenance cost records have been kept, and an effort has been made to compare the initial costs of the various types of stabilization against the indicated long-range maintenance costs. The initial cost of the standard design was $67,500 per mile, lime was $85,200 per mile, lime plus RC-1 was $93,300 per mile, PDC was $95,700 per mile, and phosphoric acid plus ferric sulphate was $120,600 per mile. These were the actual bid prices.

Laboratory Procedure

Laboratory tests were run on samples of the highly expansive Pierre shale taken from the F 039-1(1), Lyman County Project on SD-47W, which links the east river country and the west river country via the Big Bend Dam. The Pierre shale becomes very hard and slate-like when dried, and it is given a pretreatment breakdown with a wooden mallet

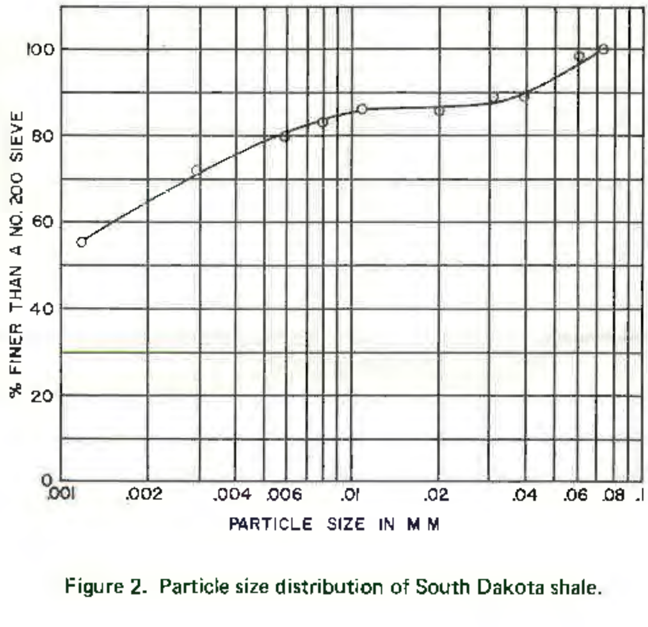

Figure 2. Particle size distribution of South Dakota shale.

prior to running it through a jaw crusher. The soil is further pulverized in revolving barrels in which rubber covered steel rollers have been placed. These rubber covered steel rollers are very effective in reducing the hard shale to a very fine grain size. This type of pulverization facilitated the mixing of lime, oil, phosphoric acid, ferric sulphate, and PDC and allowed a reduced curing period. The particle size distribution of the Pierre shale is shown in Figure 2.

A mechanical analysis of the soil was determined using the standard AASHO T-88-57 method. Hydrometer tests and the standard Atterberg AASHO T-89-60 and T-90-61 liquid limit and plastic limit tests were made. A sufficient amount of soil was prepared in all of the original samples to run standard AASHO T-99 densities, standard CBR tests, unconfined compression tests, and volume-change tests for both the raw samples and the treated soil samples.

To be sure that the amount of material was the same for each soil type specimen molded, with the various percentages of additives, a predetermined maximum density was used. Although nearly all of the tests made prior to construction showed that treated soils had a decided increase in unconfined compressive strengths, we were not able to extract these small undisturbed cores during post-construction testing to compare with the original laboratory results. Consequently, we had no data for this item in 1965. This test was replaced with a modified laboratory CBR by extracting 6-in. diameter cores and testing them under the same conditions as the laboratory molded CBR's.

The effects of compactive effort are shown in Figure 3, using the modified AASHO method and the standard AASHO method. The Pierre shale is quite sensitive to compactive efforts. It can be seen that there is a 17.5 lb/cu ft weight differential and a corresponding moisture differential of 10 percentage points when modified AASHO T-189 is used as compared to standard AASHO T-99. Figures 4 and 5 show that expansive pressures of raw soil are affected by both compactive effort and moisture content.

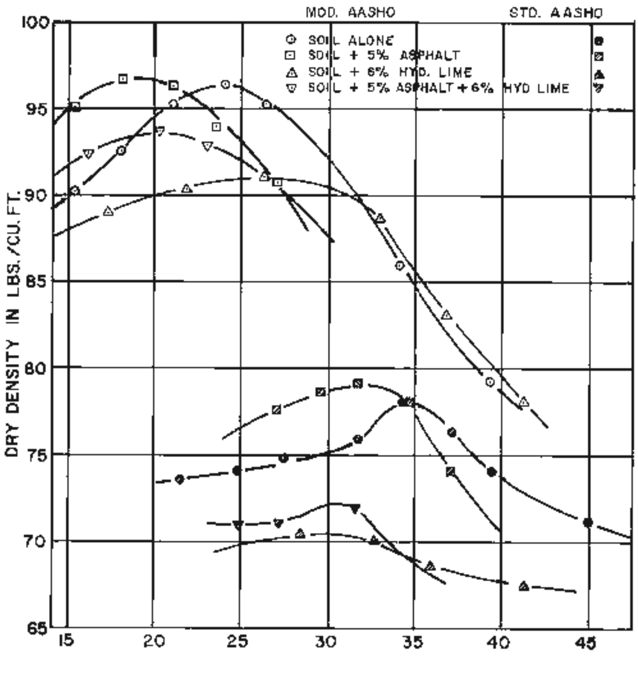

Figure 3. Effect of compactive effort on density of South Dakota shale.

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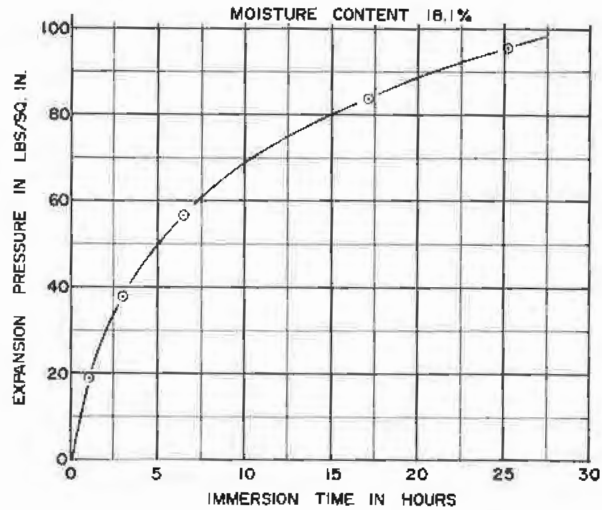

Figure 4. Expansion pressures of South Dakota soil—Modified AASHO compaction T-180.

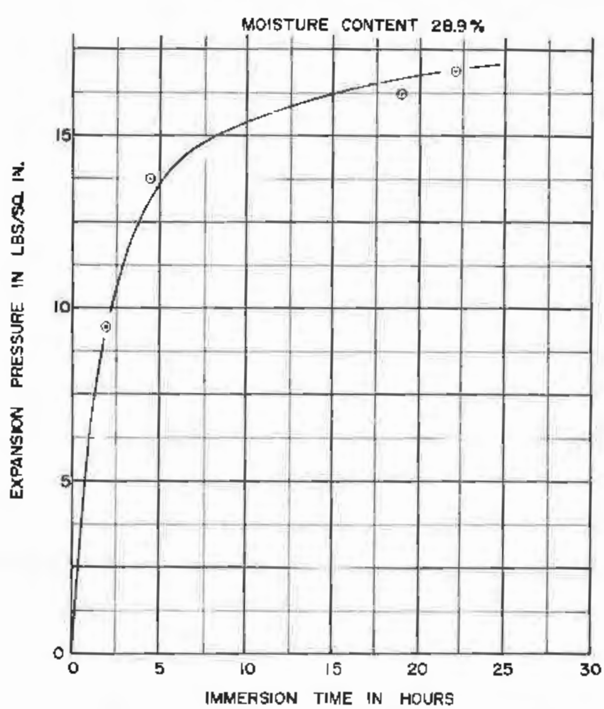

Figure 5. Expansion pressure of South Dakota soil—Standard AASHO compaction T-99.

In addition to these tests described, a series of freeze-thaw tests were conducted on samples containing the various types of additives to determine what effect freezing would have on the stabilized soil. One set of specimeus for each type of stabilization was frozen and allowed to thaw out in the air at room temperature. The other set was frozen and thawed out under water at room temperature. We found that all of the stabilization types suffer quite a bit of damage after 12 freeze cycles. The difference in the degree of deterioration of specimeus within each stabilization type indicated that variation in laboratory procedure and technique have some effect on how well the specimens withstand the freezing cycles. Figure 6 shows that some specimens deteriorated completely and other stood up quite well when thawed at room temperature. Figure 7 shows the results of the soak thaw.

Our previous experience indicated that the expansive soil produced warping effects on either concrete or asphalt surface roads. However, we included approximately 1 mile of concrete surfacing as well as a short section of deep-strength asphalt and 1 short section of cement-treated base with an asphalt overlay. A cement-treated base was also placed under portions of the concrete surfacing. These surfacing types were introduced for observation purposes and to determine the effects of warping on the riding quality of the surfacing.

Field Procedure

Preconstruction—Prior to the beginning of stabilizing the subgrade, the service gravel that had been placed to carry local traffic had to be removed. After this operation there were still a few gravel particles remaining in the upper 6 in. of roadbed. These particles were screened out and ignored during the molding operations of samples taken from the roadbed.

Construction—The average liquid limit of the soil through the first 6 miles of the test section is approximately 91 percent. The average optimum moisture is 30 percent. The last 2.5 miles of project has an average liquid limit of 61 percent and an optimum moisture of 24 percent.

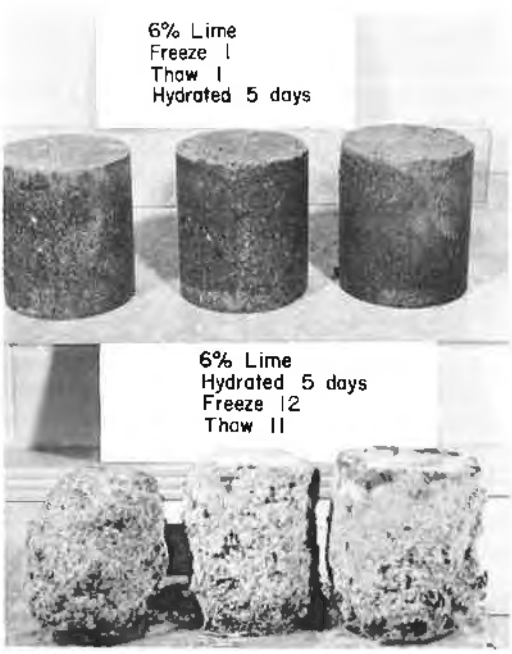

Figure 6. Samples after air thaw.

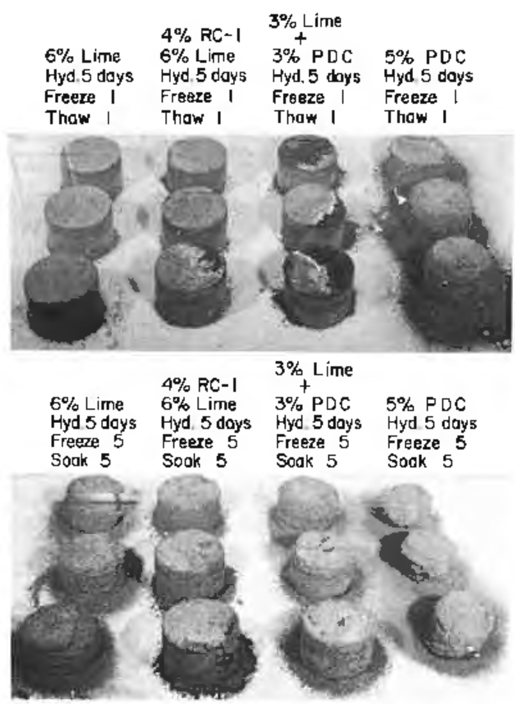

Figure 7. Samples after soak thaw.

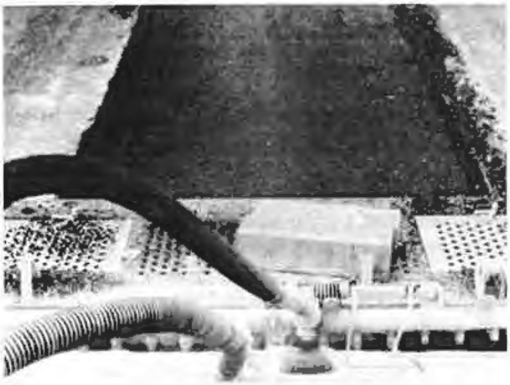

Figure 8. Single-pass pulverizing machine.

Figure 9. Project identification markers.

Specifications required that the soil should be thoroughly pulverized prior to addition of the additives with any type of single-pass machine that the contractor believed would produce the desired results. It was required that not less than 95 percent of the material would pass the 1½-in. sieve and not less than 50 percent would pass the ¾-in. sieve. The contractor used a single-pass machine; and, although he had to move at a slow speed, pulverization specifications were met in a single pass (Fig. 8). This greatly facilitated the progress of the stabilization work.

The roadbed was treated with the stabilization materials during the spring of 1964, and the surfacing materials placement was completed during September 1964. Benchmarks are set along the right-of-way at locations convenient to the various stabilized sections in order to establish precise level data in connection with the rideability and roughness study.

Upon completion of stabilization work, identification markers were placed at the ends of the project and at the end of each type of stabilization and control sections. These markers at each test section are a graphic, coded picture of the thickness and type of each surfacing and stabilizing component used in each test section (Fig. 9).

POST-CONSTRUCTION TESTING

Laboratory Tests and Procedures

The standard AASHO T-89-60 test was used to determine the liquid limit of the treated and raw soils. These results are tabulated on a yearly basis and are compared to the original liquid limits determined during preconstruction and during construction. Figures 10 through 13 show that the average test results of all of the treated soils show some tendency to rebound or move upward to a higher value when compared to the original construction tests.

The plasticity index (PI) tests were run in accordance with standard AASHO T-90-61. There is a tendency for the PI's to rise slightly above the PI's noted during construction. However, the lime has held very close to the original treated PI's, and is slightly better than the lime plus RC-1, which is second best. The PDC pretreated with lime is third. The phosphoric acid plus ferric sulphate returned almost to the original PI. The average test results of each of the sections are shown in Figures 14 through 17.

Volume-change tests run on treated soils during construction show that all of the treated soils have considerably less volume change than the untreated raw soils. CBR swell tests for raw soils and treated soils, as compared with the modified CBR swell tests run on samples taken from the field during 1966, 1967, and 1968, show that the swell properties of all of the treated soils taken from the field compared favorably with

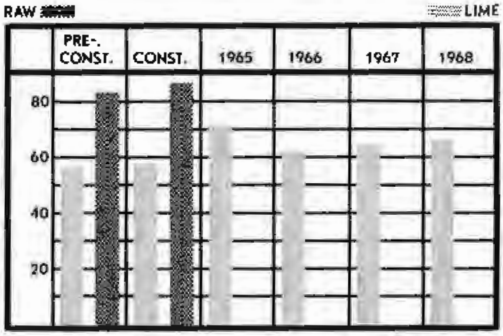

Figure 10. Liquid limit, lime stabilization.

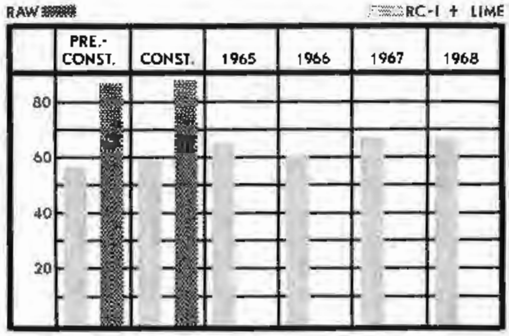

Figure 11. Liquid limit, lime-asphalt stabilization.

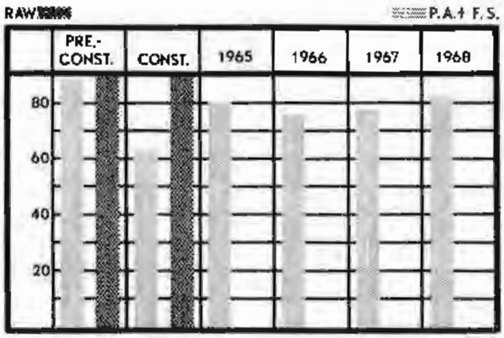

Figure 12. Liquid limit, phosphoric acid plus ferric sulphate stabilization.

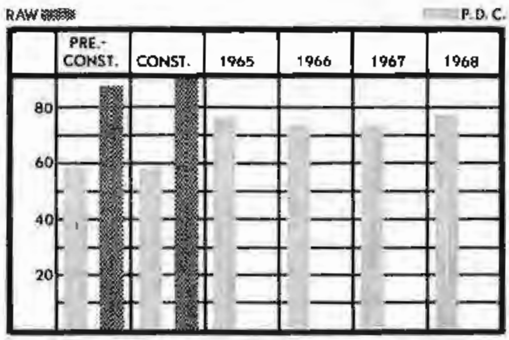

Figure 13. Liquid limit, PDC formula stabilization.

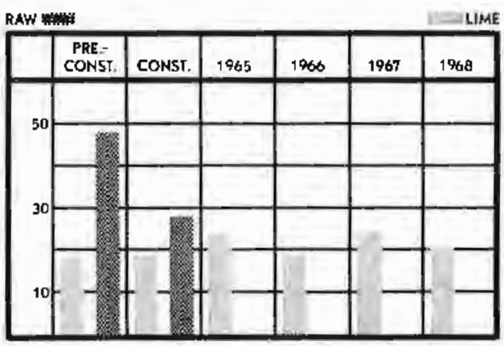

Figure 14. Plasticity index, lime stabilization.

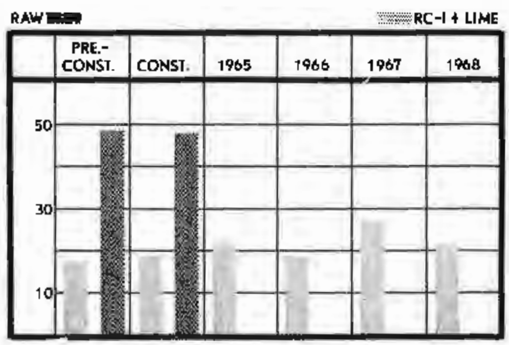

Figure 15. Plasticity index, lime-asphalt stabilization.

the preliminary laboratory tests that were run prior to construction and during construction. Also, all of the treated soils have swell values considerably below those of the raw soils. The average results of each of the various test sections are shown in Figures 18 through 21.

In 1967 and 1968 we ran some pH tests to determine how much calcium oxide was still available for reaction with the soil. The pH of the raw soils varies from about 5.9

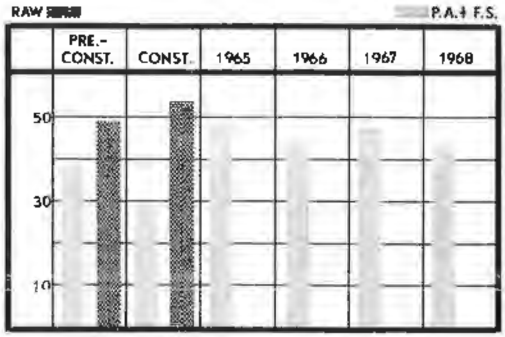

Figure 16. Plasticity index, phosphoric acid plus ferric sulphate stabilization.

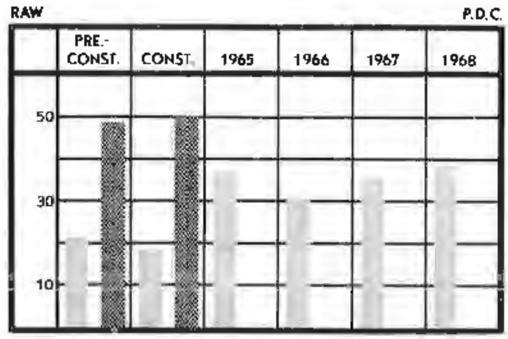

Figure 17. Plasticity index, PDC formula stabilization.

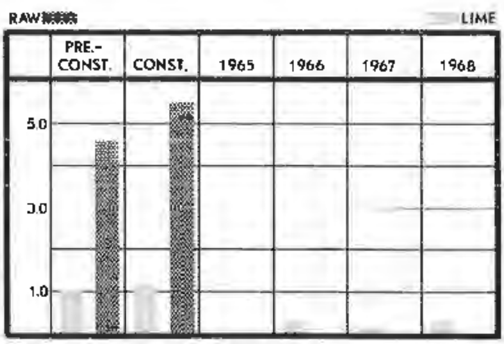

Figure 18. Percentage CBR swell, lime stabilization.

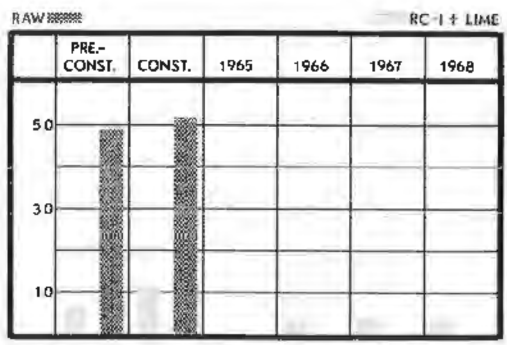

Figure 19. Percentage CBR swell, lime-asphalt stabilization.

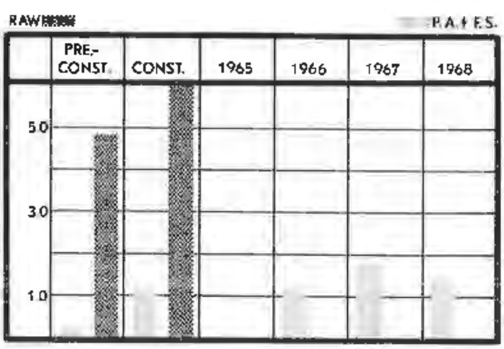

Figure 20. Percentage CBR swell, phosphoric acid plus ferric sulphate stabilization.

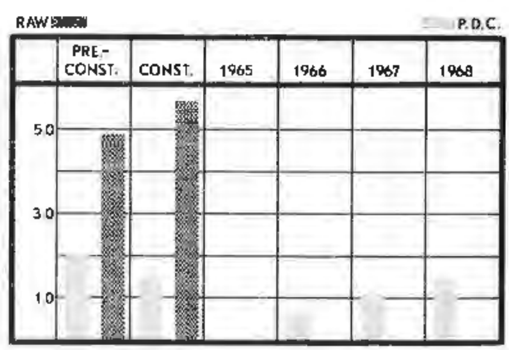

Figure 21 Percentage CBR swell, PDC formula stabilization.

to 8.2. We found that almost all of the treated sections, with the exception of the acid-treated soil, have a pH of 9 to 11. One PDC section, one lime section, and one lime plns RC-1 section show very little if any calcium oxide remains.

Field Tests and Procedures

We had planned to run our post-construction tests at the rate of 4 times per year, during each season of the year. Because of limited equipment and personnel, it was not possible to adhere to this schedule of testing. We were forced to sample and test the in-place materials on the basis of once a year through the period of approximately April 15 to October 15.

Stationing of the test sites in each test section was selected, and sampling operations were begun in April 1965. The Physical Research Section of the Department of Highways conducted standard plate tests and field CBR tests during the spring and summer months. A series of plates varying from 9 to 18 in. in diameter were used, and loads were applied to the mat as well as to each layer of surfacing, including the stabilized subgrade soil. In order to perform these tests, it was necessary to cut a series of 5 holes at each test site. The average test results of the 18-in. plate loads are shown in Figures 22 through 25.

In order to obtain samples of the treated subgrade for laboratory testing and field tests, it was necessary to bore 3 holes into the surfacing at each test site. A thin-walled, Shelby tube was forced into the exposed subgrade of one of the holes to a depth of 2 ft to obtain laboratory samples. A second hole was used to obtain an in-place specimen on which to conduct a modified CBR test and swell test. The third hole was

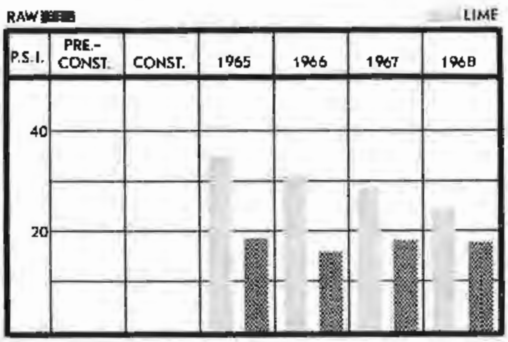

Figure 22. Plate load, lime stabilization.

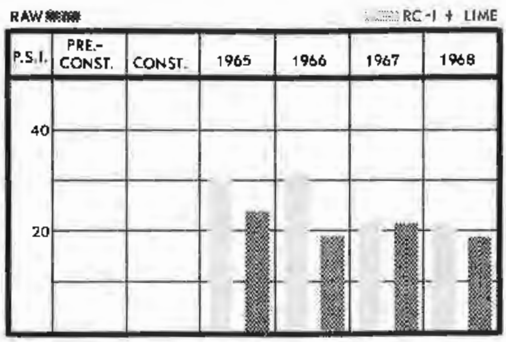

Figure 23. Plate load, lime-asphalt stabilization.

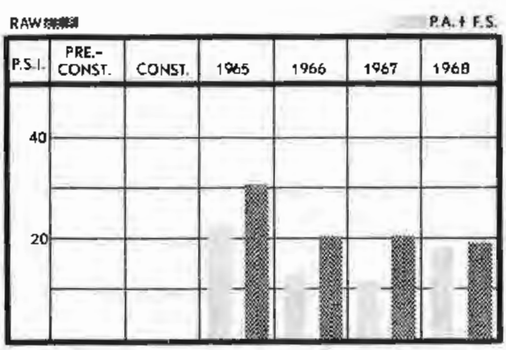

Figure 24. Plate load, phosphoric acid plus ferric sulphate stabilization.

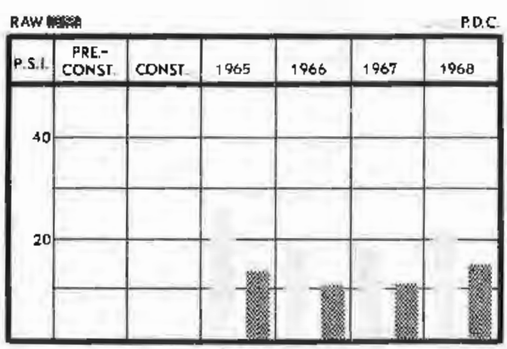

Figure 25. Plate load, PDC formula stabilization.

Figure 26. Cracks that developed in areas of bentonite soil.

Figure 27. Fault lines and bentonite layers below roadbed.

used to conduct a modified 6-in. plate load test. During the fourth year a fourth hole was dug to perform a modified field CBR test.

Large cracks developed where concentrations of bentonite soil are present beneath the roadbed. Investigations of these areas showed fault lines and nearly pure bentonite layers as far down as 15 ft below the roadbed, as well as free water accumulation (Figs. 26 and 27). A study of the crack pattern shows the average number of cracks per mile in the lime sections varied from 83 in 1966 to 145 in 1968. Those in the phosphoric-acid sections varied from 46 in 1966

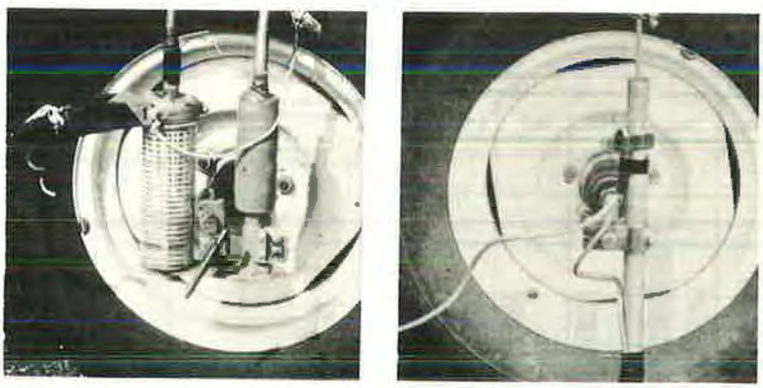

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Figure 28. Old roughometer (left) and new LUDT coil roughometer (right).

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On page 24, in the caption for Figure 28, and on page 25, third line from bottom, the reference to "LUDT" should be "LVDT" (linear variable differential transformer).

to 143 in 1968. The lime-plus-RC-1 crack pattern varied from 85 in 1966 to 147 in 1968. The cracks in the PDC sections varied from 101 in 1966 to 211 in 1968. The raw sections had a crack pattern range from 126 in 1966 to 211 in 1968. The cracks in the cement-treated base sections varied from 122 in 1966 to 550 in 1968. With the exception of the PDC and cement-treated bases, the treated soils definitely have some influence on the crack pattern of the surface.

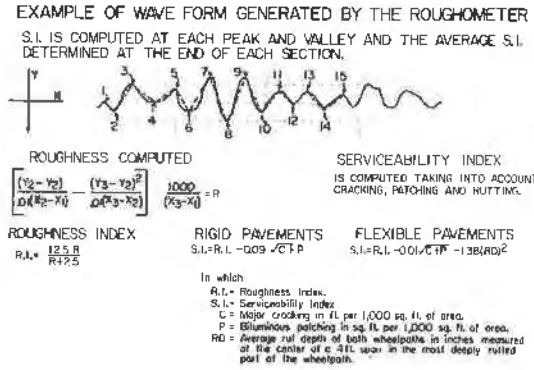

Figure 29. Formulas for determining SI.

CBR tests indicate that the lime-treated soils in nearly all test sections have considerably higher bearing values than the raw soil for both the soak CBR and the modified field CBR. The lime plus RC-1 rates second best, the PDC material is third, and the phosphoric acid is only slightly better than the raw soil for both types of tests.

In order to determine how the various degrees of warping were affecting the rideability in each test section, a high-speed roughometer was developed that travels the legal speed limit of 70 mph. This roughometer traces the wheel movement on a paper tape and also is recorded on a magnetic tape for introduction into a digitizing unit. The degree of displacement was recorded by setting permanent bench marks adjacent to the roadway and driving bolts in the road surface. Permanent marks were cut into the concrete. The bolts and marks were set at 25-ft intervals on centerline and in each outside driving lane. Precise level data were recorded 4 times a year at the seasonal changes through the 4-year period.

Total displacement, or average displacement, is not always indicative of the rideability or serviceability. However, when the displacement levels are extremely differentiated, the roughometer graph and the displacement graph correlate quite well. Figure 28 shows the old roughometer on the left and the new LUDT coil roughometer on the right. Figure 29 shows formulas for determining SI, and Figure 30 shows an example of the displacement as determined by the precise level data.

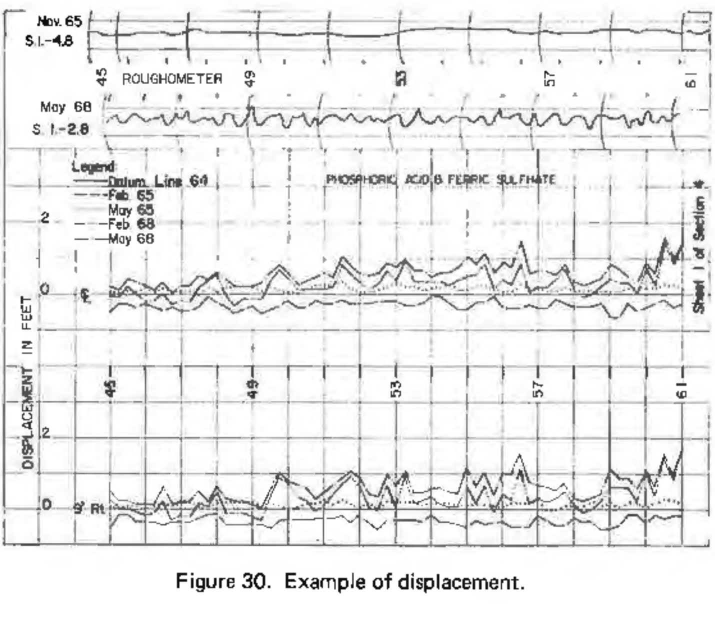

Figure 30. Example of displacement.

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OBSERVATIONS

In order to ascertain how effective the additives are in achieving the objectives of the study, a composite or an average evaluation of the various tests that relate to these items was made for each type of stabilization. The evaluations for each of the test sections are as follows:

Lime-Treated Subgrade—A review of the test data shows the PI for the average of all lime sections has been reduced from 44.0 to 16.0. The average CBR shows a loss in value during the second and third year and then regains some of the initial strength. The modified field CBR value in 1968 is higher than the average laboratory CBR value in 1964 (Fig. 31).

Lime- and RC-1-Treated Subgrade—The PI of the treated soil during the 4-year study averages approximately 22.5 as compared with an average PI of 50.7 for untreated soil. The average CBR of the lime plus RC-1 soils shows the same trend as the lime-treated soil, namely, a loss of strength during the second and third year with a regain of strength in 1968. The modified field CBR also shows a higher value in 1968, being nearly equal to the original laboratory CBR (Fig. 32).

PDC-Treated Soil—The average plasticity index of the treated soil during the 4-year study period is maintained at approximately 32.0 as compared with a plastic index of approximately 50.4 for the untreated soil. The average CBR values show a loss during the second and third year of freeze and thaw and show only a small recovery. However, the modified field CBR of the treated soil is considerably higher in 1968 than that of the untreated soil (Fig. 33).

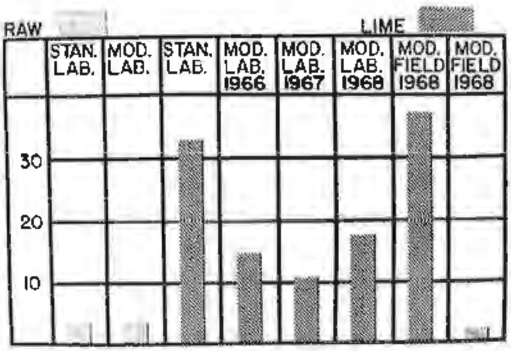

Figure 31. CBR, lime stabilization.

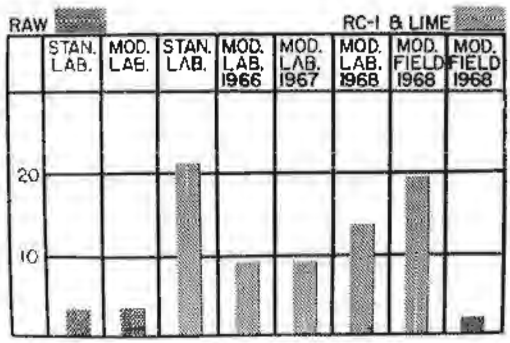

Figure 32. CBR, lime-asphalt stabilization.

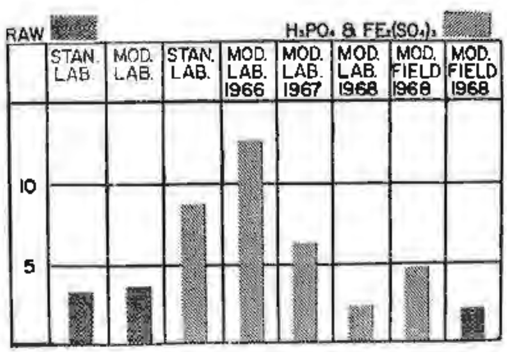

Figure 33. CBR, PDC formula stabilization.

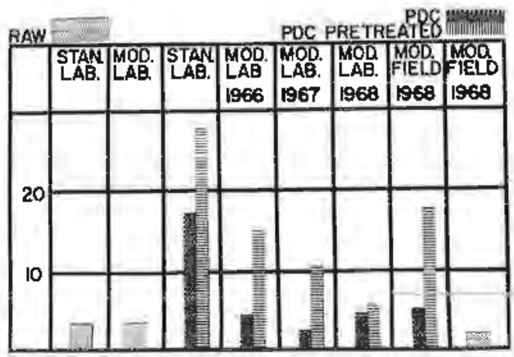

Figure 34. CBR, phosphoric acid plus ferric sulphate stabilization.

Phosphoric Acid plus Ferric Sulphate—The average plasticity index of the treated soil during the 4-year study is approximately 44.0 as compared with an approximate average plastic index of untreated soil of 53.0. The modified laboratory CBR values have dropped to almost the value of the untreated soil. However, the modified field CBR shows there is a slight retention of strength when compared with the untreated soil (Fig. 34).

The overall average comparison of serviceability index for cuts and fills for all of the treated soils is shown in Figure 35.

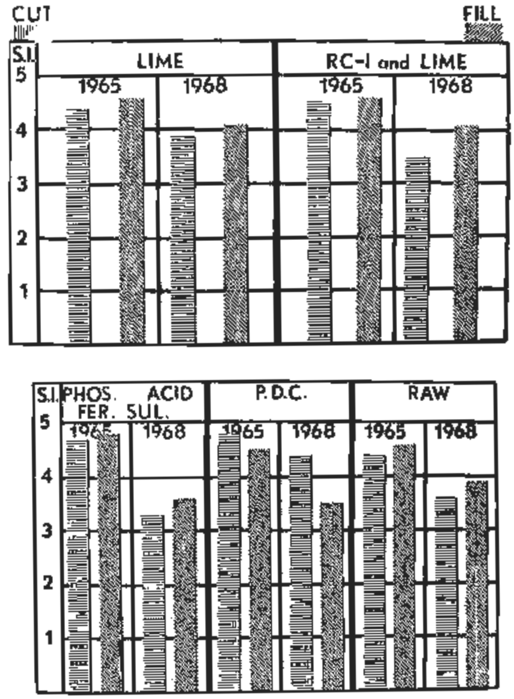

Figure 35. Serviceability index, all treated materials.

CONCLUSIONS

More than 5,200 laboratory and field tests were run on the treated and untreated soils during the course of this study. More than 95,000 elevation readings of the road surface were taken.

It is important to understand that, although all of the soils within the test road area have an AASHO classification of A-7-6(20), the physical characteristics, in regard to liquid limit, vary from a low of 65 to a high of 118. The plastic index, shrinkage, and volume change vary in the same degree of magnitude. These variaable conditions can and do take place within a distance of 20 ft. These variations are the cause of variable test values obtained in some of the test sections by virtue of the fact that the percentage of additives was not adequate to completely stabilize the extremely high liquid limit soil.

Our interpretation of the data is therefore based on the average conditions in regard to the ability of the various stabilizing agents to accomplish the objectives as set forth in the foregoing portion of this report. These conclusions are as follows:

1. All of the stabilizing agents have altered the physical characteristics of the high liquid limit soil to some degree. The field condition tests indicate that lime has a more permanent effect in altering these characteristics than the other combination additives used in this test road.

2. The serviceability index ratings, as determined by the applied formula used in this report, indicate that all of the stabilized sections, except the acid, are better than the standard design sections. The average SI ratings show that lime-treated sections have the best ratings followed very closely by the PDC and lime plus RC-1 stabilization. The phosphoric acid plus ferric sulphate rating is slightly below that of the untreated soil.

3. The sections having lime or lime combinations show a loss of CBR strength when compared with the initial laboratory CBR during the second and third year with a recovery of some bearing strength during the fourth year. The sections with lime only have the best CBR value after a 4-year, in-service period, with the lime plus RC-1 being second and the PDC formula being third best. CBR values of the phosphoric acid are about the same as the untreated soils.

4. The recovery of bearing in the lime-treated soils appears to confirm the findings of Dr. Marshall Thompson, University of Illinois, in regard to the autogenous healing theory of lime-treated soils. Dr. Thompson's laboratory tests show that lime-treated soils tend to recover bearing strength after suffering a loss of bearing due to frost action (1).

5. A review of the serviceability index indicates that the use of additives capable of maintaining a permanent change in the physical characteristics of the treated soil tend to be more effective in reducing surface warping than the use of nonexpansive regular material over the expansive soils.

6. As noted earlier in the report, the cost per mile was computed from the actual bid price for various stabilizing material. The prices are no doubt higher than they would normally be if large quantities of the materials were being purchased.

The fact that there are less cracks per mile in some of the treated sectious, as compared with the untreated soil, indicates that the future long-range maintenance will be less. If the serviceability index differential between the lime and lime combination soils and the untreated soil continues at its present ratio, it appears that the future maintenance work in these sections will be delayed for a greater period of time than in the untreated sections.

7. In view of the fact that the stabilized subgrade maintains a higher stability and bearing capacity throughout the year, we are able to design thinner surfacing components, which allows us to conserve our dwindling gravel supply.

We believe that one of the big benefits derived from this study is the development of the high-speed roughometer, which is now being used as an aid in determining maintenance needs. We are in the process of developing and maintaining a yearly serviceability index rating on all Interstate, primary, and secondary routes. These data will be used to determine more precisely what the actual conditions of the road surfaces are and furnish the Maintenance Division with more realistic data on which to determine the type and amount of maintenance necessary for any given project. A report outlining the development, operation, and application of this roughometer will be written and published.

REFERENCE

1. Thompson, M. R., and Dempsey, B. J. Autogenous Healing of Lime-Soil Mixtures. Highway Research Record 263, 1969, pp. 1-7.