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Final Report
CPAR-GL-94-2
May 1994

CONSTRUCTION PRODUCTIVITY ADVANCEMENT RESEARCH (CPAR) PROGRAM

STABILIZATION OF HIGH PLASTICITY CLAY AND SILTY SAND BY INCLUSION OF DISCRETE FIBRILLATED POLYPROPYLENE FIBERS (FIBERGRIDS®) FOR USE IN PAVEMENT SUBGRADES

by

William P. Grogan, Wayne G. Johnson

A Corps/Industry Partnership to Advance
Construction Productivity and Reduce Costs

Construction Productivity Advancement Research (CPAR) Program

Technical Report
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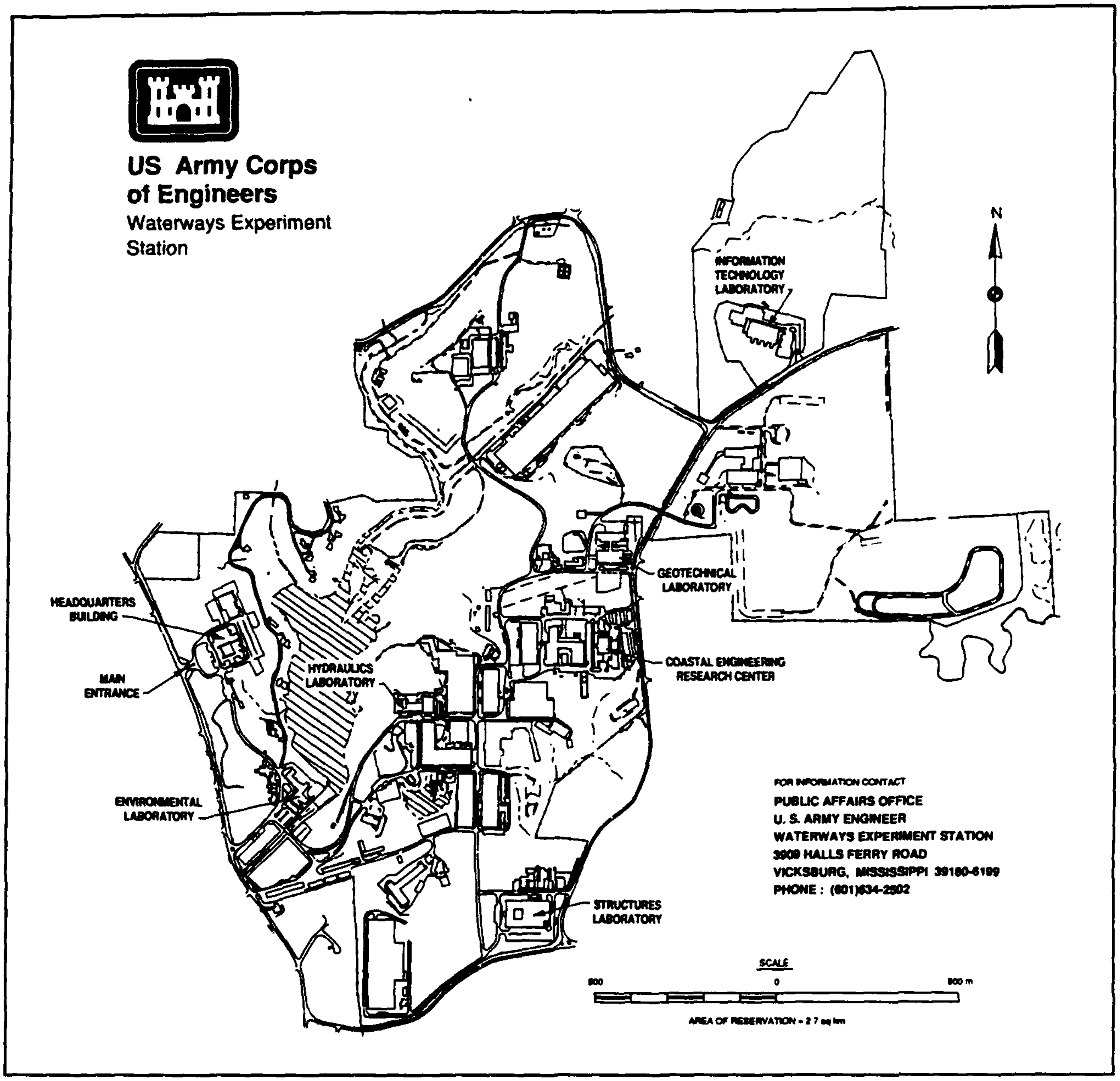

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Preface

The study reported herein was conducted by the Geotechnical Laboratory (GL), U.S. Army Engineer Waterways Experiment Station (WES), Vicksburg, MS, for Headquarters, U.S. Army Corps of Engineers (HQUSACE), as part of the Construction Productivity Advancement Research (CPAR) Program. The industry partner for this study was Synthetic Industries, Chattanooga, TN. Synthetic Industries contracted with the Texas Transportation Institute (TTI) to perform a portion of the industry partner's work effort. The HQUSACE Technical Monitors were Messrs. J. Chang and G. Hughes.

This study was conducted under the general supervision of Dr. W. F. Marcuson III, Director, GL, and Dr. G. Hammitt II, Chief, Pavement Systems Division (PSD), GL. This report was produced under the direct supervision of Mr. J. W. Hall, Jr., Chief, Systems Analysis Branch (SAB), PSD. Personnel engaged in the collection and compilation of data for this study included Messrs. J. A. Harrison, P. S. McCaffrey, Jr., and W. Mason of the PSD, and Messrs. George Ivy, Avery Harris, and Roosevelt Felix of the Engineering and Construction Services Division, WES. Dr. W. N. Brabston, formerly of the PSD and presently of the Concrete Technology Division, Structures Laboratory, WES, provided critical efforts in originating, organizing, and implementing this research. This report was prepared by Messrs. William P. Grogan and Wayne G. Johnson, PSD, with input from Messrs. David S. Chill, C. Ted Koerner, and Steven L. Shrader of Synthetic Industries and Dr. William Crockford of TTI. Mr. L. Nelson Godwin provided valuable comments for the preliminary guide specifications contained in Appendix D. This report is the final report for the CPAR project entitled "Stabilization of High Plasticity Clay and Silty Sand by Inclusion of Discrete Fibrillated Polypropylene Fibers (Fibergrids®) for Use in Pavement Subgrades."

During the publication of this report, Dr. Robert W. Whalin was the Director of WES. COL Bruce K. Howard, EN, was the Commander.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic inches	16.38706	cubic centimeters
cubic yards	0.7645549	cubic meters
Fahrenheit degrees	5/9	Celsius degrees or Kelvins[1]
feet	0.3048	meters
foot-pounds (force)	1.355818	meter-newtons
gallons per square yard	4.5273	cubic decimeters per square meter
inches	2.54	centimeters
kips (mass)	453.5924	kilograms
pounds (force) per inch	175.1268	newtons per meter
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic meter
tons (2,000 pounds, mass)	907.1847	kilograms

[1] To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F-32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

1 Description of Research and Development Partnership

In May 1991, the U.S. Army Engineer Waterways Experiment Station (WES), Vicksburg, MS, and Synthetic Industries, Chattanooga, TN, entered into a Cooperative Research and Development Agreement (CRDA). This agreement was a part of the Corps of Engineers' Construction Productivity Advancement Research (CPAR) Program. The purpose of the research under this agreement was to investigate the structural benefits that may be achieved by the inclusion of discrete fibrillated polypropylene fibers (Fibergrids®) in untreated and chemically stabilized soil layers used in pavement structures.

CPAR is a cost-shared research and development partnership between the Corps and the U.S. construction industry, academic institutions, or other public or private entities who are interested in construction productivity and competitiveness. CPAR is designed to promote and assist in the advancement of ideas and technologies that will have a direct positive impact on construction productivity and project costs and on Corps mission accomplishment. The CPAR Program has received strong support from the U.S. construction industry, and numerous projects have been funded since the program was initiated in 1989.

This research was conducted jointly by WES and Synthetic Industries, Chattanooga, TN. Synthetic Industries contracted with the Texas Transportation Institute (TTI) for laboratory testing of the materials, construction of the test track, and trafficking of the test track. TTI engaged several other local subcontractors to construct the test track and to provide trafficking support and materials testing.

To date, two publications have resulted from the research reported herein. William Crockford of TTI, William Grogan of WES, and David Chill of Synthetic Industries have jointly written a paper entitled "Strength and Life of Stabilized Layers Containing Fibrillated Polypropylene" (Crockford, Grogan, and Chill 1993). This paper was presented at the 1993 meeting of the Transportation Research Board. Also, this CPAR report was written in partial completion of WES' obligation to the research effort.

2 Introduction

Background

Better soil stabilization techniques for roads and road appurtenances are of benefit to Government (both state and national) and to private industry. Joint interest in technology development in this area resulted in a CRDA between Synthetic Industries and the U. S. Government, represented by WES. This cooperative effort investigated innovative soil stabilization techniques for potential use in pavement layers. Specifically, the investigation centered on determining the structural benefits of including discrete fibrillated polypropylene fibers (Fibergrids®) as a stabilizing additive to soil used in pavement layers. The term "discrete fibrillated polypropylene" implies a fibrous polypropylene material that is individually distinct or one that is not mathematically continuous (Freed 1989). The fibers used in this study were nominally 1 in.[1] long.

In general, the responsibilities of WES under this agreement were to provide field and laboratory testing, monitor the construction and trafficking of the test track, and analyze and report the data resulting from the field and laboratory testing. Synthetic Industries was responsible for building and trafficking the test track. Synthetic Industries contracted with TTI, College Station, TX, to perform these services.

Objective

The specific objectives of this study were to (a) determine if discrete fibrillated polypropylene fibers (hereafter called fibers) manufactured by Synthetic Industries could be adequately mixed into the materials to be stabilized, (b) evaluate the structural benefits that addition of the fibers might provide for an unstabilized material such as a silty sand, and (c) evaluate the structural benefits that addition of the fibers might provide for a lime-stabilized heavy clay and a cement-stabilized silty sand.

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[1] A table of factors for converting non-SI units of measurement to SI units is presented on page viii.

Scope

Design quantities of admixtures such as the fiber content, cement content for the sand, and lime content for the clay were determined from laboratory testing. A test track containing various sections with different materials and properties was constructed. Field tests were conducted prior to trafficking of the test track, at various times during trafficking, and after failure of the various sections of the test track. Field testing included California Bearing Ratio (CBR) tests, plate bearing tests, Dynamic Cone Penetrometer (DCP) tests, density and moisture content with the nuclear gage, oven moisture content, drive cylinder density, longitudinal and transverse elevations, and falling weight deflectometer (FWD) tests. Undisturbed specimens were also obtained for laboratory testing.

Laboratory testing included the determination of moisture/density relationships, confined uniaxial compressive testing, and unconfined compressive strength tests on laboratory molded samples and undisturbed samples. The combination of laboratory test results, field test results, and traffic testing provided valuable information concerning the performance characteristics of this type of stabilization method.

Literature Review

A literature review was conducted to determine the extent of data available on the topic of fibrillated media reinforcement of soil. This review revealed that few general references on the subject matter have appeared in the literature and very few technical studies have been conducted. Most of the publications to date have been in the form of magazine articles and reports resulting from studies conducted by TTI. The information reported herein apparently contains the first and only reported data from a field test on this technique.

3 Laboratory Testing and Test Track Design

Initial Laboratory Testing

TTI identified sources for a silty sand (SM) material and a heavy clay (CH) material. TTI conducted tests for gradation, moisture/density relationships, and design percentages of stabilizing material and fibers.

The sand material was tested in four configurations: (a) with fibers only, (b) with cement only, (c) with cement and fibers, and (d) the natural (untreated) material. The cement content for the stabilized sand sections was determined somewhat qualitatively. General guidance for selection of the cement content was found in the Portland Cement Association (PCA) guidelines as described by Terrel et al. (1979); however, the PCA guidelines were not strictly followed. Laboratory test data showed that the strain energy density for the cement-stabilized sand continued to increase with increasing cement contents up to 9 percent (the largest percentage tested). This approaches an uneconomical mix (Crockford 1993). High cement contents also tend to produce increased cracking potential. Test personnel at TTI adopted a cement content of 5 percent for the sand test sections. This combination produced the most desirable characteristics for test purposes.

The clay material was tested in three configurations: (a) with lime, (b) with lime and fibers, and (c) the natural material. The lime content for the stabilized clay sections was determined based on the procedure suggested by Eades and Grim (1966). This pH-based procedure resulted in an optimum lime content of 5 percent. Laboratory testing confirmed highest strengths for compressive specimens at a lime content of 5 percent.

After determination of appropriate chemical stabilizer percentages for field testing, appropriate fiber contents were determined. This was accomplished using triaxial compression tests on clay and sand samples with differing fiber contents. The compression tests were conducted using a transverse confining pressure of 5 psi. Each sample was loaded to a strain level of at least 0.05 in. per in., and the area under the resulting stress-strain curve was determined (to a strain level of 0.05). This area provides a measure of "energy" (termed the "strain energy density"). The energy versus fiber content (by weight of dry soil) curves were then plotted for clay and sand as shown in Figures 1 and 2, respectively. The peak of this curve was taken as the appropriate fiber percentage for testing. The data presented in these figures are the result of work at TTI.

The above procedure resulted in the selection of a fiber content of 0.5 percent for the silty sand and 0.3 percent for the clay for the field test sections. A clay test section was also constructed with 0.1-percent fibers for comparison.

Figures 1 and 2 reflect a significant effect due to addition of fibers. Figure 1 reveals that the strain energy density for stabilized clay with 0.3-percent fibers is 50 percent greater than the strain energy density for stabilized clay without fibers. Figure 2 reveals an even greater effect for stabilized sand with 0.5-percent fibers. The laboratory tests reflected a 125-percent increase in strain energy density for this material when compared with stabilized sand without fibers.

A study of the stress-strain curves for the clay and sand reveals the reasons for the increased strain energy density. Figures 3 and 4 give stress-strain curves for the clay and sand, respectively. Figure 3 shows that addition of fibers into the stabilized clay increases the peak strength, the modulus, and the residual strength when compared with clay with only chemical stabilization. Figure 4 shows the same type of effect for stabilized sand. Interestingly, Figure 4 also reveals that the residual strength for the sand with 5-percent portland cement and 0.5-percent fibers is significantly greater than that for the sand with 9-percent portland cement and no fibers (at larger values of strain). The data shown in Figures 3 and 4 are the result of laboratory tests conducted at TTI.

The observation noted above is significant in analyzing the benefits of adding fibers to the soil materials for enhancement of engineering properties. Both Figures 3 and 4 reflect that the fiber-reinforced materials (both clay and sand) exhibit a property analogous to "strain hardening." In this phenomenon, a material tends to exhibit enhanced resistance at strains exceeding the elastic limit. Certainly, this is true for both the chemically stabilized, fiber-reinforced clay and sand materials, especially in comparison to the materials with only chemical stabilization. This strain-hardening effect is very beneficial for materials to be applied in highway applications.

Design Thickness

The Corps' CBR-based flexible pavement design procedure was used to determine the required thickness of test track sections. The CBR design procedure is an empirically based procedure for determining the thickness of material required to protect underlying material of a certain strength (as defined by a CBR test). A history of the development of the CBR method has

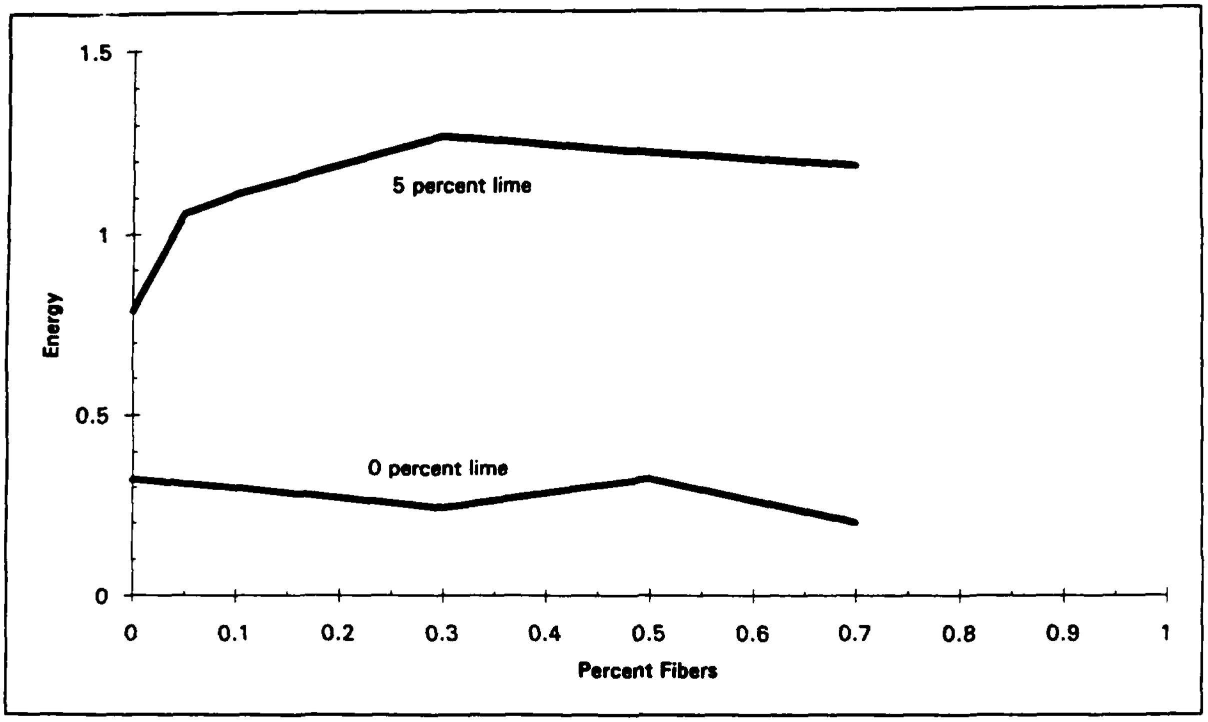

Figure 1. Energy versus percent fiber by weight of dry soil for clay (energy in ft-lb/in.^{3})

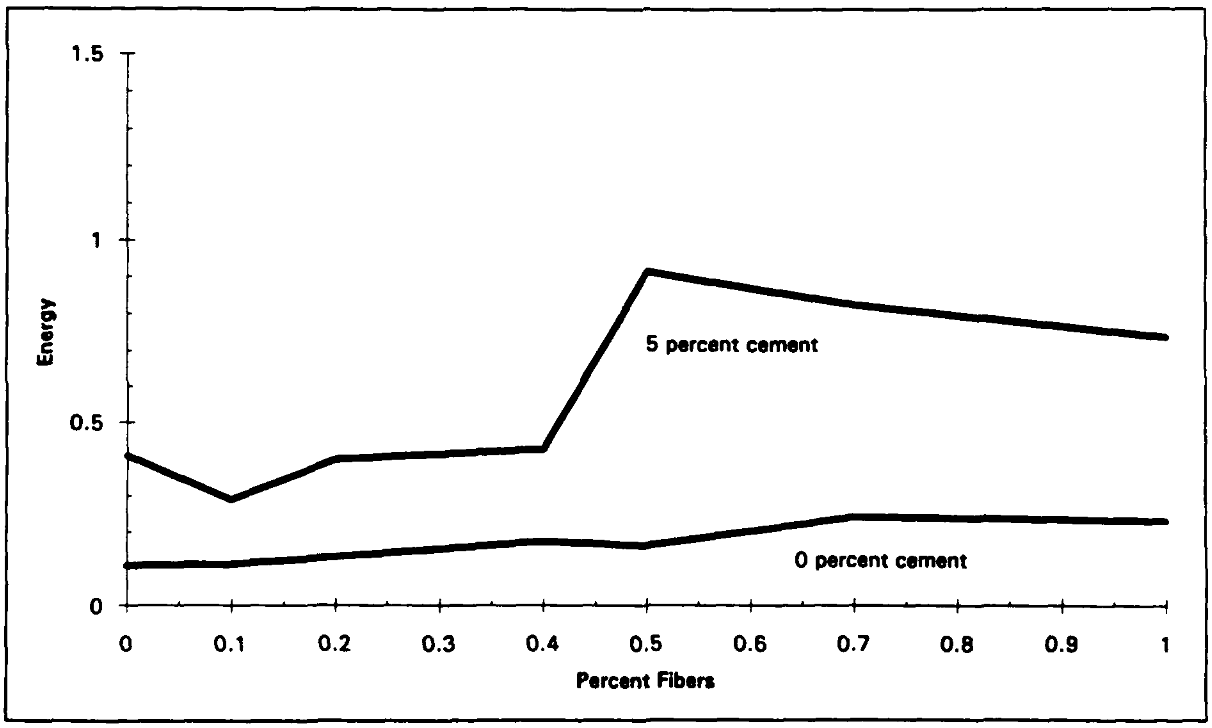

Figure 2. Energy versus percent fiber by weight of dry soil for sand (energy in ft-lb/in.^{3})

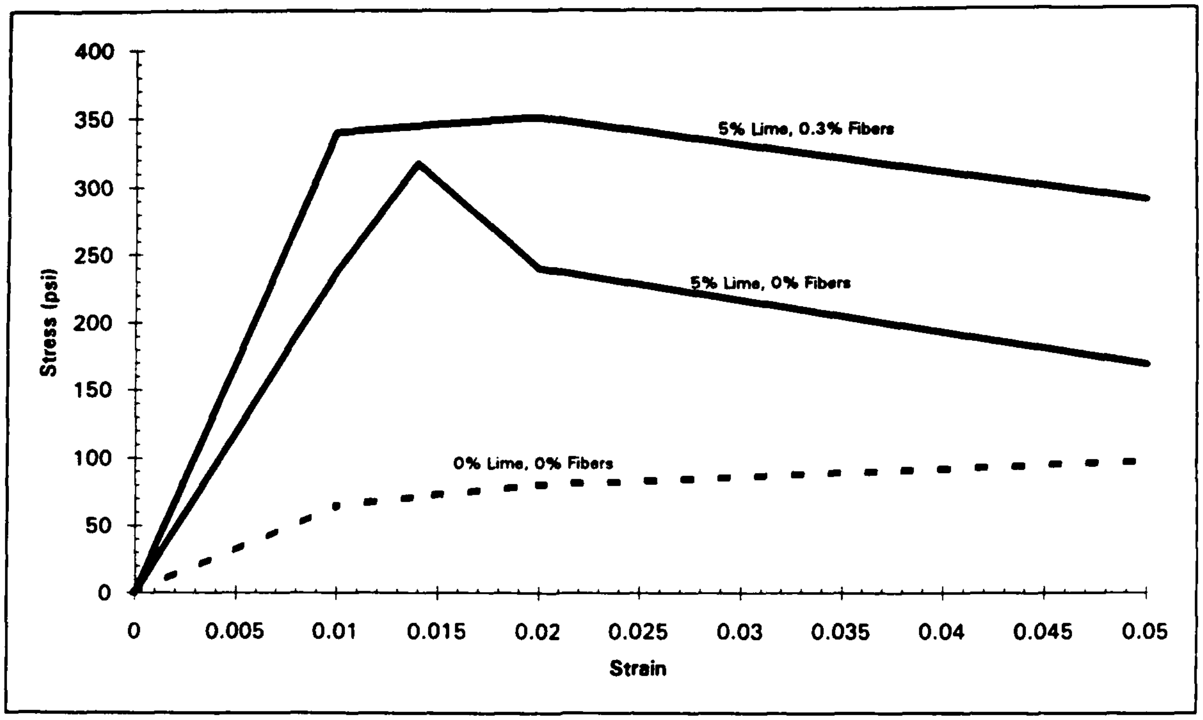

Figure 3. Stress-strain curves for clay

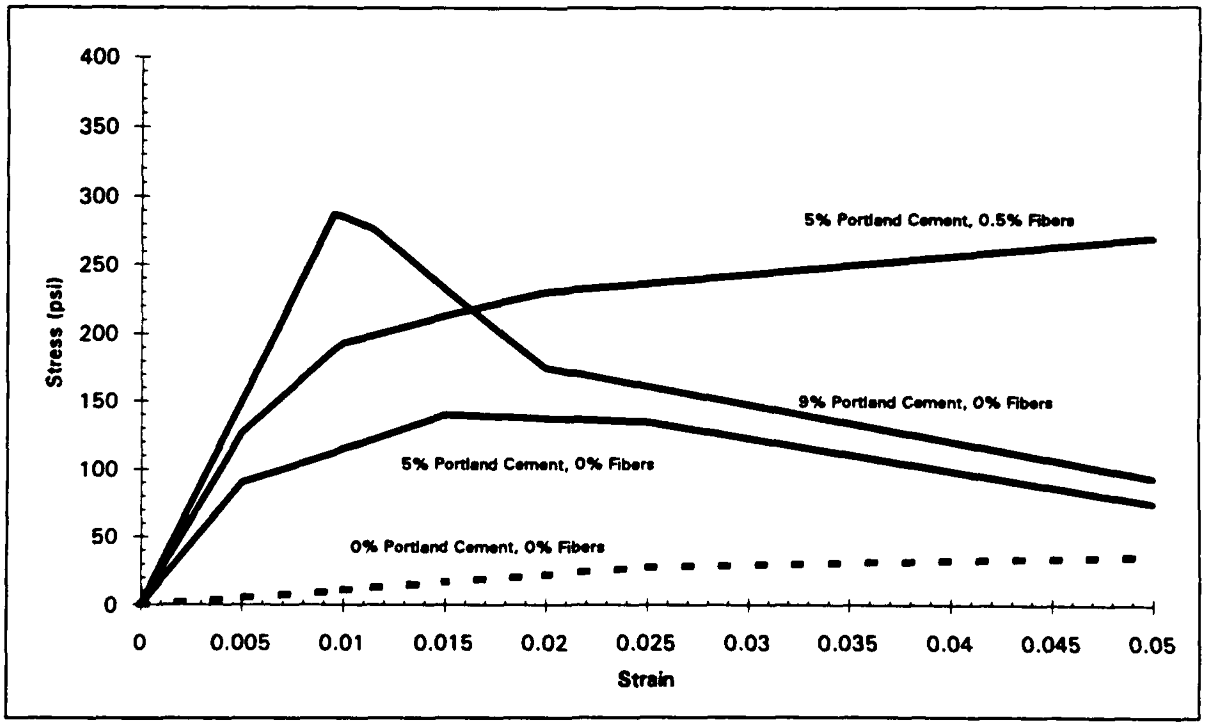

Figure 4. Stress-strain curves for sand

been documented by Ahlvin (1991). The CBR equation requires inputs such as the coverages (traffic level) of the design vehicle, tire pressure, wheel load, and subgrade CBR. Following is the basic form of the CBR equation:

$$t = \alpha \sqrt{P\left(\frac{1}{8.1\ CBR} - \frac{1}{p_e\ \pi}\right)} \tag{1}$$

where

t = required thickness (in.)
α = (0.23 log C + 0.15) for surfaced roads
α = (0.13 log C + 0.09) for unsurfaced roads
P = single tire load (kips)
C = coverages
p_e = tire pressure (psi)

The CBR design procedure requires the input of an α value that is based on coverages and pavement surfacing. The α value for the unsurfaced design procedure results in a thinner layer of material required to protect the underlying material because the failure criterion for unsurfaced roads is defined as a 3-in. rut as opposed to a 1-in. rut for surfaced roads. Values of α were calculated for unsurfaced and surfaced pavement sections to determine the design thicknesses to be used for the test section. The unsurfaced design procedure resulted in a thickness requirement of approximately 6-in. to protect a 5-CBR subgrade from 5,000 coverages of an 18-kip single-axle, dual-wheel load. Using the α value for a surfaced pavement structure resulted in a thickness requirement of approximately 12 in. Use of this design procedure implies incipient failure at 5,000 passes, where failure is defined as a 3-in. rut depth for the 6-in. sections and a 1-in. rut depth for the 12-in. sections. There were no performance data available on the materials being tested; therefore, it was advantageous to construct the materials in two thicknesses so that relative performance data could be gathered. A 6.0-in. section of well-graded crushed stone was also constructed for comparison to other materials being tested. Appendix A contains a summary of the design thickness calculations.

Field Test Plan

After the design contents of the various admixtures and thickness designs were determined, a test plan was developed. An oval test track was considered the ideal layout for testing. The materials being tested were constructed to proper thickness in the straight portions of the test track with a crushed-stone flexible base material used for the turns at each end. The test sections were arranged to facilitate construction of the test track. Figure 5 shows the layout of the test track in plan view and gives a brief description of the test sections. Table 1 summarizes the test layout.

Additional Laboratory Testing

Laboratory tests performed at WES included sieve analyses, Atterberg limits, moisture/density, triaxial compression tests on lab-molded samples, and triaxial compression tests on undisturbed field samples.

Sieve analyses results for the silty sand and clay are given in Appendix B. Classifications of the materials based on sieve analyses and Atterberg limits are noted on these figures. Moisture/density relationships for the materials tested at WES are also provided in Appendix B. The figures given in Appendix B include the natural materials as well as materials with selected amounts of stabilizing agents and fibers. Appendix B also contains moisture/density relationships for the two materials. American Society for Testing and Materials (ASTM) specification 1557 was used to determine moisture/density relationships.

WES conducted unconfined compressive strength tests on laboratory samples fabricated at the optimum water content and density. The sand material was fabricated into specimens with the fibers only, cement only, and with cement and fibers. The clay material was molded into specimens of the natural material, the clay with lime, and clay with lime and fibers. A specimen consisting of the clay and fibers alone was not molded. Appendix B contains tabular results of the unconfined compressive tests on the laboratory-fabricated samples.

Triaxial compression tests were conducted on specimens trimmed from undisturbed block samples obtained from the field. The block samples were cut out of the test sections, taken to WES, trimmed in the laboratory, and then tested. Samples were obtained from sections 2 (6-in. sand, 5-percent cement), 3 (6-in. sand, 5-percent cement, 0.5-percent fibers), 11 (6-in. clay, 5-percent lime, 0.3-percent fibers), and 13 (6-in. clay, 5-percent lime). Results of these tests are summarized in Appendix B.

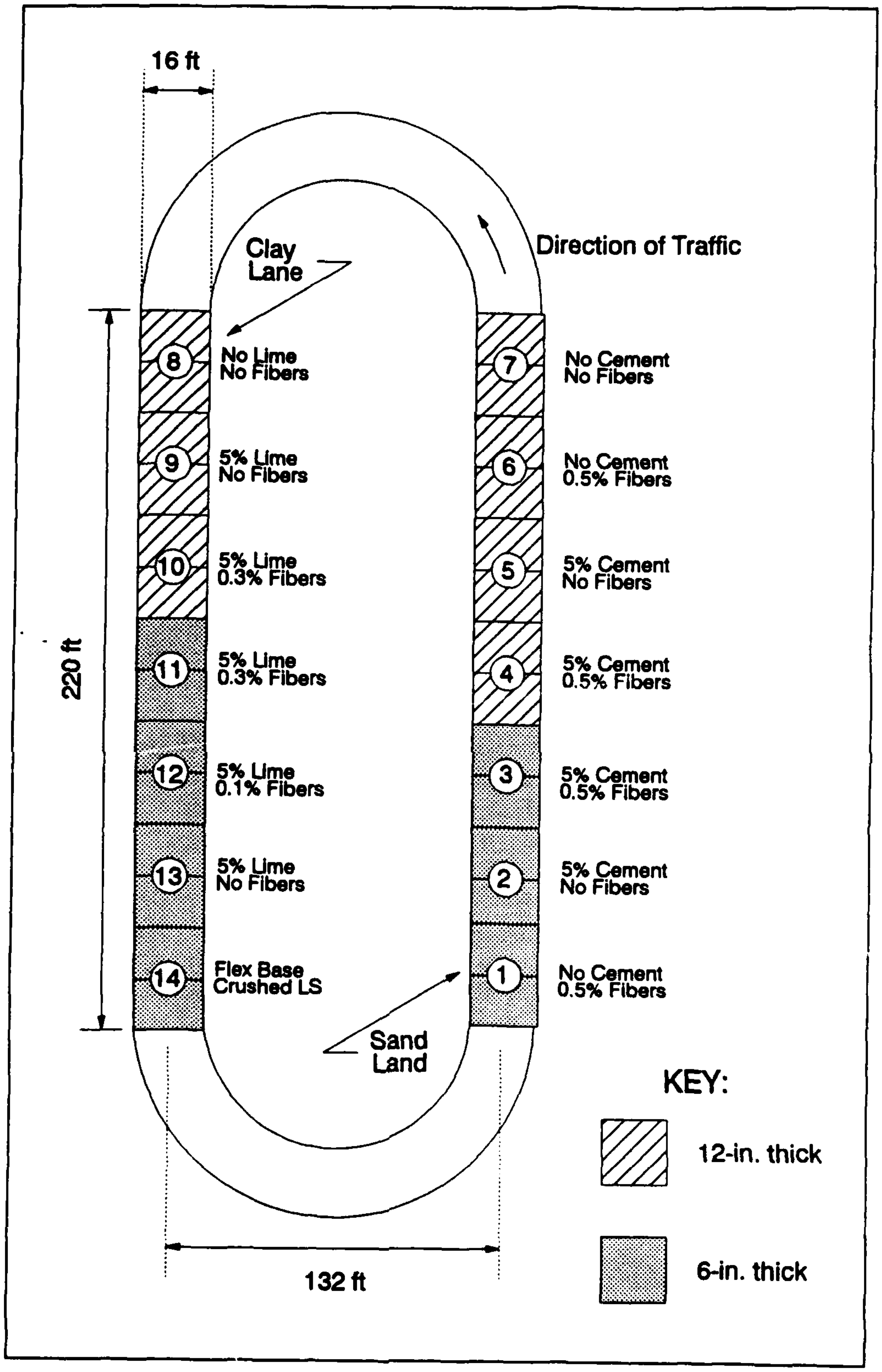

Figure 5. Layout of test track

Table 1
Percentages of Admixtures, by Weight

Section	Thickness in.	SM		CH	
		Cement %	Fibers %	Lime %	Fibers %
1	6.0	0.0	0.5		
2	6.0	5.0	0.0		
3	6.0	5.0	0.5		
4	12.0	5.0	0.5		
5	12.0	5.0	0.0		
6	12.0	0.0	0.5		
7	12.0	0.0	0.0		
8	12.0			0.0	0.0
9	12.0			5.0	0.0
10	12.0			5.0	0.3
11	6.0			5.0	0.3
12	6.0			5.0	0.1
13	6.0			5.0	0.0
14	6.0	Section 14 was a control and consisted of crushed stone, the standard base course material used in the area.			

4 Test Track Construction

Background

Construction of the test track was the responsibility of Synthetic Industries. As mentioned earlier, Synthetic Industries contracted with TTI to build the test track. A site was selected by TTI at the Texas A&M Riverside campus. This was the site of Bryan Army Airfield, a World War II era airfield. The facility was turned over to Texas A&M for use as a research site. It is located in the relatively flat area of the Brazos River Valley. The native soil at the site is a thick layer of high plasticity clay (CH). This clay can be processed to selected moisture contents and compacted in layers at low CBR strengths that would not change significantly throughout traffic testing. This in situ clay material was also the material used for constructing high plasticity sections of the test track. The sand material was transported to the site.

Construction

TTI subcontracted with Young Brothers Construction Company, Bryan, TX, to construct the test track. This company's offices and materials processing facilities are located within a few miles of the project site. They supplied the silty sand material from a local quarry. As described earlier, the clay material was available on site.

Initial steps in construction of the site included surveying and marking the test track. The contractor then removed a few inches of top soil to expose the in situ clay material. At this point, approximately 6 in. of crushed stone was placed on the turns at each end of the test track, and 6 in. of native material was removed from sections 1, 2, 3, 8, 9, and 10, and 12 in. of material was removed from sections 4, 5, 6, and 7. This allowed for the entire subgrade to be exposed and worked as necessary to obtain proper moisture and density. Initial plans called for use of the clay material removed from the sand side to construct the clay side of the test track. However, this material included too much organic material and was stockpiled to the side of the test area. A borrow pit was then excavated in the center of the test track to provide the clay material required for construction of the clay test sections (sections 8-13).

In order to make the subgrade as uniform as possible, the soil was processed by several passes of a pulver-mixer over the subgrade to a depth of 6 to 8 in. followed by recompaction. A local geotechnical engineering firm then performed field CBR tests. These CBR tests and nuclear gage readings showed values close to the design requirements.

After the top 6 in. of the subgrade was reasonably uniform at the design strength and density, the stabilized material layers were constructed. Construction of the clay layer started with placement of the first 6-in. lift for sections 8, 9, and 10. Lime was placed on the surface of sections 9 and 10 and pulver-mixed into the clay using two passes of the mixer. (The clay material in section 8 was not stabilized.) Next, the fibers were placed on the surface of section 10 and pulver-mixed with an additional five passes of the mixer to ensure proper opening of the fibers. Additional experience has shown that two passes of the mixer are adequate to ensure that the fibers are adequately mixed. After the fibers had been mixed into section 10, the first lift of sections 8, 9, and 10 were compacted. This involved the use of various compactors including a vibrating pad foot roller, a light pneumatic roller, a steel-wheeled roller, a loaded track loader, and a heavy pneumatic roller. It was difficult to achieve the desired densities in the clay layers because of the underlying soft subgrade. After compaction, the surface was scarified to prevent a slippage plane from being constructed between lifts. After the first 6-in. lift had been constructed for sections 8, 9, and 10, the top 6-in. lift was constructed for sections 8-13 in a similar fashion.

At the time of this investigation, no field experience existed on blending fibers with clay without lime stabilization. For this reason, no section was constructed with fibers only mixed into unstabilized clay. Subsequent to this test, several successful installations of fibers in natural high plasticity clays have been performed. In fact, field experience by Synthetic Industries personnel has shown that fibers mix most efficiently at or above the optimum moisture content of the soil. Figure 6 shows the fibers used in this investigation. Figure 7 shows the lime on the surface of the clay before pulver-mixing, and Figure 8 presents the fibers on the surface prior to pulver-mixing. After the clay sections were in place, 6 in. of crushed stone was placed and compacted on the subgrade of section 14.

Construction of sections 1-7 was similar to that of sections 8-13; however, the sand material was mixed with portland cement at a pugmill plant mixer, trucked to the site, and placed in the appropriate sections. The fibers were then added to the surface and mixed into the sand layers. Seven passes of the mixer were used in these sections to ensure that the fibers were fully opened. However, additional experience has shown that two passes are adequate for proper mixing. Two sections of the sand mixed with fibers only (no cement added) were included for evaluation and comparison. The 12-in. sections were placed in two 6-in. lifts. Compaction was accomplished for each layer using five passes of a vibrating steel wheel roller, one pass without vibration, and two passes with a heavy pneumatic roller.

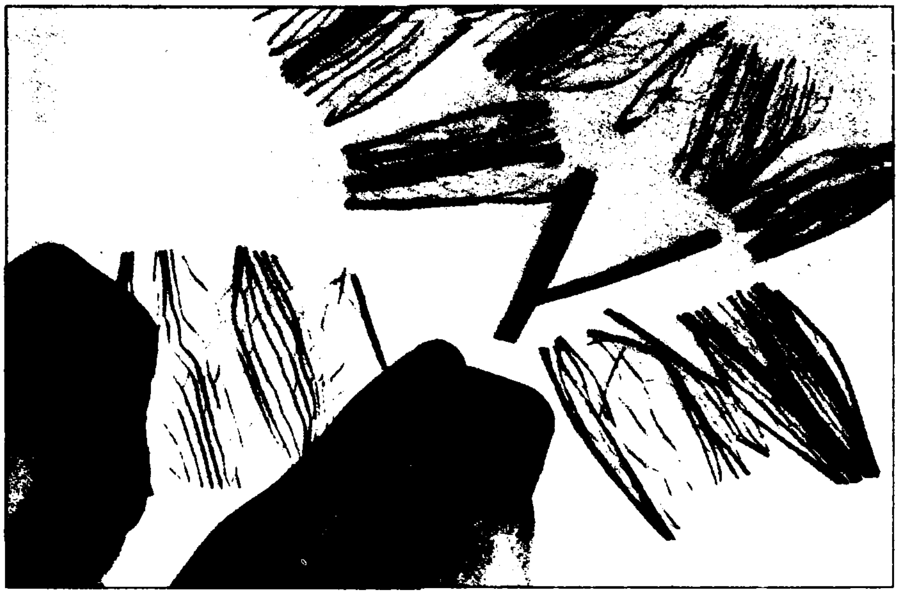

Figure 6. Illustration of fibers used in the test (1-in.-long discrete fibrillated polypropylene)

Figure 7. Lime on surface of clay prior to mixing

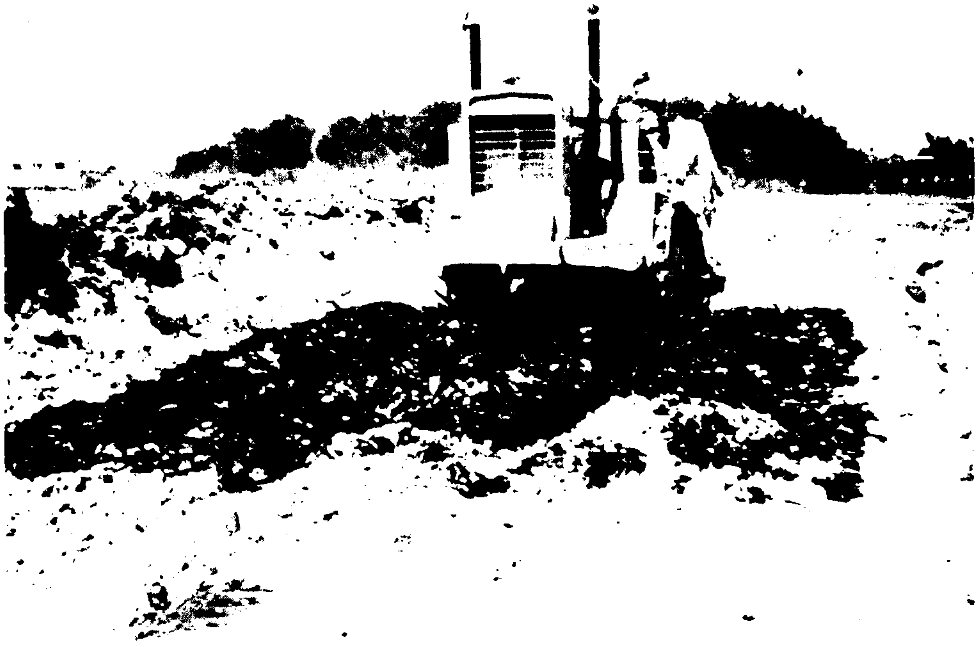

Figure 8. Fibers on clay/lime prior to mixing

During the test track construction phase, the moisture content of the materials was maintained at appropriate levels by covering them with polyethylene sheeting at all times when construction was not underway. After the entire test section had been constructed, it was covered with polyethylene sheeting for proper cure and to protect the track from weather effects. Trafficking tests were to begin following the planned cure time of approximately 3 weeks. Unfortunately, weather conditions were not adequate for testing immediately after the scheduled cure time and were inadequate for several months (until May 1992). This resulted in significantly longer cure times than planned.

5 Field Testing

Background

Initial pretraffic field testing was conducted between 12 and 21 November 1991. Scheduled traffic tests were delayed because the prevailing weather conditions prevented immediate follow-up testing, and final testing was delayed until May 1992.

For the 3 months spanning December 1991 through February 1992, 22.25 in. of rain fell in the vicinity of the test area. This is 13.8 in. above the normal rainfall average (8.45 in.) for this region during this 3-month period (National Oceanic and Atmospheric Administration (NOAA) 1991, 1992). Rainfall data were unavailable for March and April. Due to these unusual weather conditions in the College Station area during this time, trafficking was delayed. This delay brought about the need for repeating most of the initial pretraffic testing. The test data collected in November 1991 included CBR pits, plate bearing using a 30-in. plate, heavy-falling weight deflectometer (HWD) using a 17.7-in.-diam plate, DCP, oven water content, drive cylinder density, and nuclear gage testing, as well as transverse cross sections and longitudinal profile elevations. All of the testing was repeated before trafficking in May 1992 with the exception of the plate bearing and FWD tests.

Pretraffic Testing

Plate bearing tests were conducted on 13 of the 14 sections in November 1991 in accordance with Department of the Army (DoA) Field Manual "FM5-530 Materials Testing" (Headquarters, DoA 1987). Results of the plate bearing tests are summarized in Appendix B. No pretraffic plate bearing test was conducted on section 8.

FWD tests were conducted on each section in November 1991. The tests were conducted using the Dynatest model 8082 heavy-falling weight deflectometer with a 17.7-in.-diam plate. The load used in the FWD tests ranged from approximately 3,500 to 7,500 lb. Results of the FWD data were used to backcalculate modulus of elasticity values for the surface layer and subgrade of each section. The computer program WESDEF was used for back-calculating the modulus values (Cauwelaert et al. 1989). WESDEF uses the deflection basin, load, and load plate diameter from the FWD test and a user-defined system of layers and material types to backcalculate modulus values. Appendix B contains a tabular summary of the backcalulated modulus and impulse stiffness modulus values.

The remaining pretraffic tests were initially conducted in November 1991 and were repeated in May 1992 prior to trafficking of the test section. These tests included CBR, drive cylinder density, oven water content, nuclear gage density, and DCP. Elevation data were collected at four cross-section points in each section (transverse to the direction of travel). Elevation data were also collected along a line covering the length of each section on the inside and outside wheel paths and along the center line of the section. The pretraffic data were tabulated and are compared to the posttraffic data in the following section.

Trafficking and Posttraffic Field Testing

Rut depth data were collected periodically during traffic to monitor the performance of each section and to establish failure. An average 3-in. rut depth throughout the section was considered failure. Appendix B contains a tabular summary of the rut depth data collected for each section. Sections 4, 5, 9, and 10 were not trafficked to failure. Trafficking was terminated at 5,000 passes for sections 4 and 5, and at 4,350 passes for sections 9 and 10. Table 2 summarizes the number of passes applied to each section of the test track.

Although an average 3-in. rut depth was considered failure for a section, engineering judgment was necessary to determine failure of some sections due to the presence of local problem areas. Special considerations for the site included problems with achieving density in the refilled CBR pits. This caused localized failure zones in some sections. Also in sections 11, 12, 13, and 14, the inside wheel path failed more quickly than the outside wheel path due to siting of the test section. The inside wheel path of these sections was often under water due to the unusually heavy rains. Therefore, the rut depth criterion was applied to the part of the section that was behaving uniformly, usually the outside wheel path.

The test vehicle used to traffic the test section was a dual-wheel, single-axle flatbed truck provided with driver by Conley Moving and Storage, Bryan, TX, under contract with TTI. The vehicle is shown in Figure 9. Due to the potential detrimental effect caused by excessive rains prior to initiation of traffic and during the previous months, the test vehicle was loaded with approximately 12,000-lb instead of the 15,000-lb design load. This measure was taken to prevent premature failure should the materials be weaker than design strengths due to high moisture effects. The dual-wheel single rear axle was loaded to 12,795 lb, and the front single-wheel axle weighed 4,635 lb.

Table 2
Summary of Passes to Failure for Sections 1-14

Section	Passes to Failure
1 (6-in. sand, 0.5% fibers)	50
2 (6-in. sand, 5% cement)	350
3 (6-in. sand, 5% cement, 0.5% fibers)	575
4 (12-in. sand, 5% cement, 0.5% fibers)	5,000[1]
5 (12-in. sand, 5% cement)	5,000[1]
6 (12-in. sand, 0.5% fibers)	100
7 (12-in. sand)	75
8 (12-in. clay)	5
9 (12-in. clay, 5% lime)	4,350[1]
10 (12-in. clay, 5% lime, 0.3% fibers)	4,350[1]
11 (6-in. clay, 5% lime, 0.3% fibers)	2,500
12 (6-in. clay, 5% lime, 0.1% fibers)	1,700
13 (6-in. clay, 5% lime)	1,300
14 (5-in. crushed limestone)	1,700

[1] These items were not trafficked to failure; trafficking was stopped at the numbers denoted.

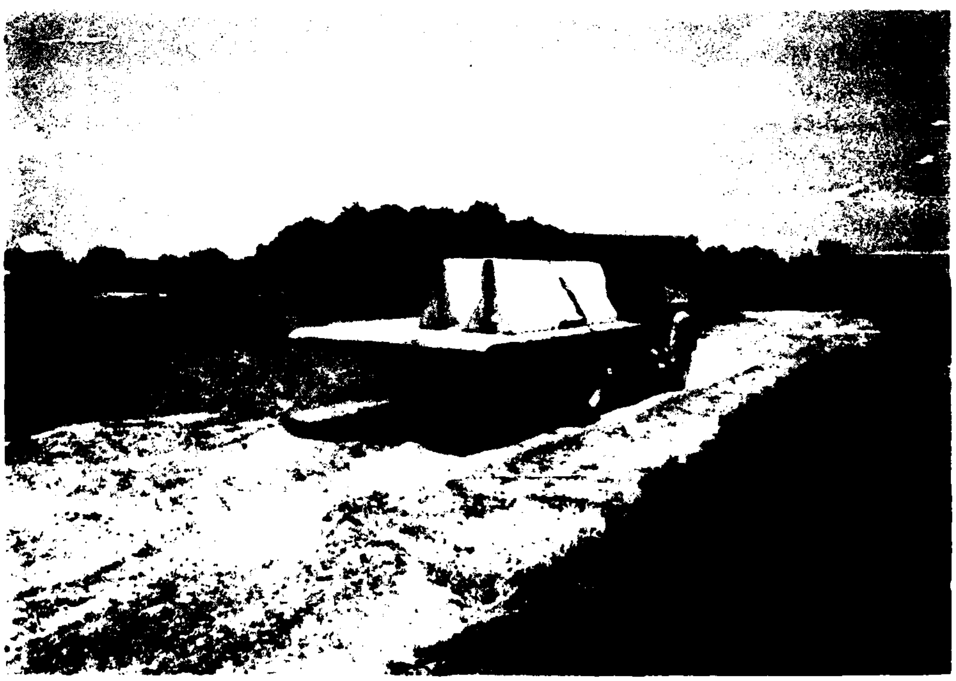

Figure 9. Vehicle used for traffic testing

This load was applied to the test section for the first 1,100 passes. After 1,100 passes, the unfailed sections were performing well, which prompted the application of an increased load. The higher load consisted of 17,400 lb on the rear axle and 4,840 lb on the front axle. Traffic was applied at the higher load level until the remaining test sections failed or traffic was terminated. Throughout the testing, the tire pressure was monitored and remained near a constant 80 psi for all tires. All traffic was applied to the test section in the counterclockwise direction (see Figure 5).

Cross-section profile data were collected before, periodically during, and after trafficking of each section. Figures 10-23 show plots of cross sections at several pass levels for each test section. The elevations were measured from a benchmark established at the center of the adjacent taxiway. The benchmark was given an arbitrary elevation of 30 in. An additional benchmark was established to ensure that no movement of the primary benchmark occurred. The additional benchmark was located on the west side of the test track. Figures 10-23 also note at what pass level traffic was terminated for each section and why. The criterion for failure was development of a 3-in. rut.

CBR tests and moisture density tests were conducted in each section before and after trafficking. Appendix B contains a summary of the oven water content data collected for each section. Appendix B also gives a tabular summary of the drive cylinder density data. The oven water contents mentioned above

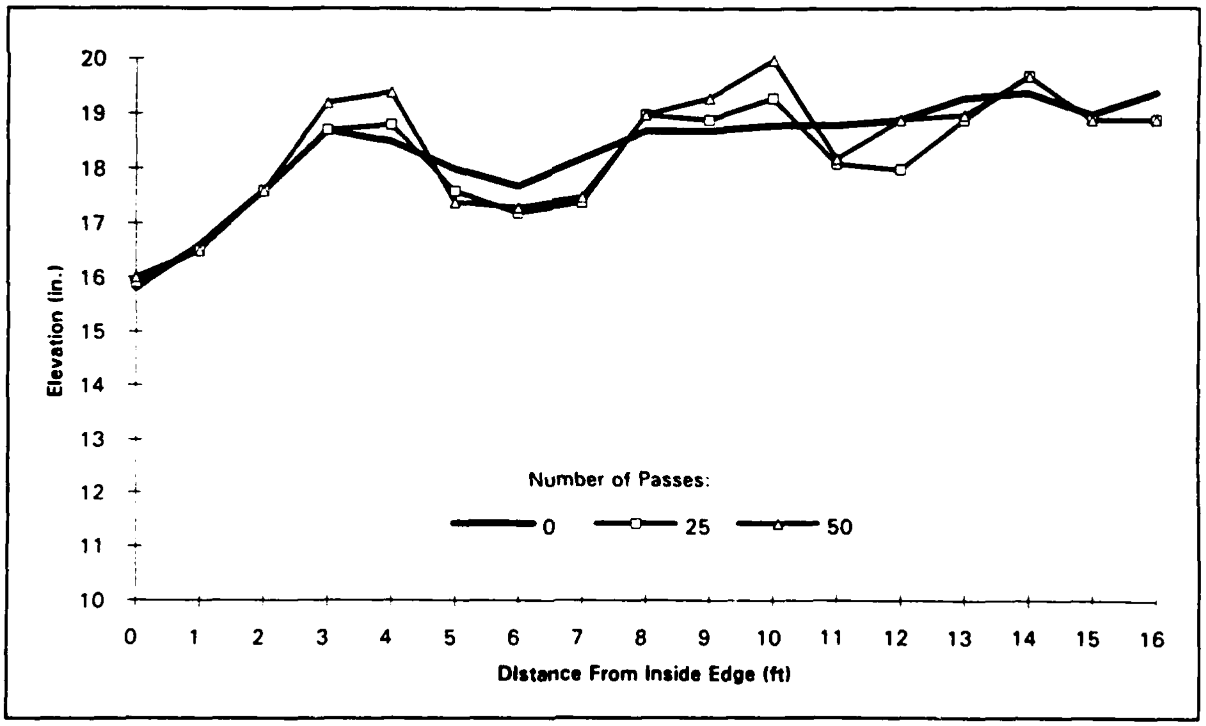

Figure 10. Section 1 (6-in. sand, 0.5-percent fiber) cross sections (sta 0 + 13) (traffic terminated at 50 passes due to failure)

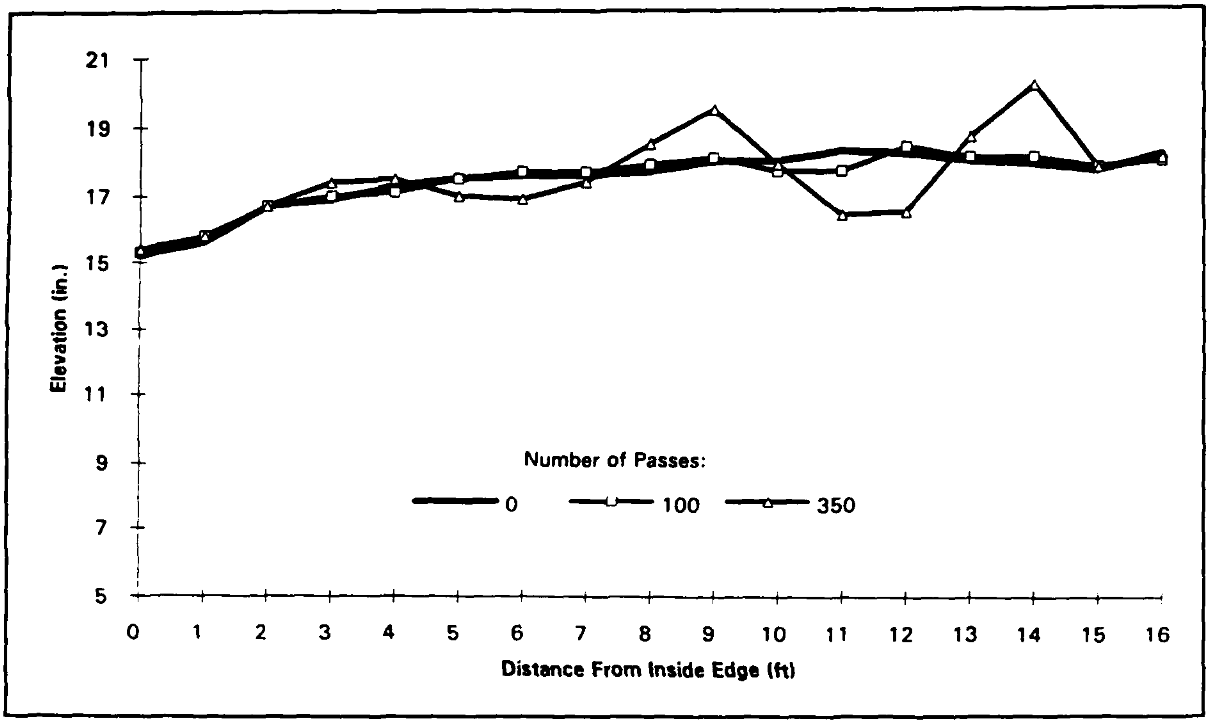

Figure 11. Section 2 (6-in. sand, 5-percent cement) cross sections (sta 0+43) (traffic terminated at 350 passes due to failure)

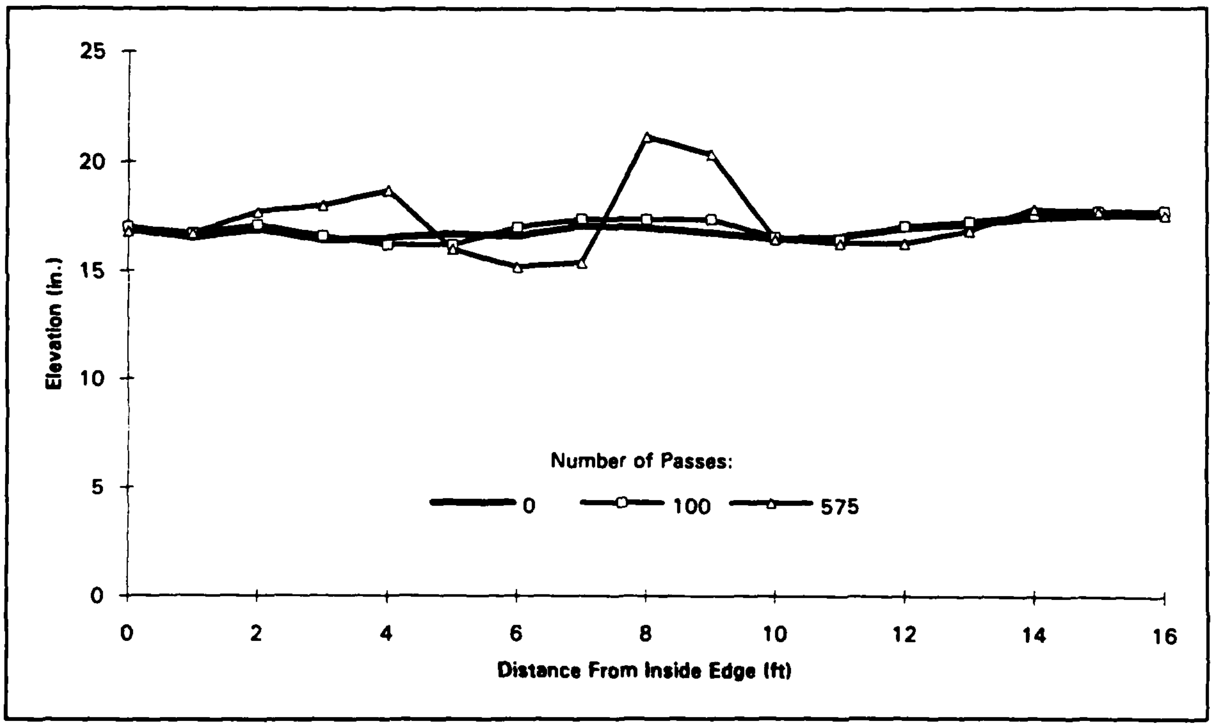

Figure 12. Section 3 (6-in. sand, 5-percent cement, 0.5-percent fibers) cross sections (sta 0+74) (traffic terminated at 575 passes due to failure)

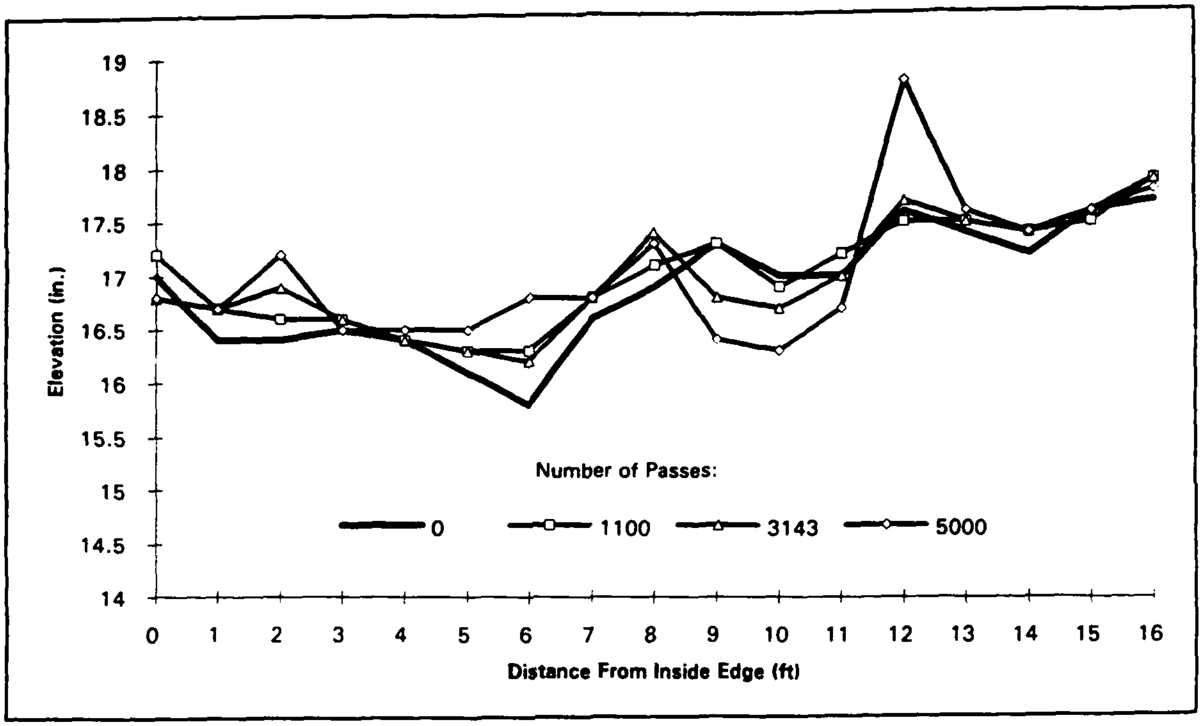

Figure 13: Section 4 (12-in. sand, 5-percent cement, 0.5-percent fibers) cross sections (sta 1 + 05) (traffic terminated at 5,000 passes due to complete application of design traffic)

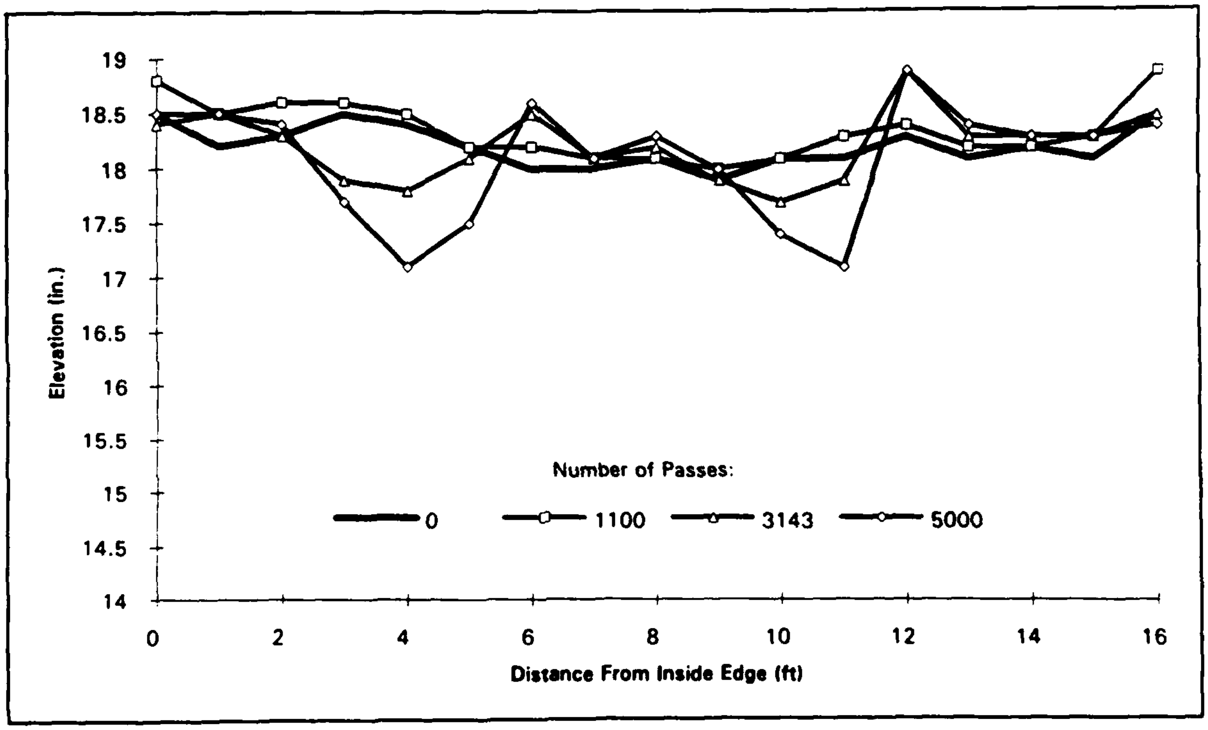

Figure 14. Section 5 (12-in. sand, 5-percent cement) cross sections (sta 1 + 36) (traffic terminated at 5,000 passes due to complete application of design traffic and impending failure)

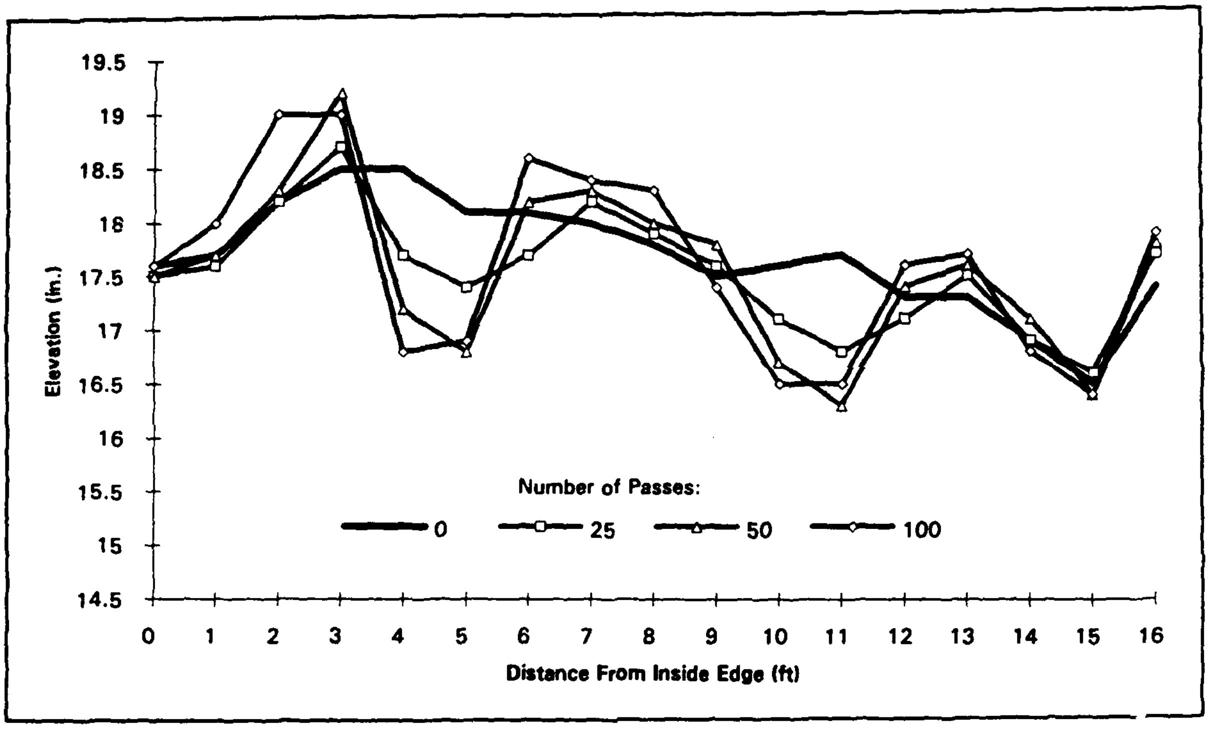

Figure 15. Section 6 (12-in. sand, 0.5-percent fibers) cross sections (sta 1 + 67) (traffic terminated at 100 passes due to failure)

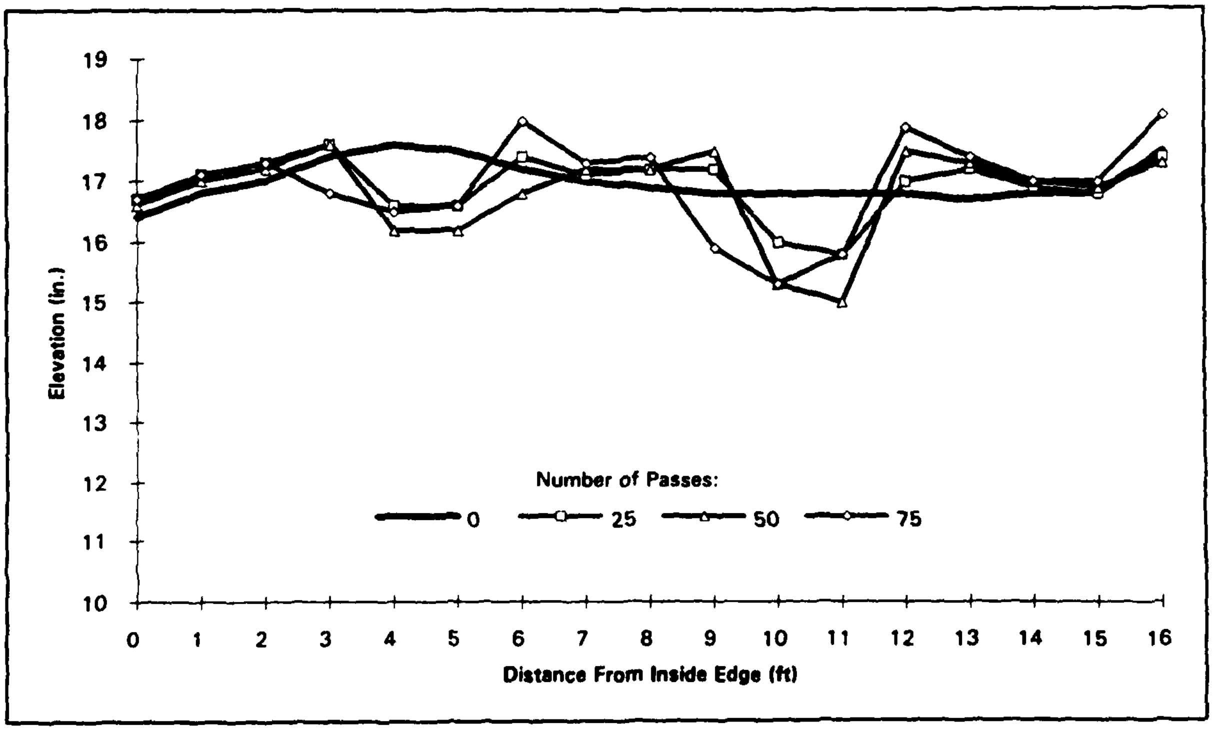

Figure 16. Section 7 (12-in. sand) cross sections (sta 1 + 99) (traffic terminated at 75 passes due failure)

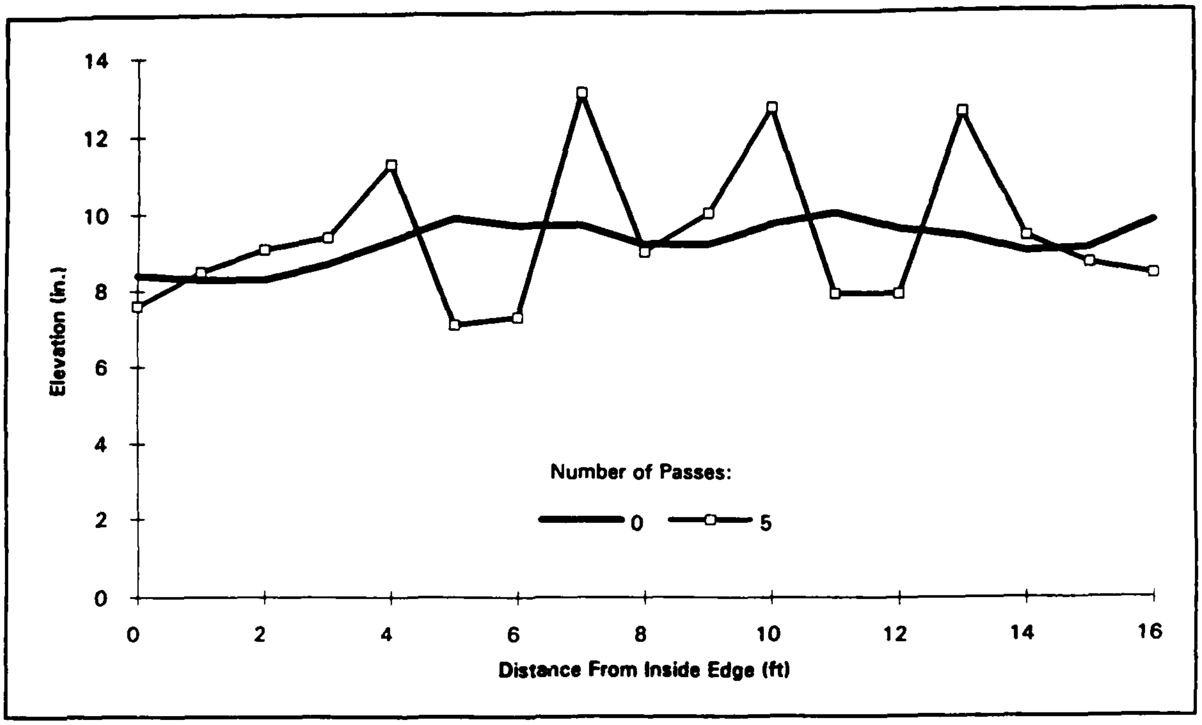

Figure 17. Section 8 (12-in. clay) cross sections (sta 0+14) (traffic terminated at 5 passes due to failure)

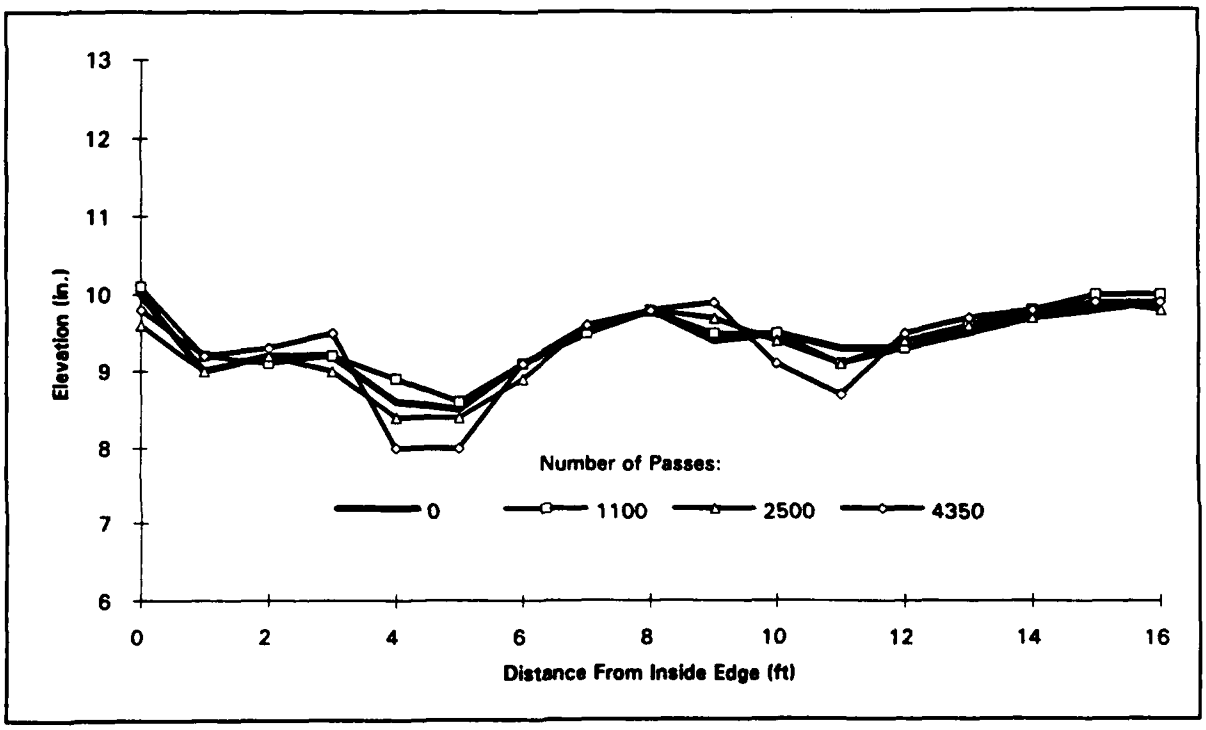

Figure 18. Section 9 (12-in. clay, 5-percent lime) cross sections (sta 0+46) (traffic terminated at 4,350 passes due to termination of testing)

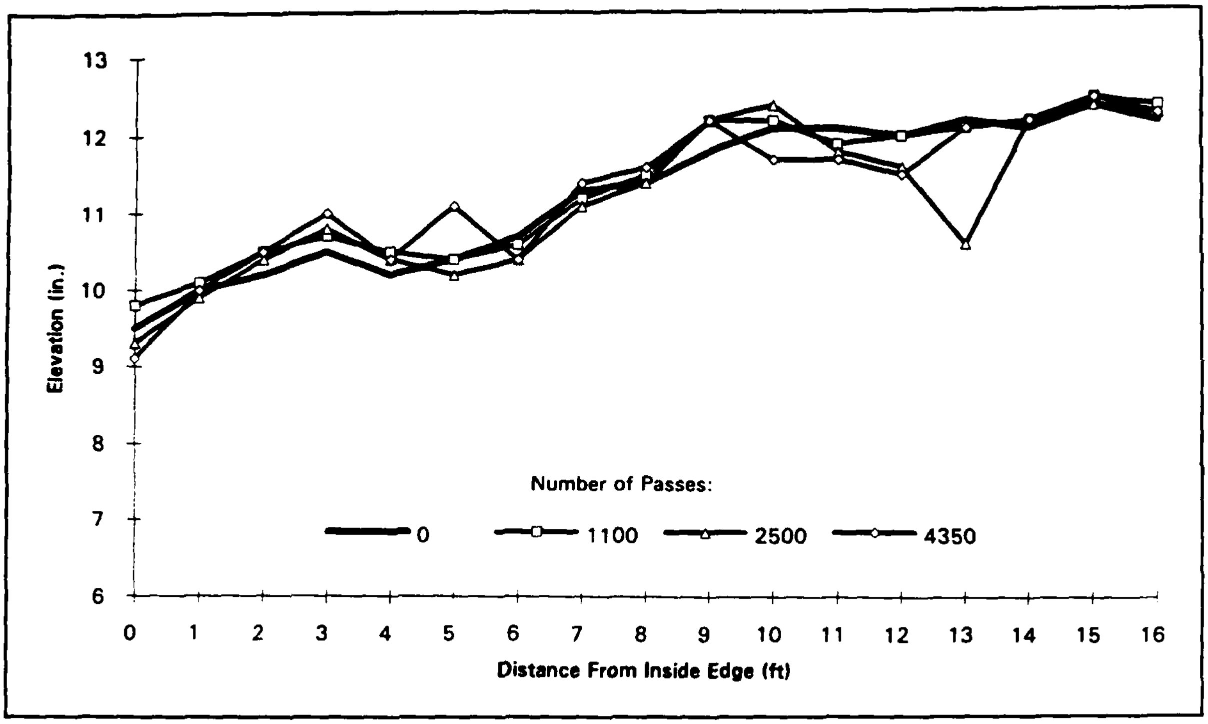

Figure 19. Section 10 (12-in. clay, 5-percent lime, 0.3-percent fibers) cross sections (sta 0+76 (traffic terminated at 4,350 passes due to termination of testing)

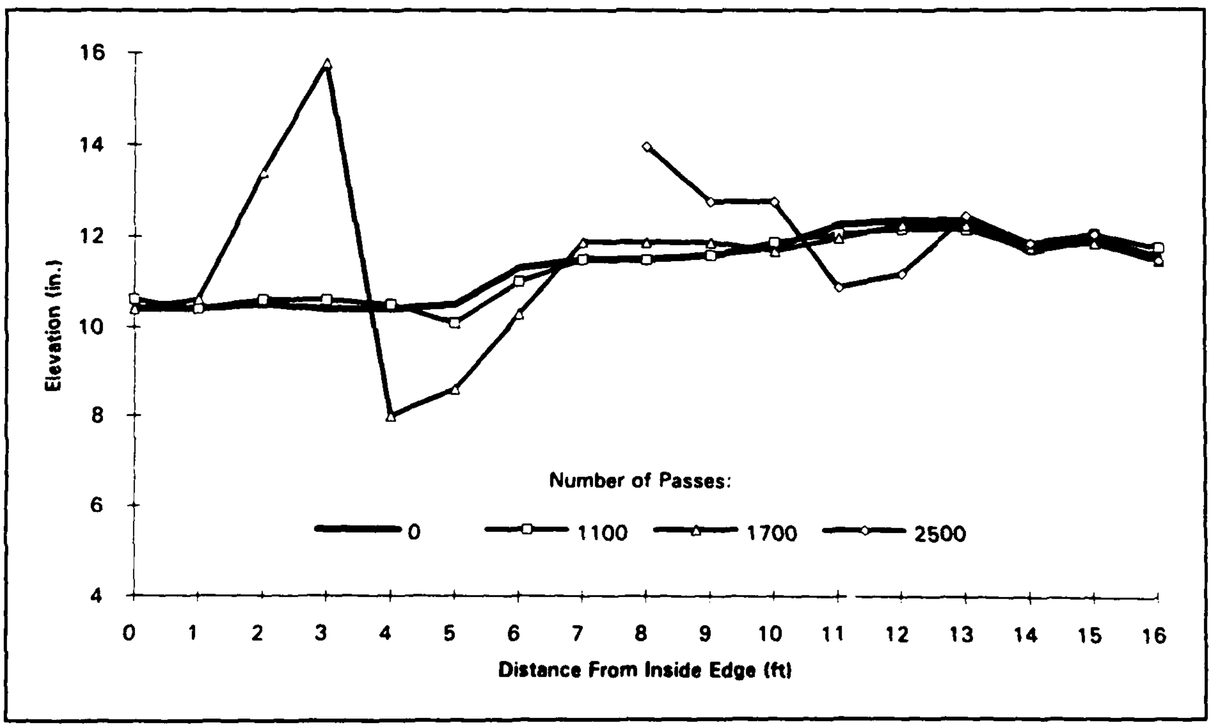

Figure 20. Section 11 (6-in. clay, 5-percent lime, 0.3-percent fibers) cross sections (sta 1+08) (traffic terminated at 2,500 passes due to failure, inside wheel path failed at 1,900 passes)

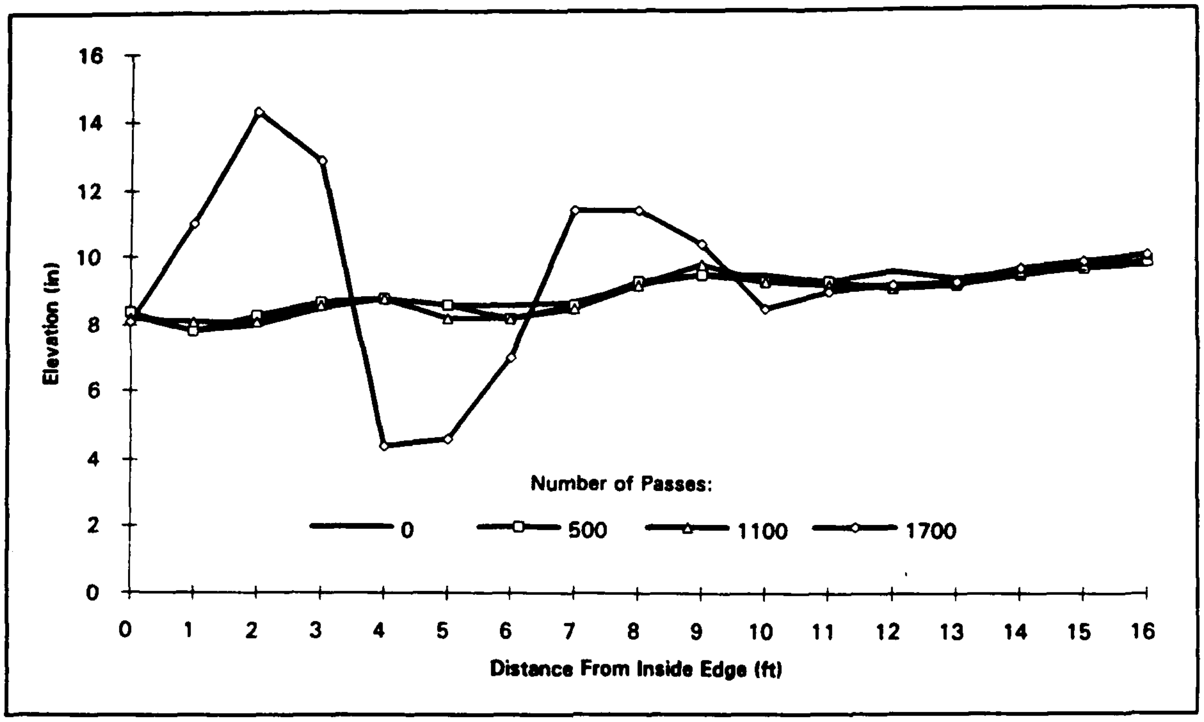

Figure 21. Section 12 (6-in. clay, 5-percent lime, 0.1-percent fibers) cross sections (sta 1 + 39) (traffic terminated at 1,700 passes due to failure)

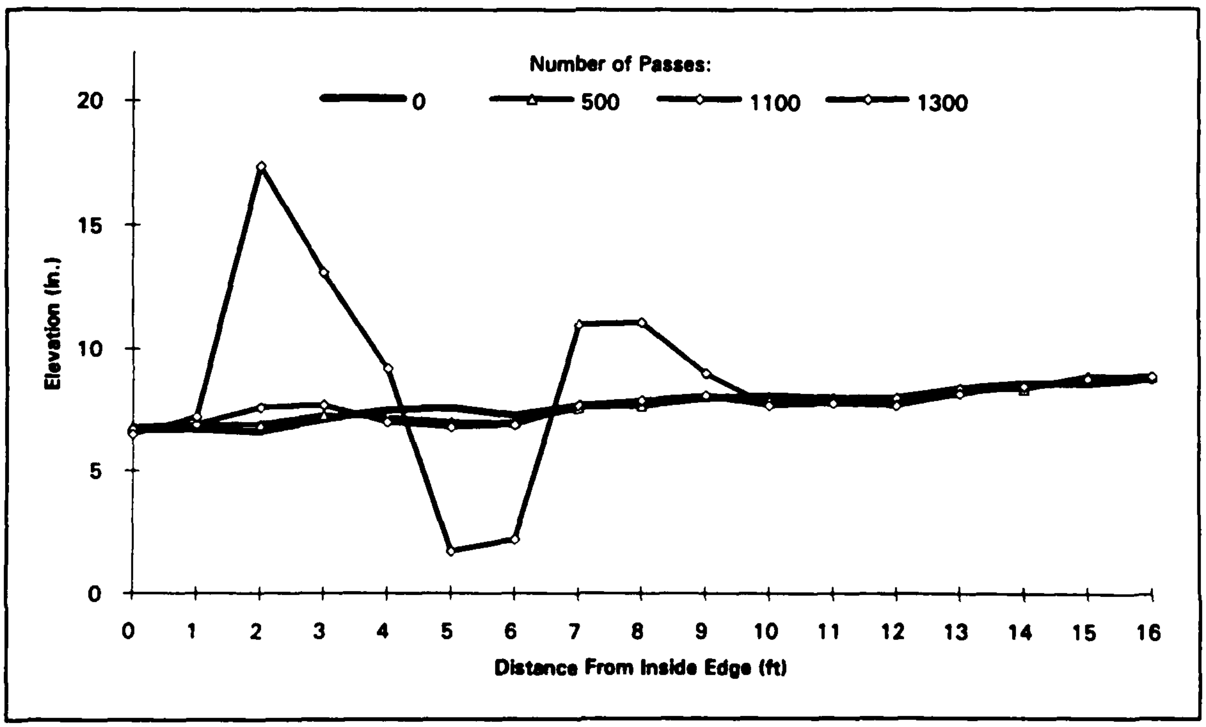

Figure 22. Section 13 (6-in. clay, 5-percent lime) cross sections (sta 1 + 70) (traffic terminated at 1,300 passes due to failure)

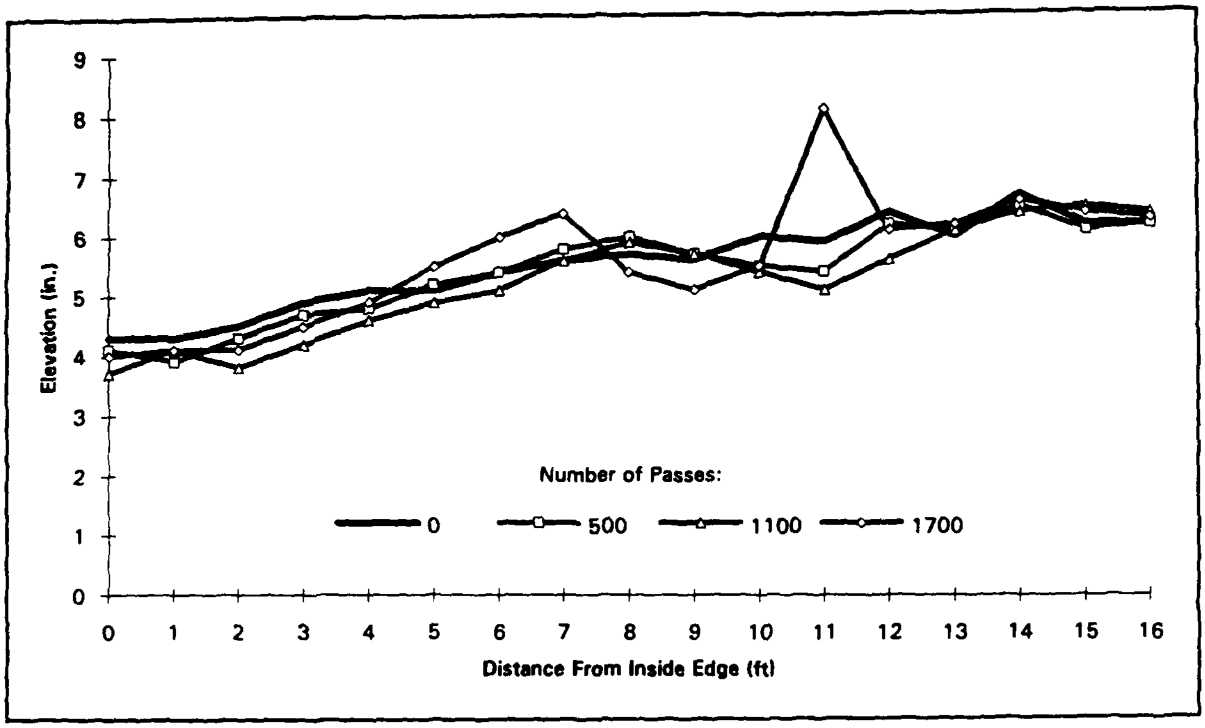

Figure 23. Section 14 (6-in. crushed limestone) cross sections (sta 2+00) (traffic terminated at 1,700 passes due to failure)

were used to determine the dry densities given in the drive cylinder density data. Nuclear gage densities are also summarized in Appendix B. The nuclear gage wet densities given in the appendix are as output from the gage; however, the dry density data shown were calculated using the wet density gage values and the oven water content data previously described. Appendix B also gives a summary of the CBR data collected for each section.

6 Field Testing Results

The performance of each test section in terms of total passes applied is summarized in Table 2. Figure 24 presents a chart comparing the performance of test sections 1 (6-in. sand, 0.5-percent fibers), 6 (12-in. sand, 0.5-percent fibers), and 7 (12-in. sand). This figure reveals that the increased thickness of the fiber-stabilized sections resulted in twice the performance of section 6 over section 1. Figure 24 shows that test section 6 withstood 1.33 times the number of passes withstood by section 7 prior to failure. However, the pass to failure levels were so small for both the sand and sand-with-fibers sections (no chemical stabilizing agents) that no practical benefit is gained.

Figure 25 contains a comparison of section 2 (6-in. sand, 5-percent cement) and section 3 (6-in. sand, 5-percent cement, 0.5-percent fibers). This figure reflects that section 3 has 1.6 times the load carrying capacity of section 2.

Figures 24 and 25 show that addition of fibers improves the engineering properties of a sand with binder but not without. Section 14, which contains 6-in. crushed limestone (considered an industry standard), performs much better than any sand section. These results are expected because the crushed limestone has very desirable properties for this application, whereas the unmodified sand material is not desirable for this application. The test shows that with modification such as tested in this experiment, engineering properties of the sand can be modified for use in pavement applications. Although performance can be enhanced, performance equivalent to the crushed limestone is not necessarily expected and could probably not be economically achieved.

Figure 26 presents a chart comparing the performance of test sections 11 (6-in. clay, 5-percent lime, 0.3 percent-fibers), 12 (6-in. clay, 5-percent lime, 0.1 percent fibers), 13 (6-in. clay, 5-percent cement), and 14 (6-in. crushed rock). This figure reflects that there was also increased performance resulting from fiber inclusion with stabilized clay. Test sections 12 and 14 showed identical passes-based performance characteristics. These sections provided 1.33 times the number of passes provided by section 13. Section 11 outperformed sections 12 and 14 by a factor of 1.5 and provided 1.9 times the number of passes provided by section 13. The number of passes (five) supported by section 8 (12-in. clay) was so small that it is not considered a reasonable alternative for trafficking.

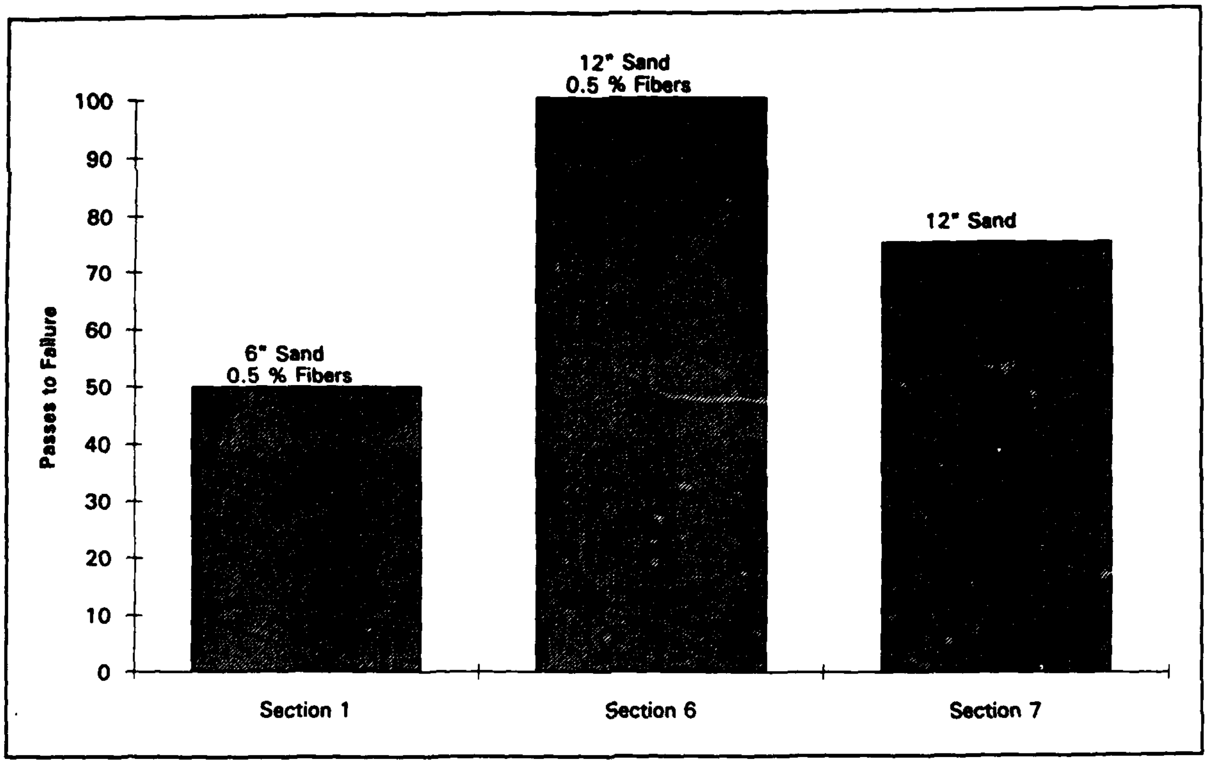

Figure 24. Comparison of sections 1, 6, and 7

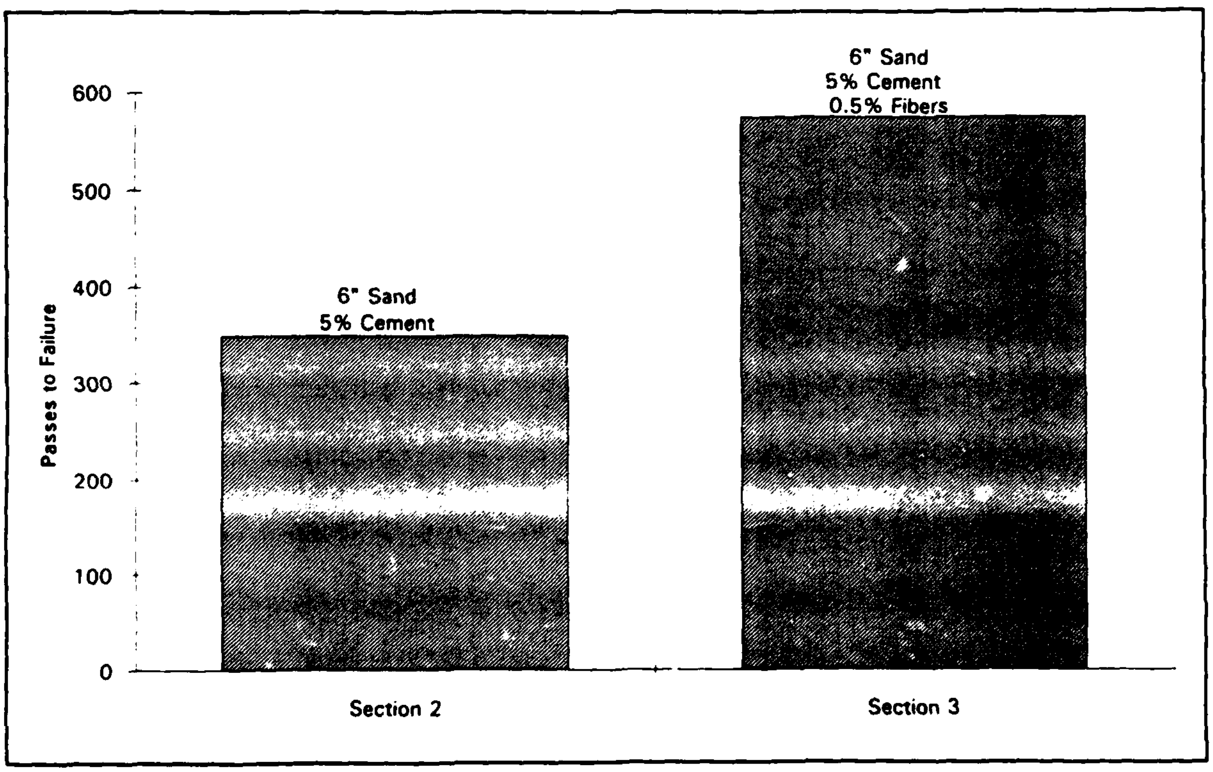

Figure 25. Comparison of sections 2 and 3

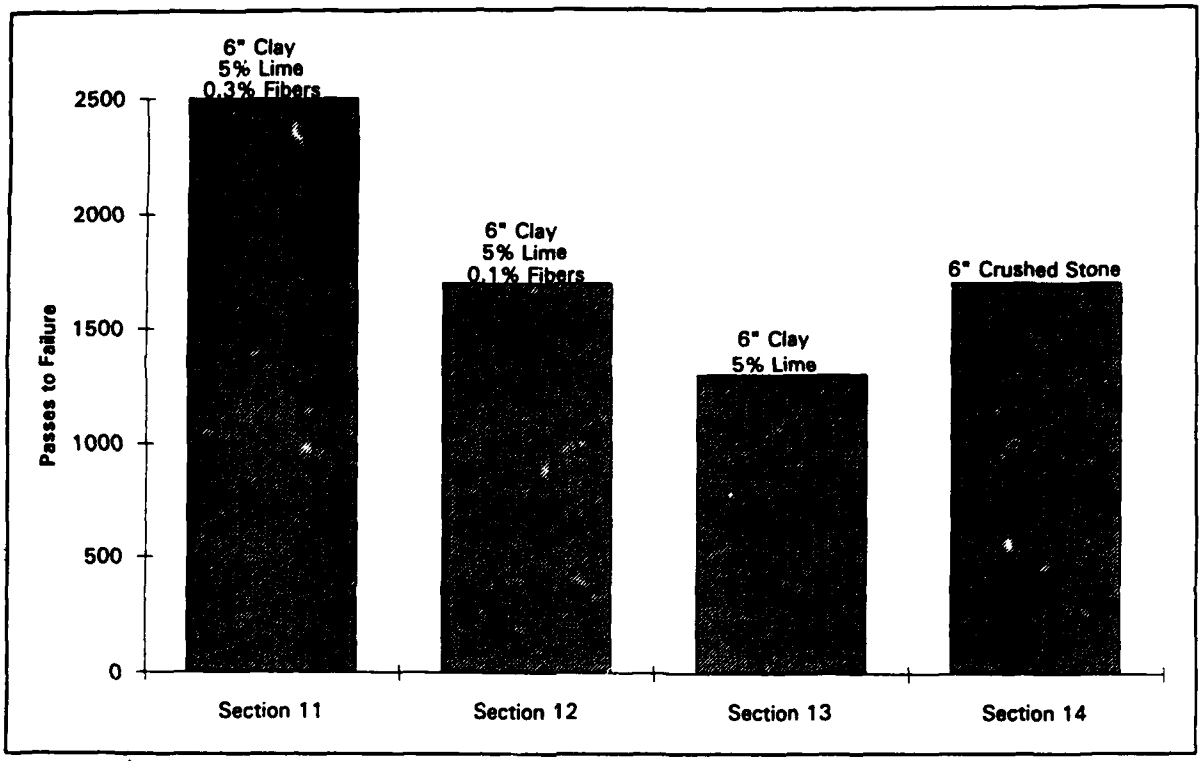

Figure 26. Comparison of sections 11, 12, 13, and 14

It is interesting to note that test section 11 (6-in. clay, 5-percent lime, 0.3-percent fibers) achieved a higher degree of performance enhancement than section 3 (6-in. sand, 5-percent cement, 0.5-percent fibers) relative to their respective stabilized counterparts (sections 13 (6-in. clay, 5-percent lime) and 2 (6-in. sand, 5-percent cement), respectively). Section 11 showed a performance improvement of 90 percent over section 13, while section 3 reflected an improvement of 60 percent in trafficking to failure over section 2. This, along with visual observations in the field concerning mixing and compaction, indicates a possible fiber addition rate that was much higher than necessary in the stabilized sand material. Work performed since this study has indicated that an addition rate of 0.2 percent performs extremely well in soil cement. This indicates that better performance might be achieved at lower dosage rates.

Although sections 4 (12-in. sand, 5-percent cement, 0.5-percent fibers), 5 (12-in. sand, 5-percent cement), 9 (12-in. clay, 5-percent lime), and 10 (12-in. clay, 5-percent lime, 0.3-percent fibers) were not trafficked to failure, some interesting observations were made based on the accumulation of rut damage with progressive trafficking. For comparison of data, the passes data were converted to coverages of an equivalent 18-kip single-axle dual-wheel load (see American Association of State Highway and Transportation Officials (1986) for equivalency relationships). This conversion allowed comparison of all the trafficking data, even though the load was changed during trafficking of the test track. Figure 27 contains plots of accumulated rut depth versus coverages for sections 4 and 5. No data were available for the zero coverages

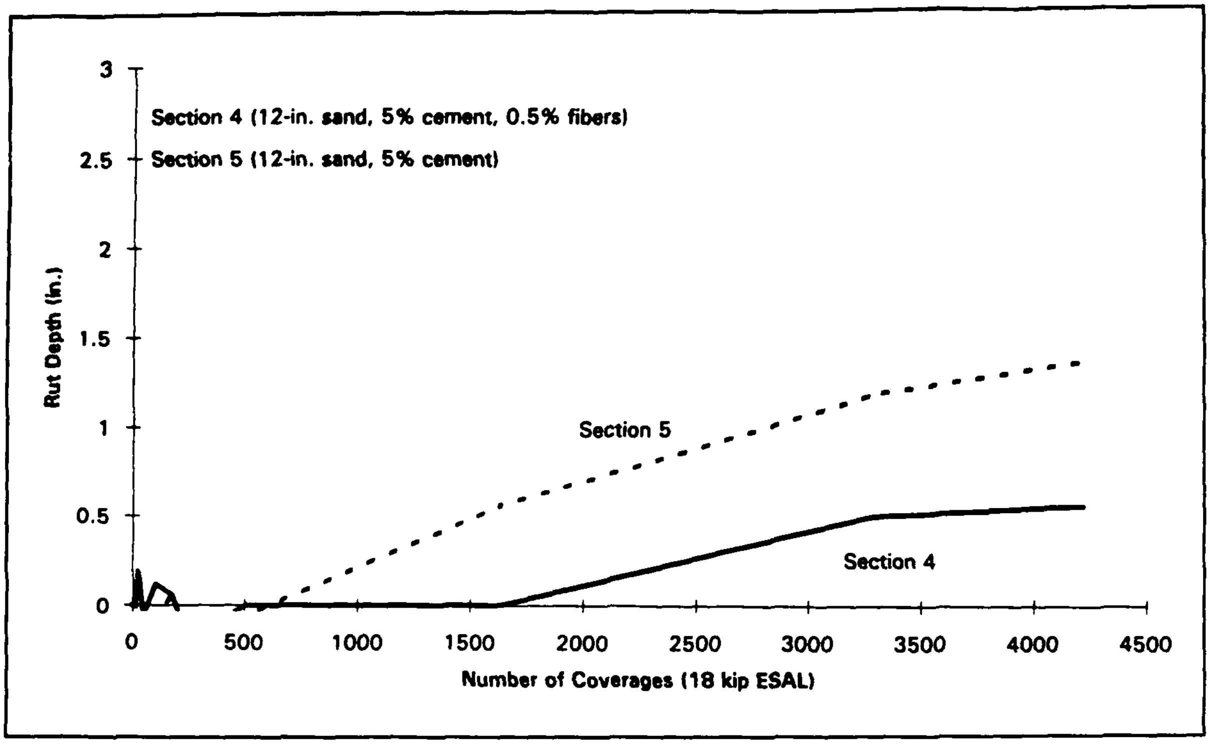

Figure 27. Measured rut depth progression, sections 4 and 5

condition; therefore, the first available data point was used as the zero point, and the data were adjusted based on this initial point (13 coverages of an 18-kip equivalent single-axle load (ESAL). The smaller coverage values reflect a certain amount of "kneading" action of the surface and, due to the small values, reflect some measurement error. The data show that rut accumulation is significantly more rapid for section 5 (sand, cement) than for section 4 (sand, cement, and fibers).

For better visualization, the data were truncated below 250 passes, and a first-order least squares fit was conducted for both sets of data. This fit was conducted for a qualitative comparison only and is not intended to provide quantitative comparisons of any nature. Figure 28 contains a plot of the resulting two lines. Although the data are limited, these curves reflect a benefit in including the fibers, even though these sections were not trafficked to failure.

Figure 29 contains a coverages versus rut depth plot for sections 9 (12-in. clay, 5-percent lime) and 10 (12-in. clay, 5-percent lime, 0.3-percent fibers). These data were also zeroed using the first available reading (three coverages of an 18-kip ESAL). The trend for these data is not as obvious as for sections 4 and 5. The data were truncated below 500 passes, and a first-order fit to the remaining data provided the curves shown in Figure 30. A comparison of these two curves indicates that at higher pass levels, inclusion of the fibers results in a reduced rate of rut depth growth.

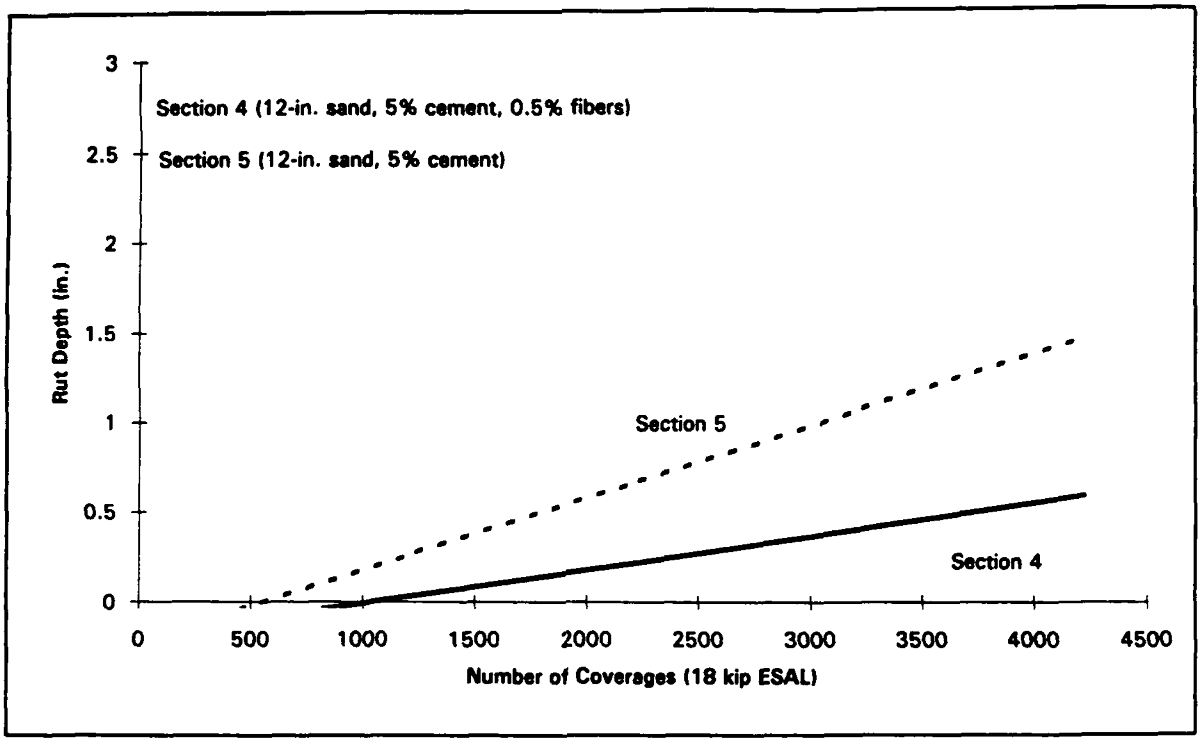

Figure 28. Lines fitted to data for sections 4 and 5

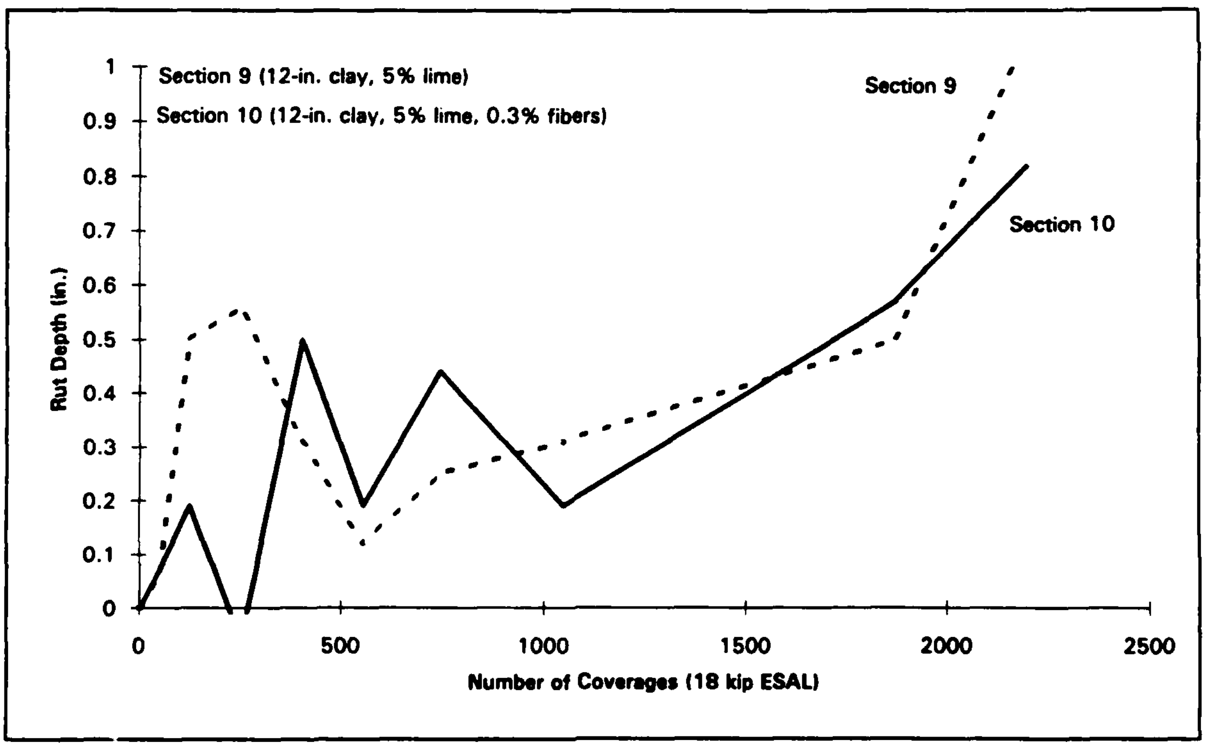

Figure 29. Measured rut depth progression, sections 9 and 10

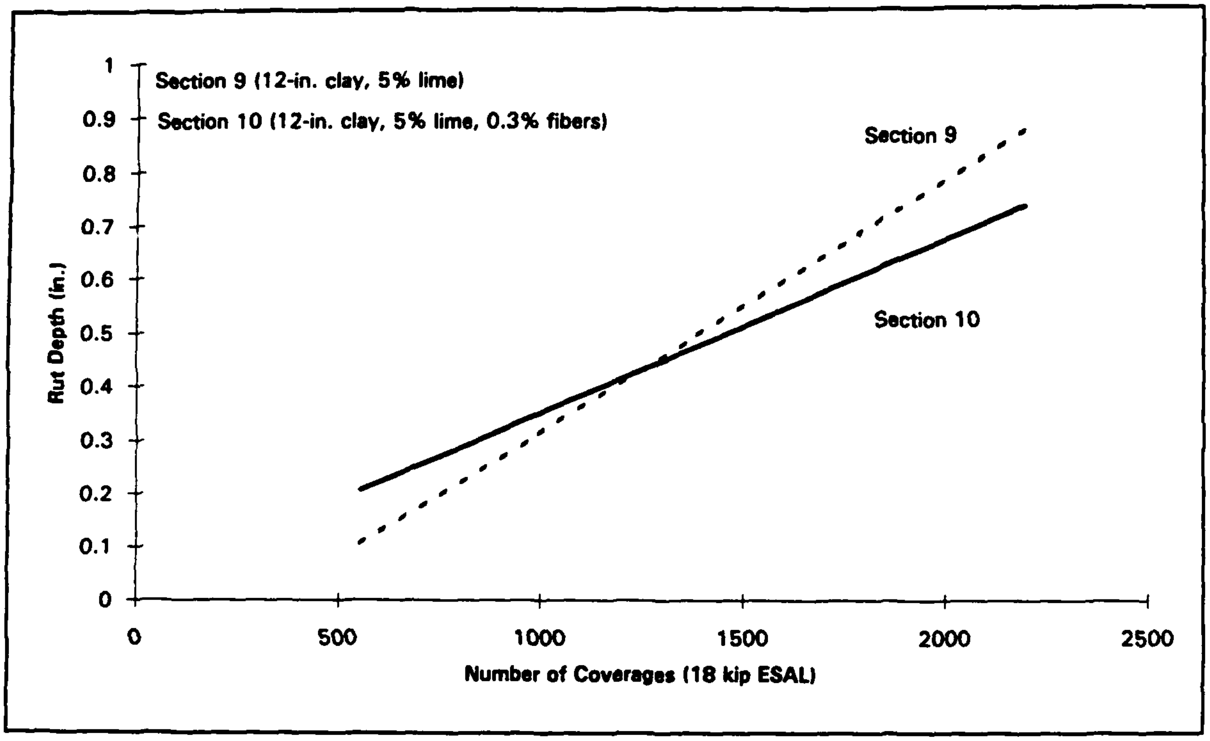

Figure 30. Lines fitted to data for sections 9 and 10

Some interesting results were also obtained by comparing predicted to actual passes to failure (failure based on a 3-in. rut depth and coverages converted to coverages for an 18-kip ESAL). Published empirically based equations were used to predict passes to failure. One equation used was the regression equation for aggregate surfaced roads developed by Barber, Odom, and Patrick (1978). This equation has the form:

$$(\log\ t)^{2.002} = \frac{P_k^{0.4704} \times t_p^{0.5695} \times R^{0.2476}}{RD \times C_1^{0.9335} \times C_2^{0.2848}} \qquad (2)$$

where

t = aggregate depth (in.)
P_k = equivalent single-wheel load (ESWL) (kips)
t_p = tire pressure (psi)
R = passes to failure
RD = rut depth (in.)
C_1 = CBR of aggregate surface
C_2 = CBR of subgrade

This is the primary design equation in use by the U.S. Forest Service. It was used in the present study to predict passes to failure for sections with a measured surface/subgrade CBR ratio of less than 10.

A modified regression equation was developed by Smith (in preparation) which includes additional data not available to Barber, Odom, and Patrick in 1978. This equation has the form:

$$\log t = \frac{P_k^{0.2016} \times t_p^{0.2481} \times R^{0.0747}}{RD \times C_1^{0.2414} \times C_2^{0.0596}} \tag{3}$$

The variables have the same connotation as in Equation 2. Equation 3 was also used to predict passes to failure for sections in which the measured surface CBR was less than 10 times the measured subgrade CBR. The CBR design equation (Equation 1) (used in design of the sections) was used to estimate passes to failure for sections in which the measured surface/subgrade CBR ratio was greater than 10.

A comparison of actual coverages (1 coverage = 1 pass) to failure with projected coverages based on the equations revealed that, in situations where the measured surface CBR was 2 to 5.5 times greater than the subsurface CBR (see Appendix B for CBR measurements), Equations 2 and 3 generally were better predictors of the noted test performance. In cases where the measured surface CBR was significantly larger than the subsurface CBR (a factor of 10 or higher), the CBR equation (Equation 1) proved to be a better predictor, in general.

The CBR equation is best suited for flexible (asphalt concrete surface) pavements where the material at the surface generally has significantly higher strength than the subgrade material. Also, the form of the CBR equation for unsurfaced roads ($\alpha = 0.13 \log C + 0.09$) was developed from tests on dense graded, well-compacted aggregate-surfaced and soil-surfaced roads with low-strength subgrades. Strictly speaking, neither the stabilized test sections nor the fiber-reinforced stabilized sections conform to these conditions. The regression equations were developed from data for aggregate-surfaced roads where the surface material strength is larger than that for the subgrade; however, this ratio is smaller than for the flexible pavement configuration. Figure 31 gives a chart of the predicted versus actual passes to failure for sections with measured surface to subgrade CBR ratios greater than 10. Figure 32 gives similar information for sections with measured surface to subgrade CBR ratios of less than 10.

The figures show that the prediction equations are only partially effective. This is not surprising given the nature of the formulas. The empirical nature of the formulas implies that they were developed under certain conditions. Any variation from these conditions introduces error into the results. The CBR test results (the basis for the above comparison) also contain error in the measurement process. Setup and commencement of the field CBR test contain a significant degree of subjectivity. The field CBR test, by its nature, may not be indicative of the actual performance of the fibers.

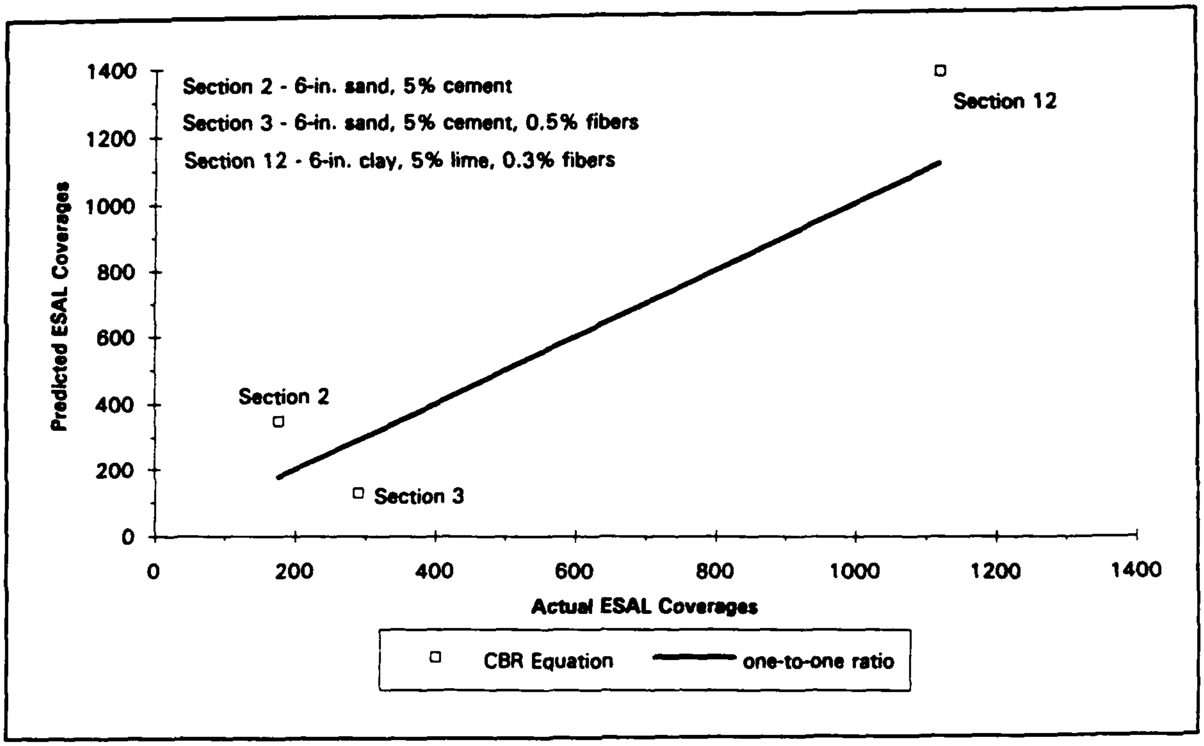

Figure 31. Comparison of actual to predicted coverages (ratio of measured surface CBR to subgrade CBR of 10 or greater)

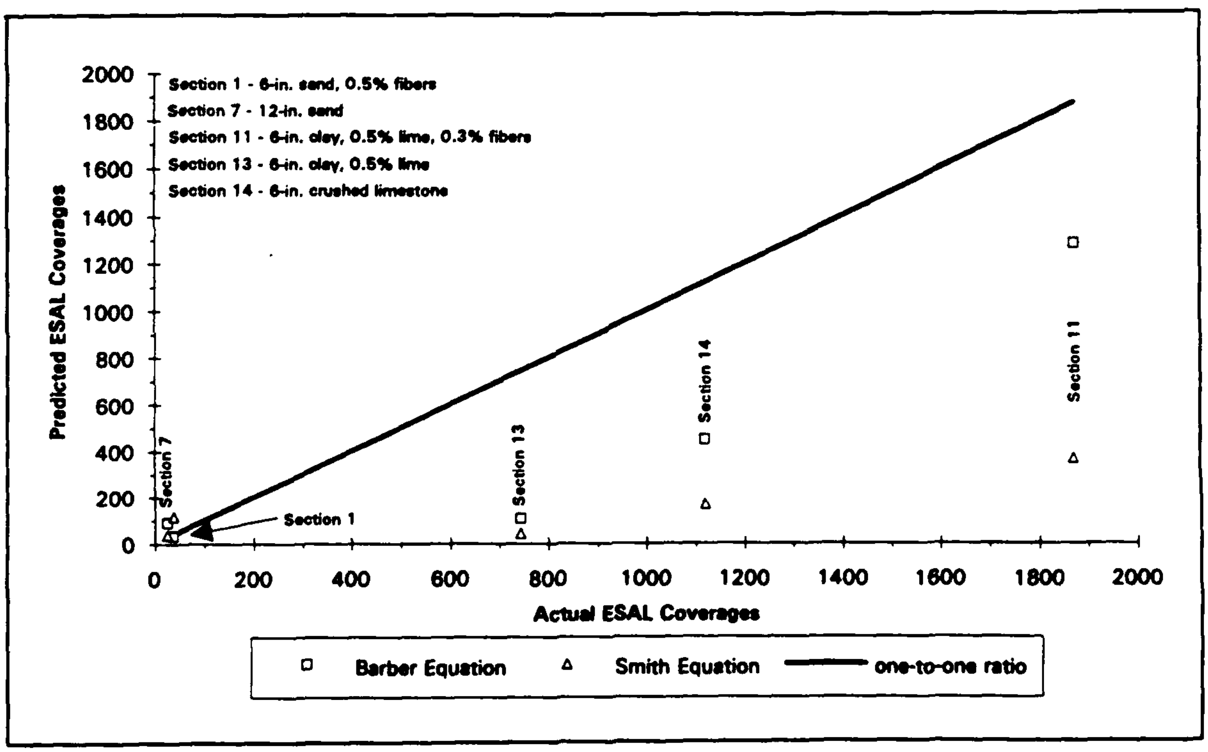

Figure 32. Comparison of actual to predicted coverages (ratio of measured surface CBR to subgrade CBR of less than 10)

Plate bearing tests (30-in. plate diameter) were conducted on each section prior to trafficking. This test provides a measure of system stiffness and does not well reflect the relative strengths of individual layers. The plate bearing test results are contained in Appendix B.

Table 3 compares passes-based results to plate bearing test results for several sections of interest. The plate bearing results are not fully consistent with the performance results and do not reflect all the trends observed in the performance-based results.

The backcalculated modulus values based on FWD test results also are not fully consistent with passes-based performance data. Table 3 shows the results of comparing the stiffness as determined from the modulus values to the passes-based performance data for several sections of interest. The stiffness data follow the same trend as the plate bearing results for sand sections, but there is less agreement in the results for clay sections.

The plate bearing and FWD tests are specialized tests that provide a measure of the system stiffness for a pavement system. The plate bearing test is usually performed on the subgrade and provides a subgrade coefficient that is a measure of the system stiffness when subjected to a static load. Many materials exhibit enhanced stiffness when subjected to dynamic loads, as appears to be the case for this type of structure. The FWD is a dynamic test that assumes a continuous surface deflection. It is possible that the surface of the sections which include fiber interferes with the deflection measurements. Also, the FWD test provides a single loading and does not take into account the fatigue resistance of the fiber-reinforced material.

As implied above, a primary benefit of the fibers appears to be in control of "fatigue-type" damage. As the materials are repeatedly loaded, progressive damage occurs. A part of the function of the fibers appears to be in reinforcing the material structure after loading damage has occurred.

Uniaxial compression tests show that desirable engineering properties such as the strain energy density and modulus of elasticity are enhanced by inclusion of fibers. TTI has recently conducted cylinder tests, notched beam tests, and impact tests which also reflect enhanced performance in fiber-reinforced soil material, especially for materials subjected to strains that exceed the elastic limit of the nonfiber-reinforced material. Appendix C contains plots from some of these tests. These figures show definite performance enhancement by inclusion of fibers. These increases in fiber-related performance are not evidenced through many standard laboratory testing methods that primarily measure peak bearing or compressive strengths. The more detailed tests described above show that modulus, peak strength, and strength after peak are all increased by inclusion of fibers.

Table 3
Comparison of Plate Bearing Results and Backcalculated Surface Modulus Results to Passes-Based Performance Results

Sections A and B	Passes to Failure, A ÷ B	Plate Bearing Test Results, Subgrade Modulus A ÷ B	Backcalculated Surface Modulus, from FWD Tests A ÷ B
6 (12-in. sand, 0.5% fibers) and 1 (6-in. sand, 0.5% fibers)	2.0	1.6	1.0
6 (12-in. sand, 0.5% fibers) and 7 (12-in. sand)	1.3	0.9	0.7
3 (6-in. sand, 5% pc, 0.5% fibers) and 2 (6-in. sand, 5% portland cement)	1.6	0.6	0.2
12 (6-in. clay, 5% lime, 0.1% fibers) and 13 (6-in. clay, 5% lime)	1.3	0.9	1.4
14 (6-in. crushed limestone) and 13 (6-in. clay, 5% lime)	1.3	0.7	0.7
12 (6-in. clay, 5% lime, 0.1% fibers) and 14 (6-in. crushed limestone)	1.0	1.3	1.9
11 (6-in. clay, 5% lime, 0.3% fibers) and 12 (6-in. clay, 5% lime, and 0.1% fibers)	1.5	1.2	2.3
11 (6-in. clay, 5% lime, 0.3% fibers) and 14 (6-in. crushed limestone)	1.5	1.5	4.5
11 (6-in. clay, 5% lime, 0.3% fibers) and 13 (6-in. clay, 5% lime)	1.9	1.1	3.4

7 Conclusions and Recommendations

Conclusions

The test results show that the inclusion of discrete fibrillated polypropylene fibers (Fibergrids®) in both stabilized fine-grained (clay) and stabilized coarse-grained (sand) soils is of benefit for support. Passes-based test results for the sand material show that the greatest benefit is achieved through inclusion of the fibers in a chemically stabilized composite, although some benefit might be realized without the cement additive. Inclusion of fibers with stabilized clay material also shows benefit over the clay system including only chemically stabilized material.

The application of discrete fibers for mechanical stabilization of subgrades, unsurfaced roads, and retaining wall backfills shows promise in both clay and sand. For the sand material tested in this experiment, the fibers used in conjunction with 5-percent chemical stabilization (portland cement) provided an additional 60 percent of trafficking prior to failure in the 6-in.-thick sections versus similar sections without fibers. The 12-in.-thick fiber and cement-stabilized section (section 4) showed a smaller rate of rut accumulation than did the counterpart section with only cement stabilization (section 5).

The passes-based data also clearly show performance improvement for clay material with inclusion of the fibers in a chemically stabilized system. This can be observed by comparing sections 11 (6-in. clay, 5-percent lime, 0.3-percent fibers), 12 (6-in. clay, 5-percent lime, 0.1-percent fibers), and 13 (6-in. clay, 0.5-percent lime). The passes-based test results reflect an additional 30 percent of traffic to failure for section 12 when compared to section 13. Section 11, with an equal amount of lime and 0.3-percent fibers, reflects a 90-percent improvement over section 13. The 12-in.-thick sections show the same trend as the 6-in. sections with slower accumulation of rut depth in the fiber-stabilized section.

The passes-based data reflect significant improvements in durability for both stabilized clay and sand sections by addition of fibers. Sand sections without chemical stabilization also exhibited enhanced traffic performance with addition of fibers, but not to an economically practical level. For the present, standard laboratory tests such as unconfined and triaxial tests (with stress-strain analysis) must be conducted for verification of the benefits of fiber application to stabilized material. These tests provide an indication of critical engineering properties of the material such as the modulus or peak compressive strength. These tests also provide information on postpeak strength enhancement (strain hardening) of the material in question. Other tests that have shown promise are the notched beam test and impact tests using beams (Crockford 1993).

At this point, verification of enhanced properties of fiber-reinforced material in place by means other than trafficking is difficult. Fiber-reinforced materials are unique, and no field test used in this study appears to give results fully consistent with rutting under traffic. The plate bearing tests showed the greatest promise for field verification; however, additional studies should be conducted for CBR values, plate bearing, and FWD tests.

The trafficking results from this test prove conclusively that addition of fibers into the materials studied improves the strength and durability of the tested sections. The field results show that fiber reinforcement does provide additional pavement life.

The fibers provide significant enhancement of postpeak load-carrying capacity, as demonstrated in the laboratory. The trafficking tests also showed that the fibers slow the rutting process and tend to reduce the detrimental effects of cracking. Conventional chemically stabilized soils lose load-carrying capacity quickly after initial formation of cracks. This is evidenced by stress-strain curves for uniaxially loaded samples of chemically stabilized material that exhibit obvious strain softening after peak loading. The fibers reverse this undesirable characteristic and provide a very desirable postpeak behavior analogous to strain hardening. In a similar vein, the field tests show that the fiber-reinforced sections exhibit excellent fatigue resistance, as well. Fracture studies by TTI indicate that extent and severity of cracking are reduced with addition of fibers. This would also indicate reduced reflective cracking in overlying pavement layers, which is a major problem in soil cement pavements.

The trafficking tests also reflect that smaller than laboratory-determined optimum dosages (mass fraction) of fibers provide a benefit. This is shown by comparing the results of clay sections 11 (6-in. clay, 5-percent lime, 0.3-percent fibers), 12 (6-in. clay, 5-percent lime, 0.1-percent fibers), and 13 (6-in. clay, 5-percent lime). Section 11 exhibited the greatest improvement over section 13 (90 percent more trafficking to failure) as expected. But it is important to note that section 12 provided 30 percent more traffic to failure than the section without any fibers.

The 1-in.-long discrete fibrillated polypropylene fiber mixes readily with the soils investigated in this test. Additional studies are presently being conducted to determine the effect of various fiber lengths and thicknesses.

Recommendations

The use of discrete fibrillated polypropylene fibers stabilization is recommended for consideration in situations where available construction materials are less than desirable or a reduction is desired in the percentage of lime or cement required to stabilize the system. Specifically, this technology can be used in granular soils where the in-place material has excessive fines for standard soil cement stabilization. It is also applicable in cohesive soils where the proper dosage of lime is uneconomical and/or a brittle soil composite structure is a concern. The use of discrete fibrillated polypropylene fibers should also be considered in marginal untreated soils to improve performance.

Areas of application that can be recommended based on this study include subbases and subgrades for long-term roads, wearing courses and base courses for temporary construction roads, and wearing courses for logging roads.

The database for application of this technology is increasing. This technology could have a significant impact on the construction industry for widespread application. As a step toward considering this method for use in military construction, Appendix D contains a suggested preliminary guide specification for use of this technology. This appendix is to be used only as a general guideline and might not contain all the information necessary for writing complete specifications for a specific construction project.

Additional sections could be constructed reflecting actual field conditions and long-term environmental effects. This could be accomplished by reconstruction of sections of existing paved or unpaved roads and monitoring the performance of these sections.

8 Commercialization and Technology Transfer

Availability of Fibers

Discrete fibrillated polypropylene fibers (Fibergrids®) are manufactured and distributed by Synthetic Industries. They are available from Synthetic Industries, Construction Products Division, 4019 Industry Drive, Chattanooga, TN 37416. The toll free phone number for Synthetic Industries is (800) 621-0444. Fibergrids® are packaged and sealed in polyethylene bags and placed in cardboard cartons. The cartons are shipped on pallets by the truckload. Table 4 contains shipping information for Fibergrids®.

Table 4
Shipping Information for Fibergrids®

Packaging	20-lb bags	250-lb bags
Carton dimensions	16-in. x 14-in. x 17-in.	35-in. x 42-in. x 36-in.
Cartons per pallet	30	1
Gross weight per pallet	728 lb	330 lb
45-ft trailer	19,200 lb	15,000 lb
40-ft trailer	16,800 lb	13,000 lb
20-ft trailer	7,800 lb	6,250 lb

Fibergrids® Specifications

Industry specifications for Fibergrids® require that the material be discrete fibrillated polypropylene fibers as manufactured by Synthetic Industries. Further, the fibers shall be resistant to ultraviolet degradation and to biological and chemical environments normally found in soils. The fibers supplied shall meet average physical properties shown in Table 5 when sampled and tested in accordance with the given methods.

Formal construction specifications developed by Synthetic Industries are available for use of Fibergrids®. Also, Appendix D contains suggested preliminary guide specifications for use of discrete fibrillated polypropylene fibers in military construction. Additional guidance can be found in the U.S. Patent documentation for this process (Freed 1989).

Table 5
Industry Specifications for Fibergrids®

Property	Test Method	Requirements
Polypropylene	ASTM D4101 Group 1/Class 1/Grade 2	99.4%
Color	-	Black
Moisture absorption	-	Nil
Fiber length	Measured	1 in.[1]
Specific gravity	ASTM D792	0.91 g/cm^3
Carbon black content	ASTM D1603	0.6%
Tensile strength	ASTM D2256	45,000 psi
Tensile elongation	ASTM D2256	15%
Young's modulus	ASTM D2101	700,000 psi

[1]Unless otherwise specified on the plans.

Technology Transfer and Marketing Plans

Synthetic Industries currently staffs Fibergrids® technology specialists and is represented by qualified regional distributors. Synthetic Industries and its distributors will continue to actively promote the use of Fibergrids® in a wide variety of civil engineering applications. Synthetic Industries is currently pursuing potential markets with state and local highway departments, consulting geotechnical and civil engineering firms, pavement design engineering firms, pavement and soils contracting firms, and state and Federal flood-control agencies. Many potential applications are presently being explored by the construction industry.

Fibergrids® technology is an economically feasible alternative to current construction methods and materials for soil stabilization and reinforcement. It is difficult to accurately describe the economics of application of this technology, at present, because the technology is new. One of the biggest initial economic advantages is the ability to use Fibergrids® with existing soils. This is particularly effective in pavement rehabilitation projects. Recent applications have proven that the mixing effort required to adequately blend fibers with soil is essentially the same as that required to mix chemical additives with soil. The effort required to spread the fibers is also similar to that for application of a chemical stabilizer. Cost comparisons of this technology with conventional chemical stabilization must be conducted on a project-by-project basis. The cost comparisons should give consideration to the extended useful life provided by application of fibers to the extent possible.

Other Research Supported by Synthetic Industries

Fibergrids® have been applied in a number of construction projects in a number of applications. In some cases, fibers have been applied without chemical additives and have proven effective for stabilization of soils with high plasticity indexes. Also, soils have been stabilized with water contents as high as 8 percent above optimum. Other project applications that have proven successful include slope and embankment stabilization along highways.

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Appendix A Thickness Design Calculations

California Bearing Ratio (CBR) Design Procedure

The CBR equation has the form:

$$t = \alpha \sqrt{P\left(\frac{1}{8.1\ CBR} - \frac{1}{p_e\ \pi}\right)} \qquad \text{(A1)}$$

where

t = required thickness
α = (0.23 log C + 0.15) for surfaced roads
α = (0.13 log C + 0.09) for unsurfaced roads
C = coverages
P = single tire load
p_e = tire pressure

Assuming a flexible pavement (1-in. rut depth failure criterion, the following design parameters were used:

α = 0.23 log C + 0.15
C = 5,000 (number of coverages of the design vehicle
P = 5,000 lb (single-wheel load - 20-kip axle)
p_e = 100 psi (tire pressure--note that 80 psi was used in the test)
CBR = 5 (design subgrade CBR)

Therefore,

$$t = (0.23\log 5{,}000 + 0.15) \sqrt{5{,}000\left(\frac{1}{8.1 \times 5} - \frac{1}{100 \times \pi}\right)} \qquad \text{(A2)}$$

Solving for thickness,

$$t = (1.001)\sqrt{107.5395} \quad \text{(A3)}$$

$$t = 10.35 \text{ inches} \quad \text{(A4)}$$

For practicality, this was rounded to 12 in.

For the gravel surface case (3-in. rut failure criterion), the following parameters were used:

α = 0.13 log C + 0.09
C = 5,000 (number of coverages of the design vehicle
P = 5,000 lb (single-wheel load - 20-kip axle)
p_e = 100 psi (tire pressure -- note that 80 psi was used in the test)
CBR = 5 (design subgrade CBR)

Therefore,

$$t = (0.13\log 5{,}000 + 0.09)\sqrt{5{,}000\left(\frac{1}{8.1\times 5} - \frac{1}{100\times\pi}\right)} \quad \text{(A5)}$$

Solving for thickness,

$$t = (0.5709)\sqrt{107.5395} \quad \text{(A6)}$$

$$t = 5.92 \text{ inches} \quad \text{(A7)}$$

Use 6 in.

Therefore, two design thicknesses were tested, one at 6-in. and one at 12-in.

A nomograph is also available for determination of flexible pavement design thickness given an 18,000 lb, single-axle, dual-wheel load. This nomograph is given in TM 5-330/AFM 86-3, Vol II[1] (see Figure A1). For design of the test section (flexible pavement assumed), the nomograph would be entered at the design coverage value (5,000 coverages), and the proper CBR curve would be chosen. From these two values, the design thickness is easily

[1] References are presented at the end of the main text.

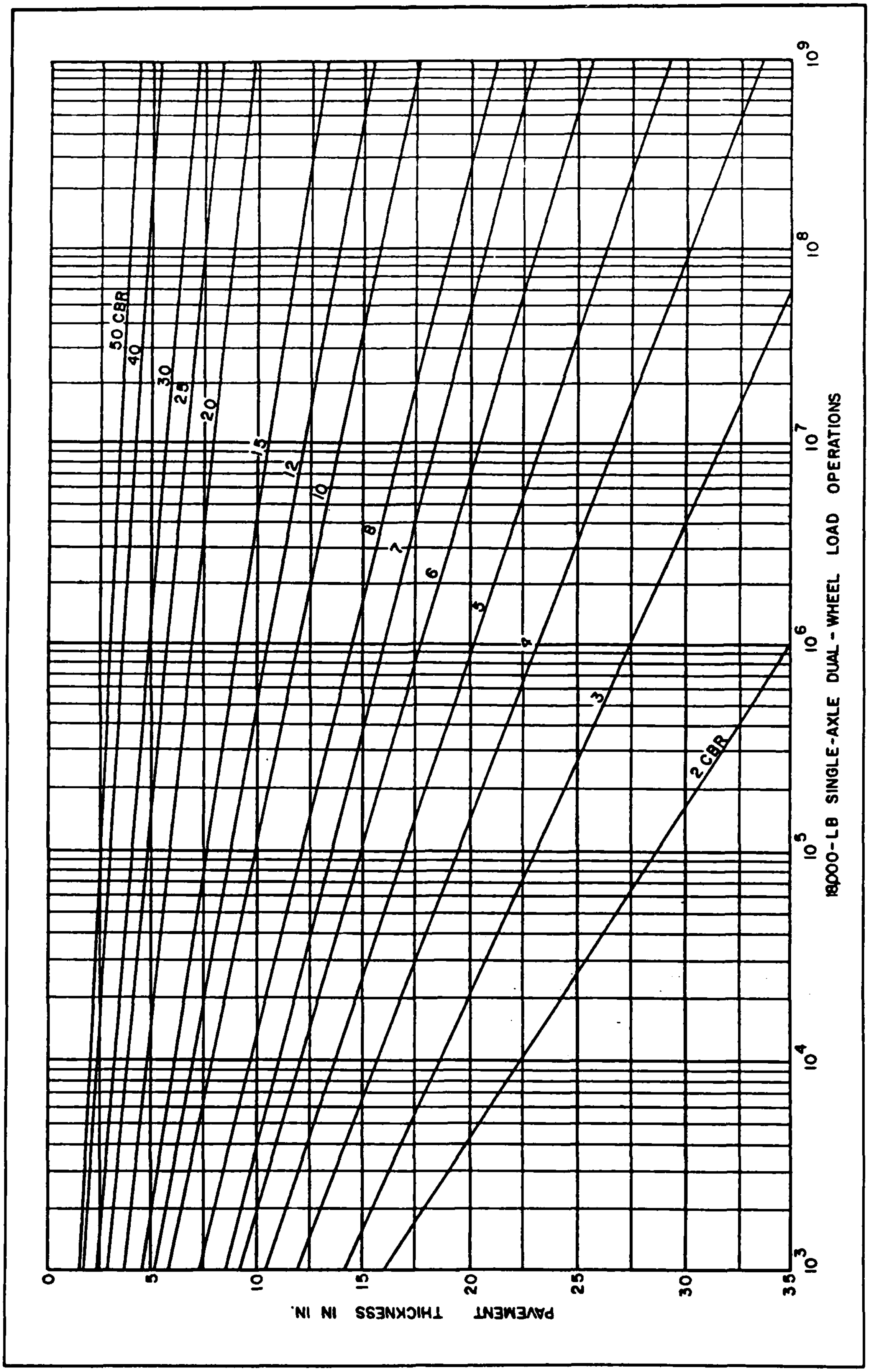


Figure A1. Flexible pavement design curves for roads, thickness versus operations for 18,000-lb, single-axle, dual-wheel load determined. For 5,000 operations and a CBR of 5, the pavement thickness is found to be approximately 12.5 in. This agrees well with the CBR equation, as expected.

Appendix B
Material and Test Data

Table B1
Moisture/Density Relationships for the Tested Material

Material	Percent Stabilizing Agent (by weight)	Percent Fibers (by weight)	WES Results	
			Dry Density, PCF (Maximum)	Water Content, % (Optimum)
SM	None	0	106	13.5
SM	Cement, 5	0	111	11.5
SM	Cement, 5	.5	112	10.5
SM	None	.5	105	10.5
CH	None	0	114	15.5
CH	Lime, 5	0	111	15.5
CH	Lime, 5	.3	108.5	16.5

Table B2
Summary of Unconfined Compressive Strength Tests Performed at WES on Laboratory Specimens

Material	Stabilizing Agent	Percent Stabilizing Agent (by weight)	Percent Fibers (by weight)	Maximum Deviator Stress (psi)
Sand (SM)	Cement	5.0	None	61
Sand (SM)	Cement	5.0	None	85
Sand (SM)	Cement	5.0	0.5	227
Sand (SM)	Cement	5.0	0.5	268
Sand (SM)	Cement	5.0	0.5	191
Sand (SM)	None	---	0.5	5
Sand (SM)	None	---	0.5	9
Clay (CH)	None	---	None	128
Clay (CH)	None	---	None	234
Clay (CH)	Lime	5.0	None	320
Clay (CH)	Lime	5.0	None	325
Clay (CH)	Lime	5.0	0.3	170
Clay (CH)	Lime	5.0	0.3	216

Table B3
Laboratory Test Data for Sections 2, 3, 11, and 13

Material	Percent Stabilizing Agent (by weight)	Percent Fibers (by weight)	Confining Pressure (psi)	Maximum Deviator Stress (psi)
SAND (SM)	Cement, 5	0	0	18.6
SAND (SM)	Cement, 5	0	5	48.5
Sand (SM)	Cement, 5	0	10	83.3
Sand (SM)	Cement, 5	0	15	80.7
Sand (SM)	Cement, 5	0	20	102.2
Sand (SM)	Cement, 5	.5	0	16.7
Sand (SM)	Cement, 5	.5	5	53.1
Sand (SM)	Cement, 5	.5	10	66.8
Sand (SM)	Cement, 5	.5	15	103.9
Sand (SM)	Cement, 5	.5	20	106.7
Clay (CL)	Lime, 5	.3	0	76.1
Clay (CL)	Lime, 5	.3	5	82.5
Clay (CL)	Lime, 5	.3	10	66.5
Clay (CL)	Lime, 5	.3	15	103.2
Clay (CL)	Lime, 5	.3	20	91.4
Clay (CH)	Lime, 5	0	0	93.3
Clay (CH)	Lime, 5	0	5	100.6
Clay (CH)	Lime, 5	0	10	116.1
Clay (CH)	Lime, 5	0	15	110
Clay (CH)	Lime, 5	0	20	115

Table B4
Plate Bearing Test Data

Section	k10	k'u	ku
(6-in. sand, .5% fibers)	47	----	----
2 (6-in. sand, 5% pc)	119	----	----
3 (6-in. sand, 5% pc, .5% fibers)	70	----	----
4 (12-in. sand, 5% pc, .5% fibers)	233	154	146
5 (12-in. sand, 5% pc)	313	96	98
6 (12-in sand, .5% fibers)	78	----	----
7 (12-in. sand)	89	----	----
8 (12-in. clay)	No Test	----	----
9 (12-in. clay, 5% lime)	263	152	144
10 (12-in. clay, 5% lime, .3 % fibers)	172	----	----
11 (6-in. clay, 5% lime, .3% fibers)	132	----	----
12 (6-in. clay, 5% lime, .1% fibers)	112	----	----
13 (6-in. clay, 5% lime)	118	----	----
14 (6-in. crushed limestone)	86	----	----

(Note: K10 calculated 10 psi divided by deformation at 10 psi.
k'u determined from load/deformation curve.
ku is k'u corrected for plate bending.)

Table B5
Summary of Backcalculated Layer Moduli from November 1991 Testing

Section	Wheel Path	Surface Layer Modulus (psi)	Subgrade Modulus (psi)	Impulse Stiffness Modulus (ISM) From FWD Tests
1	Inside	3618	8017	91
1	Outside	1600	4617	47
2	Inside	7502	6931	119
2	Outside	15268	5852	120
3	Inside	3571	6682	87
3	Outside	1409	4945	47
4	Inside	36447	7630	263
4	Outside	31310	6692	248
5	Inside	25194	6833	211
5	Outside	14931	6816	174
6	Inside	2606	5598	61
6	Outside	2812	5764	63
7	Inside	3521	5578	78
7	Outside	4322	6717	94
8	Inside	1090	6451	46
8	Outside	1028	13143	54
9	Inside	17839	7973	218
9	Outside	27272	7711	263
10	Inside	14893	5564	144
10	Outside	11551	6097	134
11	Inside	5854	5569	94
11	Outside	21495	6051	139
12	Inside	5605	4915	86
12	Outside	6085	6054	100
13	Inside	2632	4930	64
13	Outside	5517	5879	98
14	Inside	2704	6172	77
14	Outside	3346	5194	77

Table B6
Summary of Rut Depth Measurements for Sections 1-7, Passes 25-350

Section	Station	25 Passes Rut Depth (in) Inner Lane	25 Passes Rut Depth (in) Outer Lane	50 Passes Rut Depth (in) Inner Lane	50 Passes Rut Depth (in) Outer Lane	100 Passes Rut Depth (in) Inner Lane	100 Passes Rut Depth (in) Outer Lane	200 Passes Rut Depth (in) Inner Lane	200 Passes Rut Depth (in) Outer Lane	350 Passes Rut Depth (in) Inner Lane	350 Passes Rut Depth (in) Outer Lane
1	0+13	1.75	2.25	4.5	4.25	---	---	---	---	---	---
	0+17	1.75	1.75	5.5	3.25	---	---	---	---	---	---
2	0+43	0.0	0.0	0.0	0.0	0.5	1.25	1.25	2.25	3.25	4.5
	0+47	0.25	0.0	0.25	0.0	0.5	0.5	1.75	1.5	5.75	5.0
3	0+74	0.25	1.0	1.0	1.0	1.5	1.25	2.5	2.0	2.5	3.25
	0+78	0.5	1.75	1.0	1.5	1.75	2.5	4.0	5.375	...	...
4	1+05	1.5	0.5	1.5	0.75	1.0	1.0	1.5	0.75	1.5	0.75
	1+09	1.0	1.0	1.5	1.0	0.5	1.25	1.0	1.25	1.0	1.0
5	1+36	0.5	0.25	0.0	0.25	0.25	0.5	0.0	0.5	0.5	0.5
	1+40	0.5	0.5	0.25	0.5	0.25	0.5	0.25	0.5	0.5	0.5
6	1+67	1.0	1.0	2.0	1.75	3.0	2.0	---	---	---	---
	1+71	1.25	1.0	2.0	1.5	3.5	2.5	---	---	---	---
7	1+99	1.5	1.5	4.0	4.0	---	---	---	---	---	---
	2+03	1.5	1.5	1.75	2.5	---	---	---	---	---	---

Table B7
Summary of Rut Depth Measurements for Sections 3-5, Passes 500 - 5,000

Section	Station	500 Passes Rut Depth (in) Inner Lane	500 Passes Rut Depth (in) Outer Lane	1000 Passes Rut Depth (in) Inner Lane	1000 Passes Rut Depth (in) Outer Lane	2250 Passes Rut Depth (in) Inner Lane	2250 Passes Rut Depth (in) Outer Lane	4000 Passes Rut Depth (in) Inner Lane	4000 Passes Rut Depth (in) Outer Lane	5000 Passes Rut Depth (in) Inner Lane	5000 Passes Rut Depth (in) Outer Lane
3	0+74	0.5	1.0	---	---	---	---	---	---	---	---
	0+78	4.75	3.5	---	---	---	---	---	---	---	---
4	1+05	0.25	1.0	1.0	1.0	1.25	1.0	1.5	2.0	1.25	2.5
	1+09	1.0	1.0	1.0	1.0	0.75	1.0	1.25	1.25	1.25	1.25
5	1+36	0.25	0.0	0.25	0.25	0.75	1.0	1.5	1.75	1.25	2.25
	1+40	0.5	0.25	0.5	0.5	1	1.25	1.5	1.75	1.25	2.5

Table B8
Summary of Rut Depth Measurements for Sections 8-14, Passes 5 - 800

Section	Station	5 Passes		100 Passes		250 Passes		500 Passes		800 Passes	
		Rut Depth (in)		Rut Depth (in)		Rut Depth (in)		Rut Depth (in)		Rut Depth (in)	
		Inner Lane	Outer Lane	Inner Lane	Outer Lane	Inner Lane	Outer Lane	Inner Lane	Outer Lane	Inner Lane	Outer Lane
8	0 + 14	5.75	5.0	---	---	---	---	---	---	---	---
	0 + 18	7.0	5.5	---	---	---	---	---	---	---	---
9	0 + 46	1.0	0.5	1.0	1.0	1.25	1.0	1.5	1.0	1.0	1.0
	0 + 50	0.75	0.5	0.5	0.5	2.0	0.5	1.5	1.0	1.0	1.0
10	0 + 76	1.0	0.25	1.0	0.5	1.5	0.5	0.5	0.25	1.5	0.5
	0 + 80	1.0	0.25	1.0	0.25	0.75	0.5	0.75	0.75	1.0	0.5
11	1 + 08	1.0	0.0	1.0	0.5	1.0	0.25	1.0	0.0	1.0	0.0
	1 + 12	0.5	0.25	0.75	0.5	1.0	0.5	1.0	0.0	1.0	0.0
12	1 + 39	0.75	0.5	1.0	0.5	1.0	0.5	1.0	0.75	1.0	1.0
	1 + 43	0.75	0.25	0.75	0.5	0.75	0.5	0.75	0.0	0.0	0.0
13	1 + 70	0.25	0.5	1.0	1.0	2.25	1.5	2.0	1.75	1.25	1.0
	1 + 74	0.5	1.0	2.5	1.0	3.5	0.75	4.5	1.25	3.5	0.75
14	2 + 00	0.5	0.5	---	0.5	---	0.5	---	0.5	---	1.5
	2 + 04	0.5	0.75	0.5	1.0	0.5	1.0	0.5	1.0	1.0	1.0

Table B9
Summary of Rut Depth Measurements for Sections 9-14, Passes 1100 - 4350

Section	Station	1100 Passes Rut Depth (in)		1300 Passes Rut Depth (in)		1625 Passes Rut Depth (in)		2500 Passes Rut Depth (in)		4350 Passes Rut Depth (in)	
		Inner Lane	Outer Lane	Inner Lane	Outer Lane	Inner Lane	Outer Lane	Inner Lane	Outer Lane	Inner Lane	Outer Lane
9	0+46	1.0	0.75	1.0	1.0	1.25	1.0	1.5	1.25	2.25	2.5
	0+50	1.0	0.5	0.75	1.0	1.0	0.75	1.5	1.0	1.25	1.0
10	0+76	1.5	0.5	1.75	0.5	1.25	0.75	1.75	1.0	2.0	1.75
	0+80	0.75	0.5	1.5	0.5	0.75	0.5	1.0	1.0	1.0	1.0
11	1+08	1.0	0.5	1.5	0.5	5.5	1.0	---	2.75	---	---
	1+12	1.0	0.0	1.75	0.0	3.75	0.75	---	3.25	---	---
12	1+39	1.25	1.0	1.5	1.0	8.0	2.0	---	---	---	---
	1+43	1.5	1.0	2.25	0.5	12.5	3.0	---	---	---	---
13	1+70	1.75	1.0	13.0	3.75	---	---	---	---	---	---
	1+74	3.75	0.75	12.5	4.75	---	---	---	---	---	---
14	2+00	---	1.0	---	.75	---	3.5	---	---	---	---
	2+04	3.5	1.0	---	2 0	---	3.0	---	---	---	---

Table B10
Summary of Oven Water Content Data

Section	Depth	Water Content, %		
		Initial Data Nov 1991	Initial Data May 1992	After Traffic Data
1	0.0	13.9	19	14.8
1	6.0	21.5	21.4	14
1	12.0	17.1	---	---
2	0.0	15	18.7	5.2
2	6.0	20.8	20.5	20.6
3	0.0	12.3	20.2	10
3	6.0	22.1	23	21.2
4	0.0	15.4	15.7	4.7
4	6.0	11.8	11.9	9.6
4	11.5	22	21.2	17.7
5	0.0	13.8	13.4	11.8
5	6.0	12.3	13.6	34.8
5	12.0	22.3	22.7	38.2
6	0.0	16	14.8	14.9
6	6.0	15.7	16.4	14.7
6	12.0	22.9	23	23.8
7	0.0	12.3	19.3	12.1
7	6.0	15.6	17	13.4
7	12.0	22	25.6	23.3
8	0.0	27.2	28.5	31.2
8	6.0	22.6	27	27.8
9	0.0	23.7	25.9	31.3
9	6.0	32.2	32.5	33.7
9	12.0	26.4	26.2	36.9
10	0.0	24.4	23.2	39
10	6.0	36.5	32.5	61.2
10	12.0	49	28.2	37.6
11	0.0	23.9	21.8	16.1
11	6.0	29.4	27.8	25.4
12	0.0	25	20.5	18.2
12	6.0	25.2	28.9	27.8
13	0.0	22.2	32.6	5.8
13	6.0	30.9	28.8	26.9
14	0.0	7.9	9.4	1.5
14	6.0	27.2	25.9	26

Table B11
Summary of Drive Cylinder Density Data

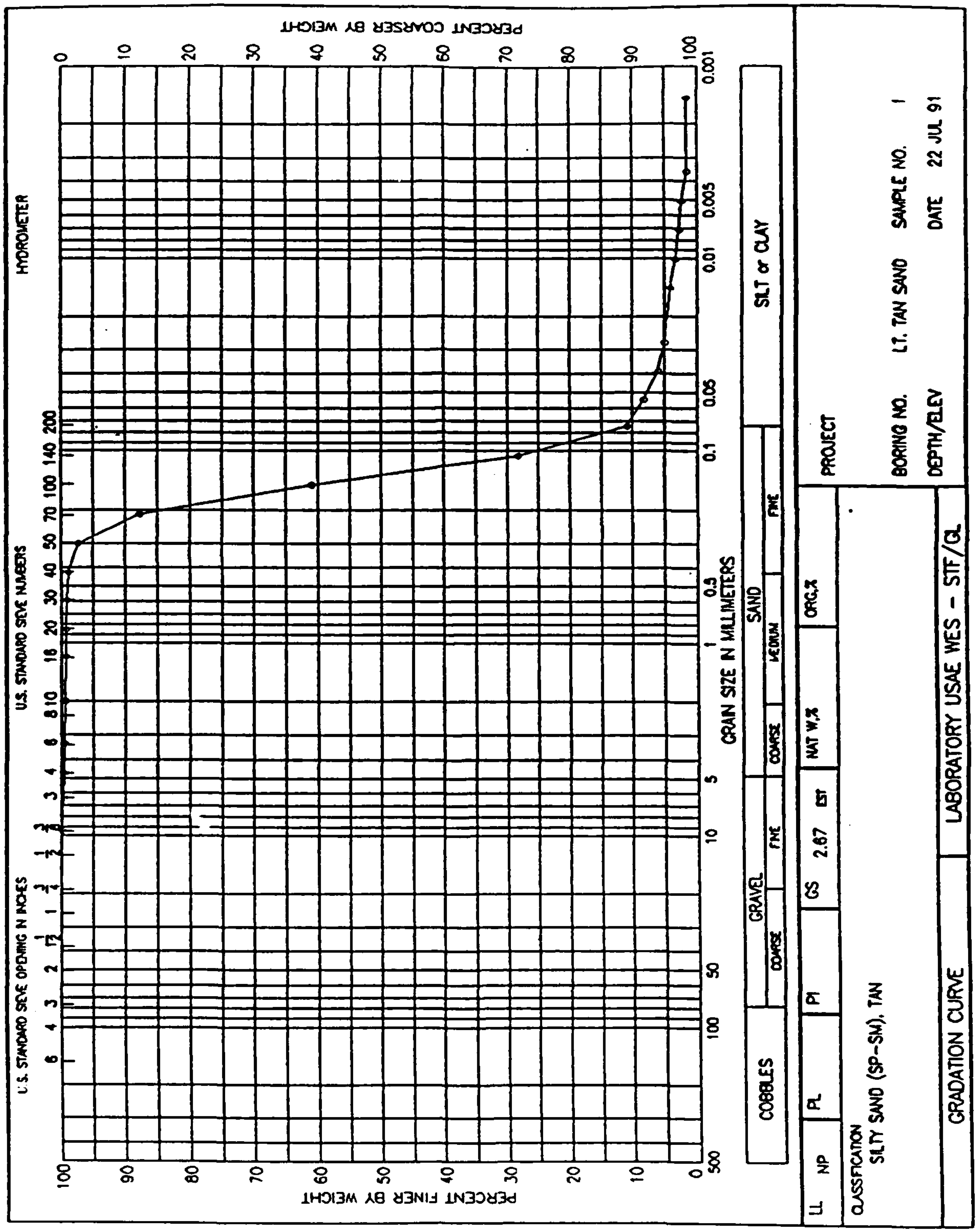
Section	Depth	Wet Density (Lbs/ft^3) Initial Data Nov 1991	Wet Density (Lbs/ft^3) Initial Data May 1992	Wet Density (Lbs/ft^3) After Traffic Data	Dry Density (Lbs/ft^3) Initial Data Nov 1991	Dry Density (Lbs/ft^3) Initial Data May 1992	Dry Density (Lbs/ft^3) After Traffic Data
1	0.0	104.1	---	---	91.7	---	---
1	6.0	124.8	127.2	108.7	103.2	104.7	95.3
1	1.0	120.9	---	---	102.1	---	---
2	0.0	119.4	---	---	105.4	---	---
2	6.0	125	128.2	126.8	101.3	106.5	105.1
3	0.0	115	---	---	101.1	---	---
3	6.0	125.9	125.5	125.4	104.1	102.1	103.5
4	0.0	115.9	---	---	100.5	---	---
4	6.0	113.5	---	---	102.1	---	---
4	11.5	123.2	126	---	100.1	104	---
5	0.0	116.1	---	---	102.2	---	---
5	6.0	114.4	---	---	102.2	---	---
5	12.0	124.5	125.1	123.9	101.5	101.9	90.3
6	0.0	108.6	---	---	93.7	---	---
6	6.0	105.6	---	---	90.7	---	---
6	12.0	126	124.8	106.5	101.7	101.5	86
7	0.0	113.7	---	---	100.2	---	---
7	6.0	122	---	---	104.9	---	---
7	12.0	121.9	121.4	97.7	99.4	96.7	79.2
8	0.0	118.4	116.4	115.7	92.9	90.6	88.2
8	6.0	110.9	115.4	116.2	88.1	91.2	90.9
9	0.0	90.1	---	---	73.1	---	---
9	6.0	109.3	---	---	79.4	---	---
9	12.0	112	118.8	---	87.1	94.1	---
10	0.0	105.2	---	---	85.2	---	---
10	6.0	107.5	---	---	84.4	---	---
10	12.0	105.8	112.2	---	72.2	87.5	---
11	0.0	108.6	---	---	87.2	---	---
11	6.0	118.3	119	121.6	92.8	73.5	97
12	0.0	108.3	---	---	85.8	---	---
12	6.0	119.2	118.3	120.3	93.4	91.8	94.1
13	0.0	105.3	87.9	---	84.4	66.8	---
13	6.0	115.6	98	119.8	88	76.1	94.4
14	0.0	---	---	---	---	---	---
14	6.0	120.6	104.4	122.9	97.9	83	97.5

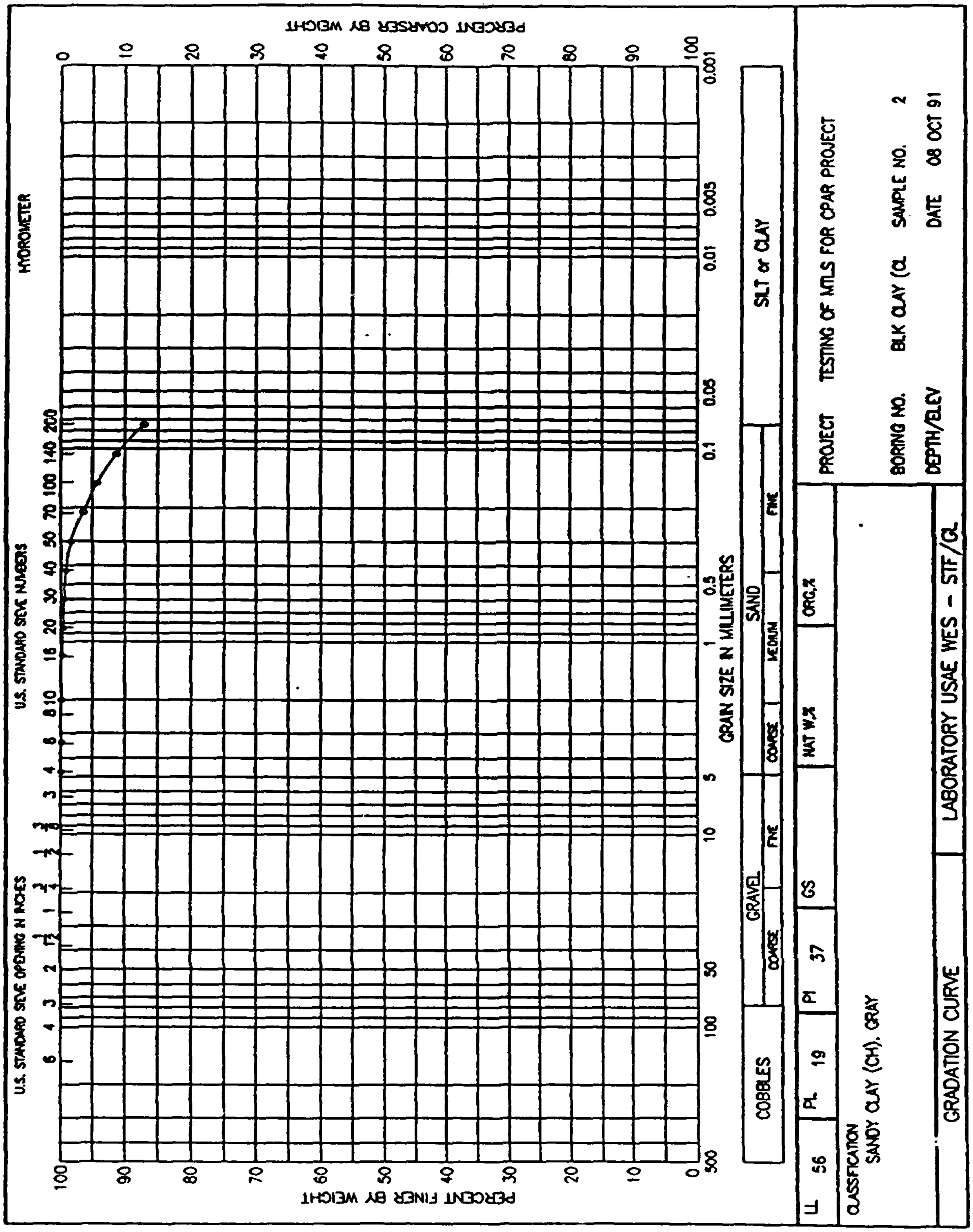
Table B12
Nuclear Gage Density Data

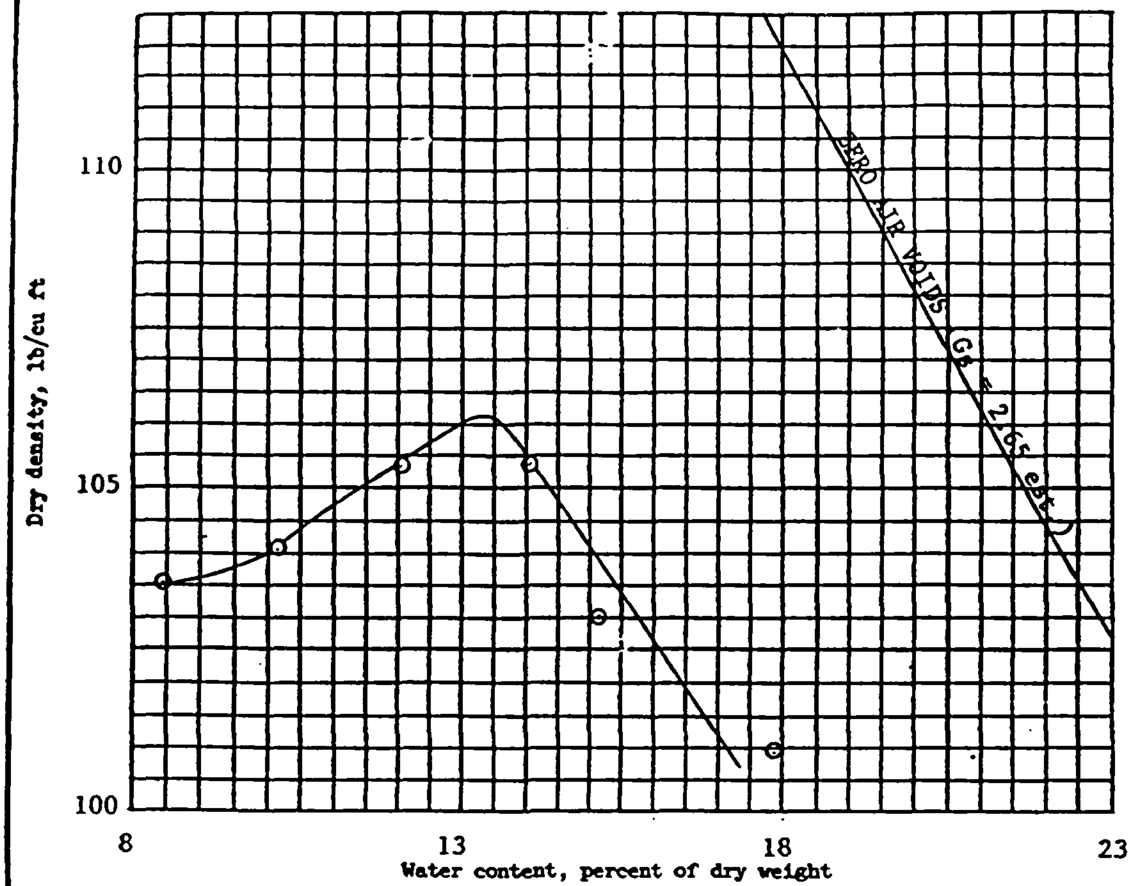
Section	Depth	Wet Density (lb/ft³) Initial Data Nov 91	Wet Density (lb/ft³) Initial Data May 92	Wet Density (lb/ft³) After Traffic Data	Dry Density (lb/ft³) Initial Data Nov 91	Dry Density (lb/ft³) Initial Data May 92	Dry Density (lb/ft³) After Traffic Data
1	0.0	116	109.8	119.7	101.8	92.3	104.3
1	6.0	121.2	---	---	99.8	---	---
1	12.0	119.6	---	---	102.1	---	---
2	0.0	121.7	113.4	112.5	105.8	95.5	106.9
2	6.0	121.6	---	---	100.7	---	---
3	0.0	117.9	110.9	---	105	92.3	---
3	6.0	123.5	---	---	101.1	---	---
4	0.0	117.4	109.3	106.7	101.7	94.5	101.9
4	6.0	119.6	109.3	110.6	106.9	94.5	100.9
4	11.5	122.4	---	116.3	100.3	---	98.8
5	0.0	102.6	120.8	104.6	106	106.5	93.6
5	6.0	120.1	---	102.6	106.9	---	76.1
5	12.0	117.7	---	113.9	96.2	---	82.4
6	0.0	116.8	116.7	111.1	100.7	101.7	96.7
6	6.0	119.5	---	111.4	103.3	---	97.1
6	12.0	119.3	---	---	97.1	---	---
7	0.0	117.5	117.1	114	104.6	98.2	101.7
7	6.0	118.8	---	116	102.8	---	102.3
7	12.0	133.6	---	117.6	109.5	---	95.4
8	0.0	113.7	115.8	---	89.4	90.1	---
8	6.0	114.8	---	---	93.6	---	---
9	0.0	113.2	11.4	104.4	91.5	88.5	79.5
9	6.0	111.5	102.2	100.6	84.3	77.1	75.2
9	12.0	114.6	---	112	90.7	---	81.8
10	0.0	110.4	111.8	101.6	88.7	90.7	73.1
10	6.0	109	---	118.9	79.9	---	73.8
10	12.0	111.6	---	108	74.9	---	78.5
11	0.0	113.6	120.7	93.6	91.7	99.1	80.7
11	6.0	114.7	113.8	112.5	88.6	89.4	89.7
12	0.0	113.1	107.2	100.4	90.5	88.9	84.9
12	6.0	116.1	---	104.6	92.7	---	81.9
13	0.0	111.4	103.1	103.3	91.2	77.8	97.6
13	6.0	117	120	110.3	89.4	93.2	86.9
14	0.0	138.8	137.2	120.4	128.6	125.5	118.6
14	6.0	126.9	106.2	112.6	99.8	84.4	89.4

Table B13
Summary of Field CBR Data and CBR Based on DCP Data

Section	Depth from Surface (in.)	CBR			DCP	
		Initial Data Nov 91	Initial Data May 92	After Traffic Data	Before Traffic Data	After Traffic Data
1	0.0	16	7	5	5.3	4.0
1	6.0	2.4	3.2	3.3	3.6	2.1
1	12.0	6	---	---	2.8	1.4
2	0.0	33	38	4.5	12.8	+
2	6.0	3.4	3.5	6.6	8.8	+
3	0.0	18	32	10	17.9	12.5
3	6.0	3	2.7	2.5	3.6	2.3
4	0.0	26	58	75	22.2	24.8
4	6.0	64	100	94	382	179.7
4	11.5	3.3	6	4.8	4.3	8.5
5	0.0	46	105.5	75	22.2	18.4
5	6.0	55	65	63	142.8	99.9
5	12.0	2.3	4	4.1	8.6	8.9
6	0.0	14	10	21.7	5.7	7.7
6	6.0	11	14	9	16.8	19.0
6	12.0	2.6	4.1	2	2.7	2.7
7	0.0	8	3.2	12	4.3	+
7	6.0	18	14	16	11.1	+
7	12.0	3.6	2.5	2.2	3.8	+
8	0.0	3.5	1.7	4	1.3	1.8
8	6.0	15	11	7	7.1	6.0
9	0.0	50	14	93	17.0	29.3
9	6.0	21	14	12	25.3	15.6
9	12.0	6	4.2	7	2.7	4.4
10	0.0	48	13	102	9.1	39.6
10	6.0	20	69	53	33.6	84.8
10	12.0	14	7	12	18.2	40.2
11	0.0	36	13	13	13.5	12.3
11	6.0	1.7	4.2	4.3	20.3	14.0
12	0.0	50	50	103	21.0	84.3
12	6.0	2.9	4.7	4.5	13.3	28.7
13	0.0	42	7	108	10.4	24.8
13	6.0	1.5	3.7	3.4	15.6	12.3
14	0.0	15	12	60	15.1	35.2
14	6.0	1.9	2.2	4.6	15.0	5.3


U.S. STANDARD SIEVE OPENING IN INCHES
U.S. STANDARD SIEVE NUMBERS
HYDROMETER
PERCENT FINER BY WEIGHT
PERCENT COARSER BY WEIGHT
GRAIN SIZE IN MILLIMETERS
COBBLES
GRAVEL
COARSE
FINE
SAND
COARSE
MEDIUM
FINE
SILT or CLAY
LL
NP
PL
PI
GS 2.67 EST
NAT W,%
ORG,%
CLASSIFICATION
SILTY SAND (SP-SM), TAN
PROJECT
BORING NO. LT. TAN SAND SAMPLE NO. 1
DEPTH/ELEV DATE 22 JUL 91
GRADATION CURVE
LABORATORY USAE WES - STF/GL


U.S. STANDARD SIEVE OPENING IN INCHES
U.S. STANDARD SIEVE NUMBERS
HYDROMETER
PERCENT FINER BY WEIGHT
PERCENT COARSER BY WEIGHT
GRAIN SIZE IN MILLIMETERS
COBBLES
GRAVEL
COARSE
FINE
SAND
COARSE
MEDIUM
FINE
SILT or CLAY
LL 56
PL 19
PI 37
GS
NAT W.%
ORG.%
PROJECT TESTING OF MTLS FOR CPAR PROJECT
BORING NO. BLK CLAY (CL
SAMPLE NO. 2
DEPTH/ELEV
DATE 08 OCT 91
CLASSIFICATION
SANDY CLAY (CH), GRAY
GRADATION CURVE
LABORATORY USAE WES - STF/GL



ASTM - 1557 compaction test

25 blows per each of 5 layers, with 10 (SLEEVE) lb rammer and

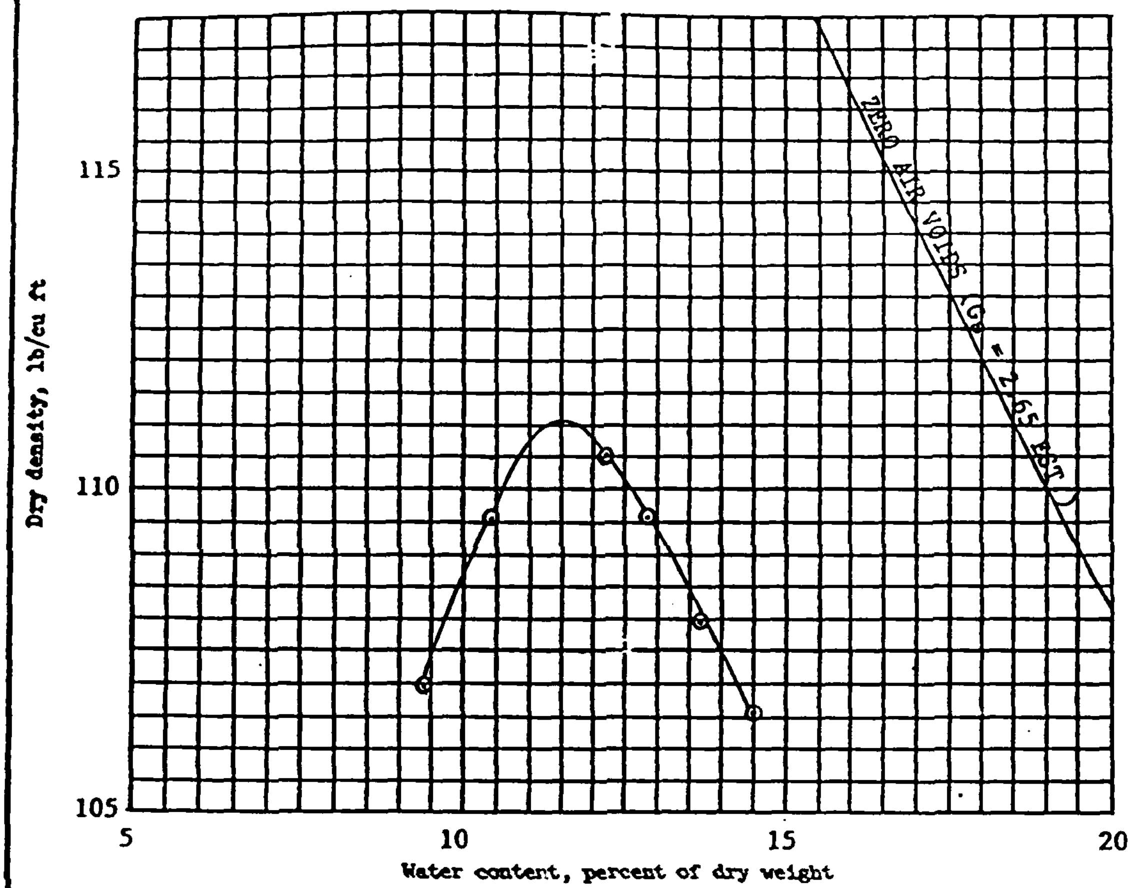
18 inch drop. 4 inch diameter mold

Sample No.	Elev or Depth	Classification	G	LL	PL	% > No. 4	% > 3/4 in.
1		SAND (SP-SM), TAN	2.65				
			EST.				

Sample No.				
Natural water content, percent				
Optimum water content, percent				
Max dry density, lb/cu ft				

Remarks	Project TESTING OF MLTS FOR CPAR PROJECTS
	Area
	Boring No. / Date 25 OCT. 1991
	COMPACTION TEST REPORT

ENG FORM 1 JUN 65 2091 PREVIOUS EDITIONS ARE OBSOLETE. (TRANSLUCENT)



ASTM - 1557 compaction test

25 blows per each of 5 layers, with 10 (SLEEVE) lb rammer and

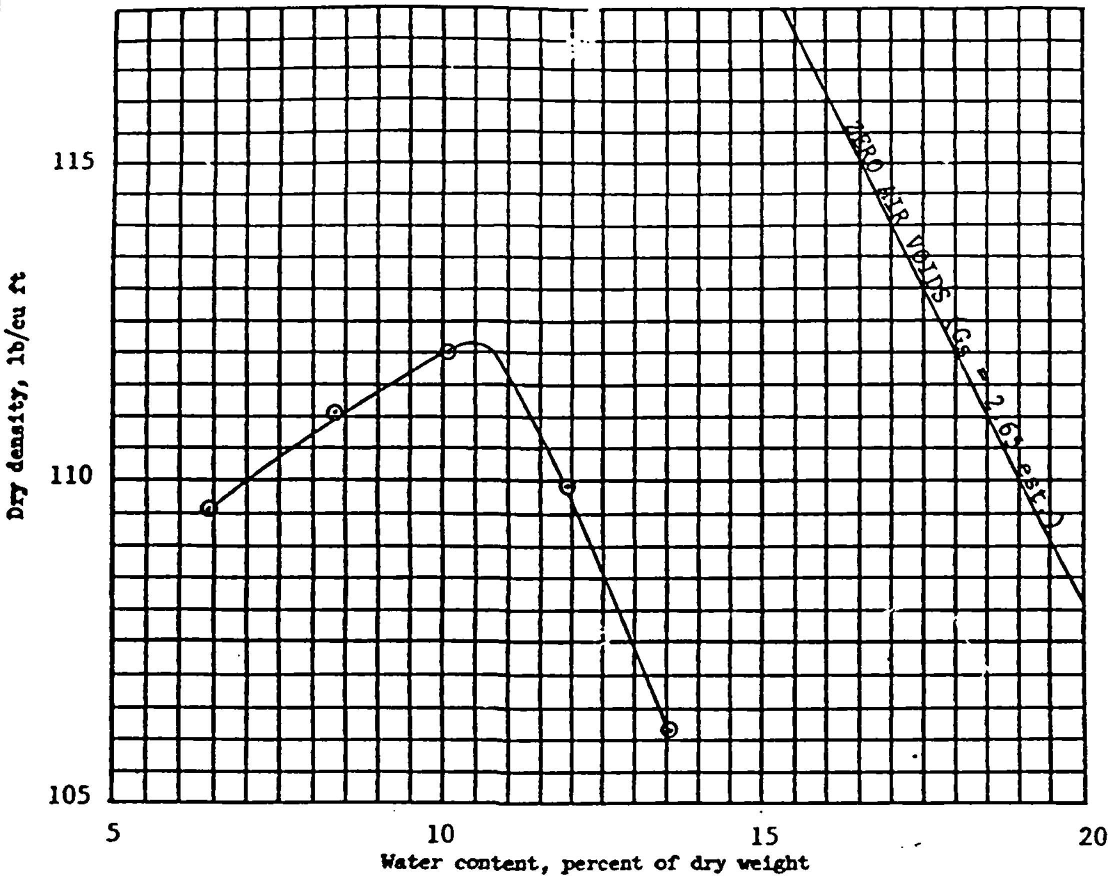
18 inch drop. 4 inch diameter mold

Sample No.	Elev or Depth	Classification	G	LL	PL	% > No. 4	% > 3/4 in.
1		SAND (SP-SM), TAN	2.65				
SAND CEMENT 5%			est.				

Sample No.				
Natural water content, percent				
Optimum water content, percent				
Max dry density, lb/cu ft				

Remarks	Project TESTING OF MTLS FOR CPAR PROJECT	
	Area	
	Boring No.	Date 25 OCT 91
	COMPACTION TEST REPORT	

ENG FORM 1 JUN 65 2091 PREVIOUS EDITIONS ARE OBSOLETE (TRANSLUCENT)



ASTM - 1557 compaction test

25 blows per each of 5 layers, with 10 (SLEEVE) lb rammer and

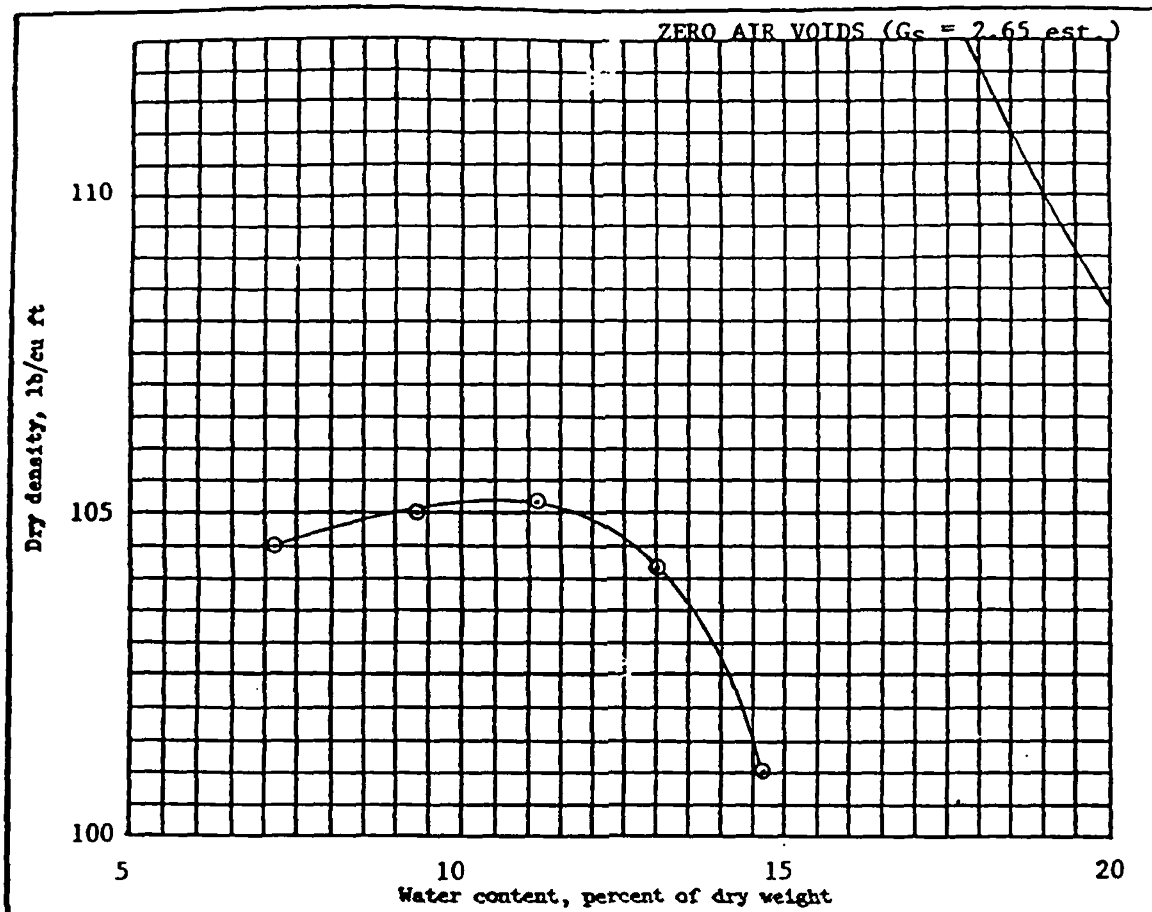
18 inch drop. 4 inch diameter mold

Sample No.	Elev or Depth	Classification	G	LL	PL	% > No. 4	% > 3/4 in.
1		SAND (SP-SM), TAN	2.65				
			(EST.)				

Sample No.				
Natural water content, percent				
Optimum water content, percent				
Max dry density, lb/cu ft				

Remarks	Project TESTING OF MLTS FOR CPAR PROJECTS	
SAND + .5% FIBER +		
5% CEMENT	Area	
	Boring No.	Date 2 MAR. 1992
	COMPACTION TEST REPORT	

ENG FORM 1 JUN 65 2091 PREVIOUS EDITIONS ARE OBSOLETE. (TRANSLUCENT)



ASTM - 1557 compaction test

25 blows per each of 5 layers, with 10 (SLEEVE) lb rammer and

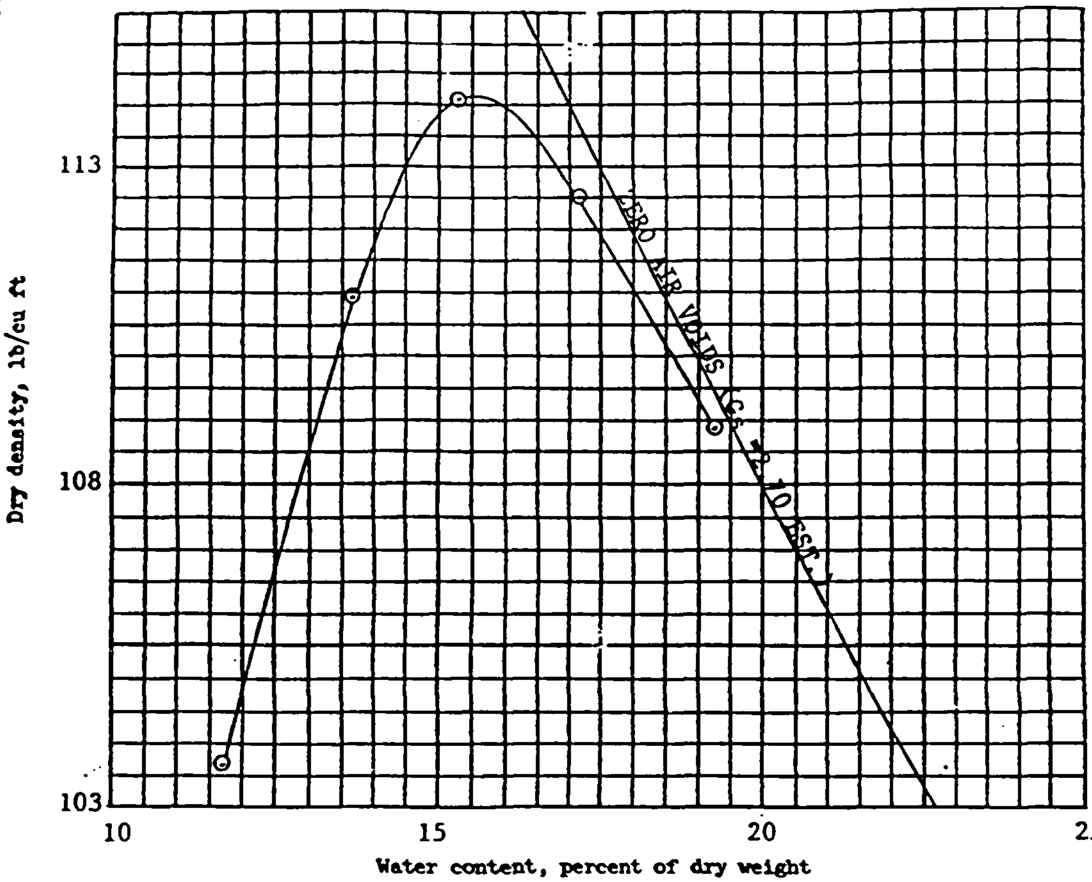
18 inch drop. 4 inch diameter mold

Sample No.	Elev or Depth	Classification	G	LL	PL	% > No. 4	% > 3/4 in.
1		SAND (SP-SM), TAN	2.65 (EST.)				

Sample No.				
Natural water content, percent				
Optimum water content, percent				
Max dry density, lb/cu ft				

Remarks	Project TESTING OF MLTS FOR CPAR PROJECTS	
SAND + .5% FIBER		
	Area	
	Boring No.	Date AR. 1992
	COMPACTION TEST REPORT	

ENG FORM 1 JUN 65 2091 PREVIOUS EDITIONS ARE OBSOLETE. (TRANSLUCENT)



ASTM - 1557 compaction test

25 blows per each of 5 layers, with 10 (SLEEVE) lb rammer and

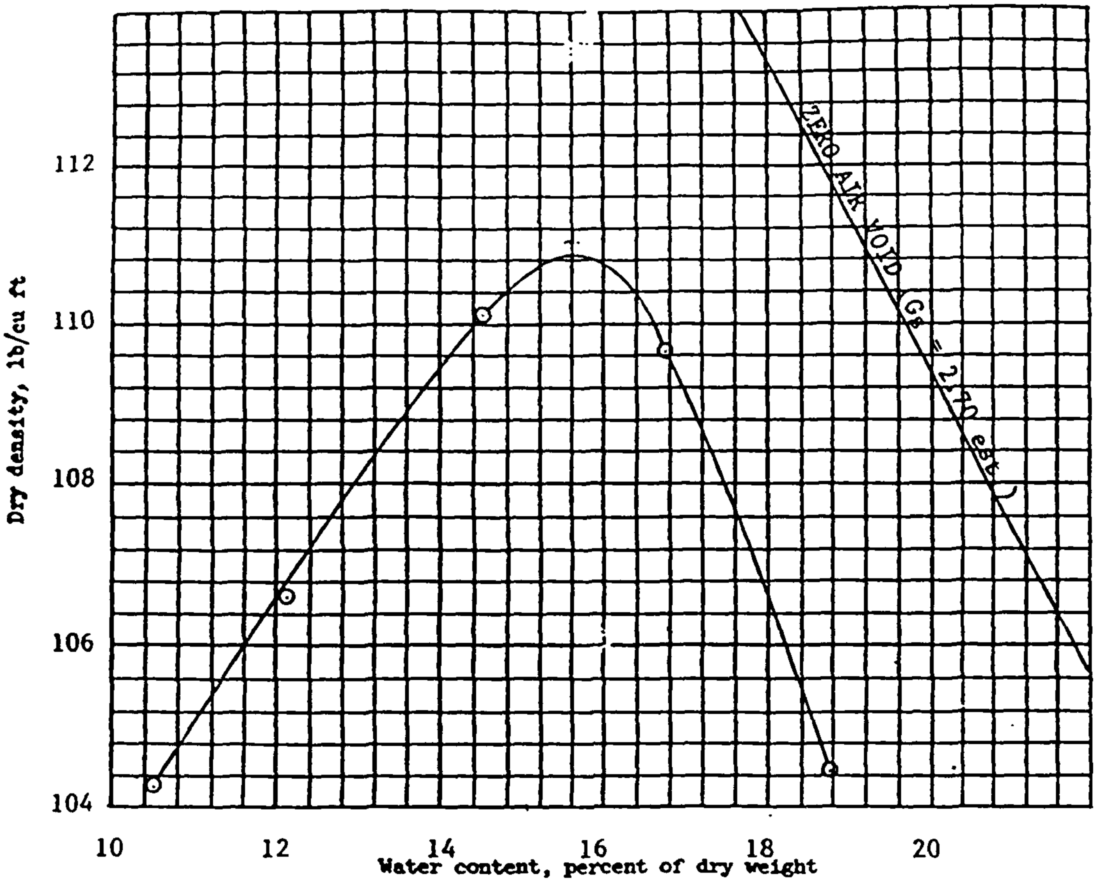
18 inch drop. 4 inch diameter mold

Sample No.	Elev or Depth	Classification	G	LL	PL	% > No. 4	% > 3/4 in.
2		CLAY (CH), BLACK	2.70 EST.				

Sample No.				
Natural water content, percent				
Optimum water content, percent				
Max dry density, lb/cu ft				

Remarks	Project TESTING OF MTLS FOR CPAR PROJECT	
	Area	
	Boring No.	Date 11 OCT. 1991
	COMPACTION TEST REPORT	

ENG FORM 1 JUN 65 2091 PREVIOUS EDITIONS ARE OBSOLETE. (TRANSLUCENT)



ASTM - 1557 compaction test

25 blows per each of 5 layers, with 10 lb rammer (SLEEVE) and

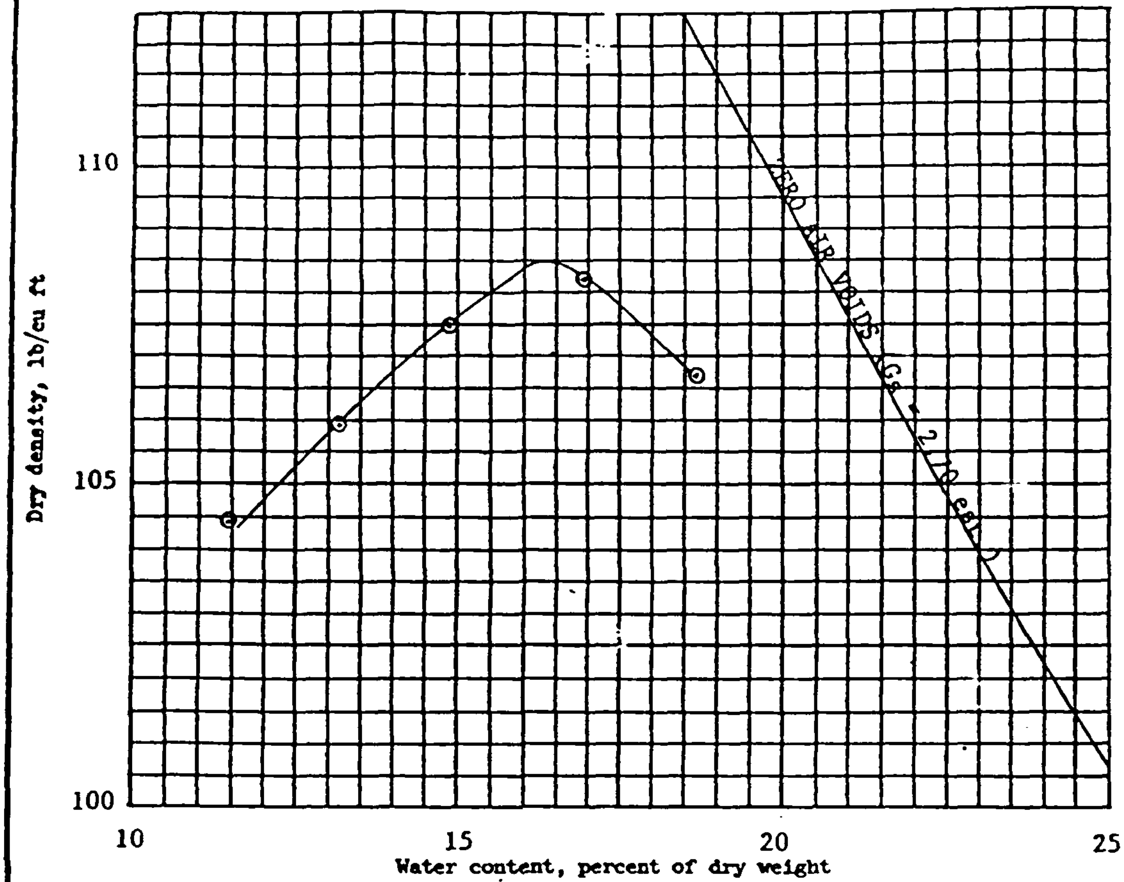
18 inch drop. 4 inch diameter mold

Sample No.	Elev or Depth	Classification	G	LL	PL	% > No. 4	% > 3/4 in.
2		CLAY (CH), BLACK	2.70				
BLACK	CLAY(CL)		EST.				
LIME 5%							

Sample No.				
Natural water content, percent				
Optimum water content, percent				
Max dry density, lb/cu ft				

Remarks	Project TESTING OF MTLS FOR CPAR PROJECT	
	Area	
	Boring No.	Date 21 OCT 1991
	COMPACTION TEST REPORT	

ENG FORM 1 JUN 65 2091 PREVIOUS EDITIONS ARE OBSOLETE. (TRANSLUCENT)



ASTM - 1557 compaction test

25 blows per each of 5 layers, with 10 (SLEEVE) lb rammer and

18 inch drop. 4 inch diameter mold

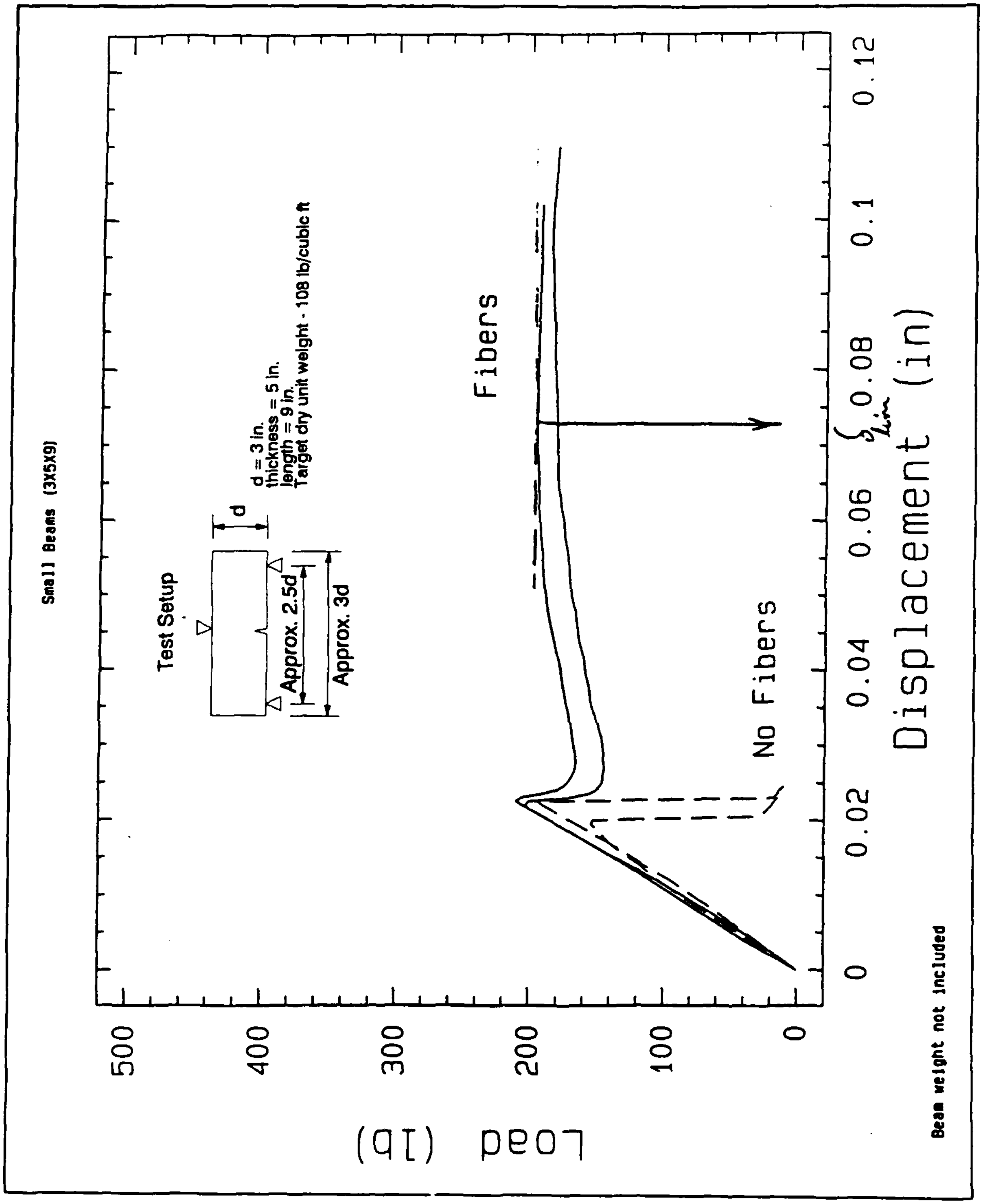
Sample No.	Elev or Depth	Classification	G	LL	PL	% > No. 4	% > 3/4 in.
2		CLAY (CH), BLACK	2.70 (EST.)				

Sample No.				
Natural water content, percent				
Optimum water content, percent				
Max dry density, lb/cu ft				

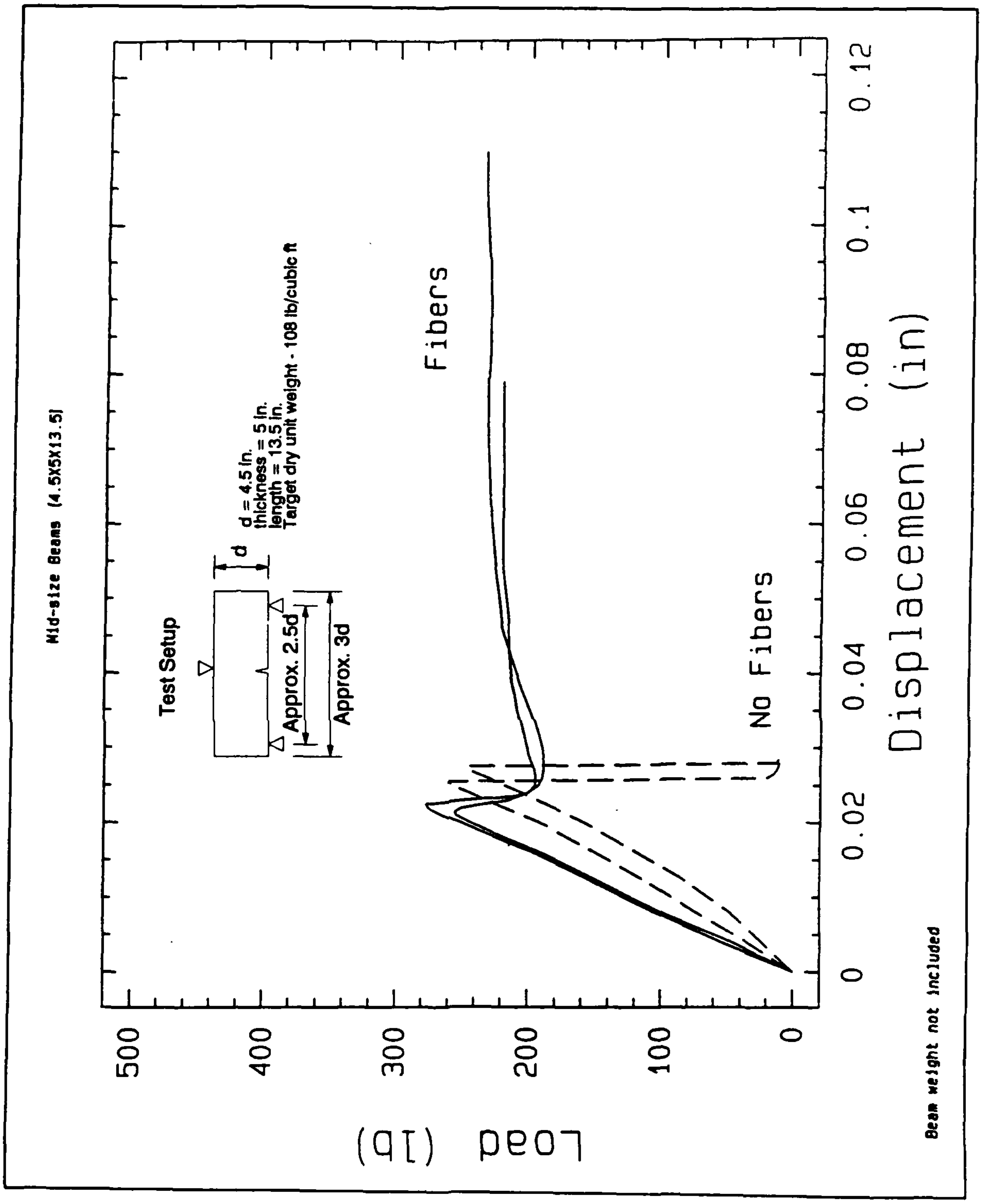
Remarks	Project TESTING OF MLTS FOR CPAR PROJECTS	
CLAY + .3% FIBER + 5% LIME		
	Area	
	Boring No.	Date 2 MAR. 1992
	COMPACTION TEST REPORT	

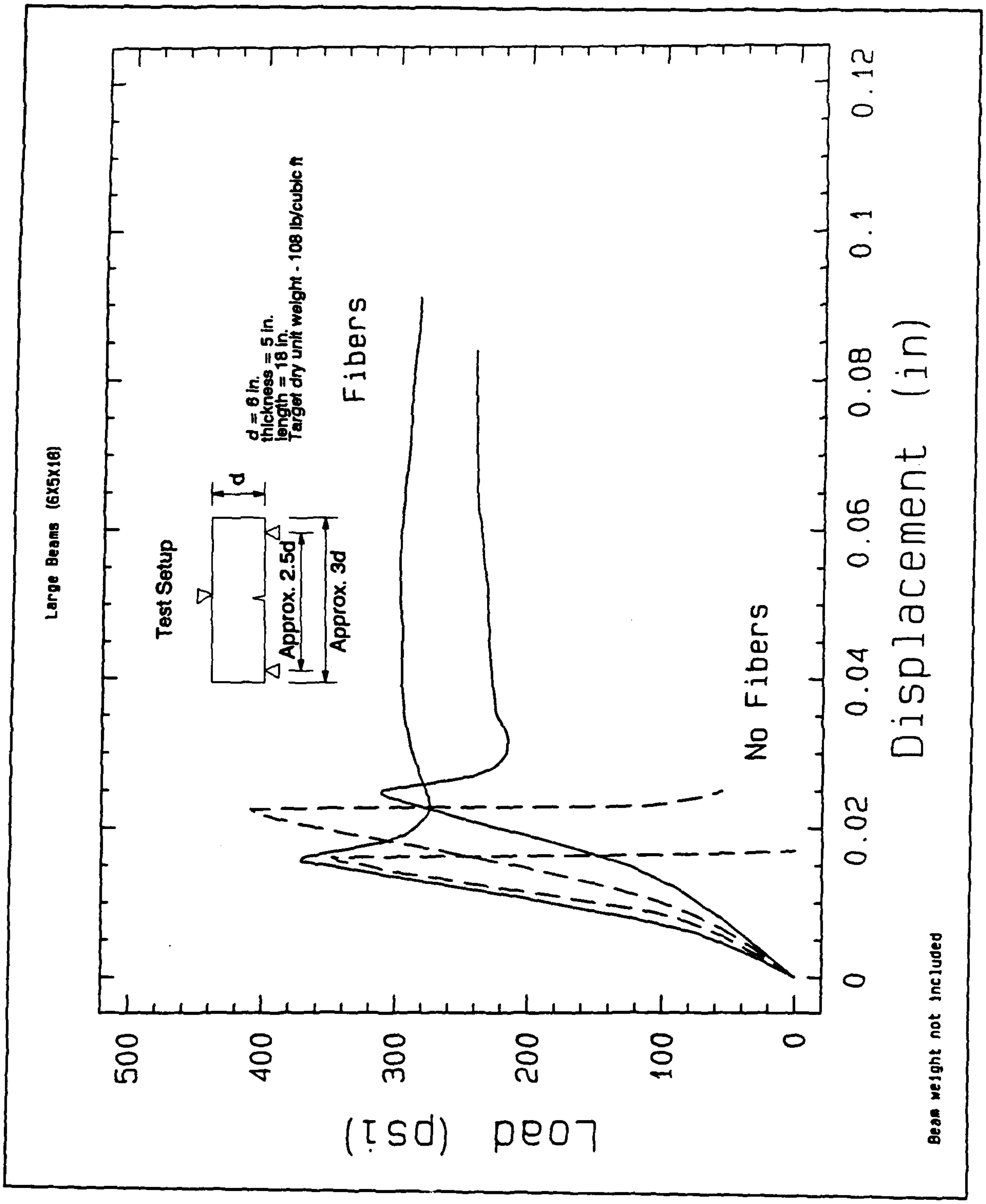
ENG FORM 1 JUN 65 2091 PREVIOUS EDITIONS ARE OBSOLETE (TRANSLUCENT)

Appendix C
Notched Beam Test Data (From Crockford 1993)



Small Beams (3X5X9)
Test Setup
d
Approx. 2.5d
Approx. 3d
d = 3 in.
thickness = 5 in.
length = 9 in.
Target dry unit weight - 108 lb/cubic ft
Fibers
No Fibers
δ_{lin}
Load (lb)
0
100
200
300
400
500
Displacement (in)
0
0.02
0.04
0.06
0.08
0.1
0.12
Beam weight not included


Mid-size Beams (4.5X5X13.5)
Test Setup
d
d = 4.5 in.
thickness = 5 in.
length = 13.5 in.
Target dry unit weight - 108 lb/cubic ft
Approx. 2.5d
Approx. 3d
Fibers
No Fibers
Load (lb)
Displacement (in)
0
100
200
300
400
500
0.02
0.04
0.06
0.08
0.1
0.12
Beam weight not included



Large Beams (6X5X18)
Test Setup
d
Approx. 2.5d
Approx. 3d
d = 6 in.
thickness = 5 in.
length = 18 in.
Target dry unit weight - 108 lb/cubic ft
Fibers
No Fibers
Load (psi)
0
100
200
300
400
500
Displacement (in)
0
0.02
0.04
0.06
0.08
0.1
0.12
Beam weight not included

Appendix D
Preliminary Guide Specifications

****
DEPARTMENT OF THE ARMY CEGS-XXXXX (May 1993)
U.S. ARMY CORPS OF ENGINEERS

PRELIMINARY GUIDE SPECIFICATIONS FOR MILITARY CONSTRUCTION
****

TABLE OF CONTENTS

SECTION ____

FIBER-STABILIZED SURFACE COURSE, BASE COURSE, SUBBASE OR SUBGRADE

-- End of Table of Contents --

****
DEPARTMENT OF THE ARMY CEGS-XXXXX (May 1993)

U.S. ARMY CORPS OF ENGINEERS
PRELIMINARY GUIDE SPECIFICATIONS FOR MILITARY CONSTRUCTION
****
SECTION ___

FIBER STABILIZED SURFACE COURSE, BASE COURSE, SUBBASE, OR SUBGRADE

****

NOTE: This guide specification is to be used in the preparation of project specifications in accordance with ER 1110-345-720.

****

PART 1 GENERAL

****

NOTE: See Additional Note A.

****

1.1 SUMMARY (Not Applicable)

****

NOTE: Paragraph "1.1 SUMMARY (Not Applicable)" is required in all CEGS in order to make CEGS compatible with guide specifications of other agencies within the SPECSINTACT system. However, this paragraph is not to be included in the Corps of Engineers project specifications.

****

1.2 REFERENCES

****

NOTE: Issue (date) of references included in project specifications need not be more current than provided by the latest change (Notice) to this guide specification.

****
The publications listed below form a part of this specification to the extent referenced. The publications are referred to in the text by basic designation only.

AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS (AASHTO)

\-M 92-\	(1985) Wire-Cloth Sieves for Testing Purposes
\-T 27-\	(1984) Sieve Analysis of Fine and Coarse Aggregates
\-T 88-\	(1986) Particle Size Analysis of Soils
\-T 89-\	(1987I) Determining the Liquid Limit of Soils
\-T 90-\	(1987I) Determining the Plastic Limit and Plasticity Index of Soils
\-T 135-\	(1976; Rev. 1986) Wetting-and-Drying Test of Compacted Soil-Cement Mixtures
\-T 180-\	(1986) Moisture-Density Relations of Soils Using a 10-Lb. [4.54 kg] Rammer and an 18-In. [457 mm] Drop
\-T 191-\	(1986) Density of Soil In-Place by the Sand-Cone Method
\-T 205-\	(1986) Density of Soil In-Place by the Rubber-Balloon Method
\-T 238-\	(1986) Density of Soil and Soil-Aggregate In-Place by Nuclear Methods (Shallow Depth)
\-T 239-\	(1986) Moisture Content of Soil and Soil-Aggregate In-Place by Nuclear Methods (Shallow Depth)

AMERICAN SOCIETY FOR TESTING AND MATERIALS (ASTM)

\-C 136-\	(1984) Sieve Analysis of Fine and Coarse Aggregate

\-C 150-\	(1989) Portland Cement
\-C 171-\	(1968; R 1986) Sheet Materials for Curing Concrete
\-D 422-\	(1963; R 1972) Particle-Size Analysis of Soils
\-D 558-\	(1982) Moisture-Density Relations of Soil-Cement Mixtures
\-D 559-\	(1982) Wetting-and-Drying Tests of Compacted Soil-Cement Mixtures
\-D 1241-\	(1968; R 1979) Materials for Soil-Aggregate Subbase, Base, and Surface Courses
\-D 1556-\	(1982) Density of Soil in Place by the Sand-Cone Method
\-D 1557-\	(1978) Moisture-Density Relations of Soils and Soil-Aggregate Mixtures Using 10-Lb. [4.54 kg] Rammer and 18-In. [457 mm] Drop
\-D 1632-\	(1987) Making and Curing Soil-Cement Compression and Flexure Test Specimens in the Laboratory
\-D 1633-\	(1984) Compressive Strength of Molded Soil-Cement Cylinders
\-D 2167-\	(1984) Density and Unit Weight of Soil In-Place by the Rubber Balloon Method
\-D 2922-\	(1981) Density of Soil and Soil-Aggregate In Place by Nuclear Methods (Shallow Depth)
\-D 3017-\	(1978) Moisture Content of Soil and Soil-Aggregate In Place by Nuclear Methods (Shallow Depth)
\-D 4318-\	(1984) Liquid Limit, Plastic Limit, and Plasticity Index of Soils
\-E 11-\	(1987) Wire-Cloth Sieves for Testing Purposes

1.3 MEASUREMENT FOR PAYMENT

****
NOTE: This paragraph will be deleted when lump-sum payment is desired.

Method of measurement not applicable to the job conditions will be deleted. If bituminous material is to be paid for separately, select the desired method of measurement. Paragraph "Select Material" will be deleted and reference to select material in article "Basis for Payment" will be deleted when select material is not required from borrow areas.
****

1.3.1 Composite Stabilization

Measurement will be by the square yard of work completed and accepted.

1.3.2 Fibers

Measurement of fibers will be by the number of [20 lb containers] [__ lb units] used in the construction of accepted work.

1.3.3 Chemical Additive (Lime or Cement)

****
NOTE: This paragraph will be deleted when the composite does not include chemical stabilization.
****

[Lime will be measured by the number of 2000-pound tons][Cement will be measured by the number of short hundred-weight (cwt) of cement] used in the completed and accepted work. No measurement will be made for wasted additive or additive used in work determined defective.

1.3.4 Bituminous Material

****
NOTE: This paragraph will be deleted when the composite does not include bituminous material
****

Bituminous material to be paid for will be measured in the number of [gallons of the material used in the accepted work, corrected to gallons at 60 degrees F in accordance with [ASTM D 633] [ASTM D 1250]. A coefficient of 0.00025 per degree F shall be used for asphalt emulsion] [2000-pound tons of the material used in the accepted work].

1.3.5 Select Material

Select material will be measured by the [cubic yard] [2000-pound ton] of material placed and used in the completed and accepted stabilization. No measurement will be made for select material that is wasted or used in work determined defective.

1.4 WAYBILLS AND DELIVERY TICKETS

****

NOTE: This paragraph will be deleted when lump-sum payment is desired.

****

Copies of waybills or delivery tickets shall be submitted during the progress of the work. Before the final payment is allowed waybills and certified delivery tickets shall be furnished for all [lime] [cement] [bituminous materials] [select materials] used in the construction.

1.5 BASIS FOR PAYMENT

****

NOTE: This paragraph will be deleted when lump-sum payment is desired.

Method of measurement not applicable to the job conditions will be deleted. If bituminous material is to be paid for separately, select the desired method of measurement.

****

Composite stabilization, constructed and accepted, including fibers [lime] [cement] [select material] will be paid for at the respective contract unit prices in the bidding schedule. No payment will be made for any material wasted, used for the convenience of the Contractor, unused or rejected, or for water used. [Select material obtained from grading and excavation operations at the project site will not be paid for under this section but will be included for payment under other sections specifying grading and excavating.] [No separate payment will be made for sanding or dusting the bituminous prime-coated surfaces, and all costs for sanding or dusting shall be included in the contract unit price for bituminous material.]

1.6 DEFINITIONS

1.6.1 Stabilized Composite Wearing Course, Base Course, Subbase, or Subgrade

Stabilized composite course, as used herein, is a mixture of fibers and in-place or select borrow material [with lime] [with cement] uniformly blended, wetted, and thoroughly compacted to produce a pavement [wearing course] [base course] [subbase] [subgrade] which meets all criteria as set forth in the plans and this specification.

1.6.2 Degree of Compaction

Degree of compaction required is expressed as a percentage of the maximum density obtained by the test procedure presented in [ASTM D 1557] [AASHTO T 180] Method D, referred to hereinafter as percent laboratory maximum density.

1.6.3 Percentage of Fibers

Percentage of fibers shall be expressed as the percentage by [weight of total weight mix] [volume of total volume mix] of fibrous material to be added to the in-place or select borrow material.

1.7 GENERAL

The work specified herein consists of the construction of a stabilized composite [wearing course] [base] [subbase] [subgrade] course. The work shall be performed in accordance with this specification and shall conform to the lines, grades, notes, and typical sections shown in the plans.

1.8 SUBMITTALS

****

NOTE: Submittals must be limited to those necessary for adequate quality control. The importance of an item in the project should be one of the primary factors in determining if a submittal for the item should be required.

****

The following shall be submitted in accordance with Section 01300 SUBMITTALS:

SD-11, Mix Designs (Contractor and Job)

****

NOTE: The designer should determine the compressive strength requirement based on the use of the final pavement.

Generally, a compressive strength of 150 psi is minimum. Designer should refer to TM's 5-822-4 and 5-825-2 for further guidance......
****

The Contractor shall develop and submit for approval a proposed mix design prior to stabilization work. Mix shall be developed using samples of the material to be stabilized. Mix design will be capable of producing a compressive strength of [___] [150] psi when compacted to the design percent of laboratory maximum density. Samples shall not show any significant loss of strength after 12 cycles of the durability test.

SD-64, Quality Assurance Plan

Tests shall provide a moisture-density relationship for the composite mixture. Tests shall be conducted in accordance with the standards specified in paragraph "Degree of Compaction."

SD-70, Test Reports

Sources of all materials shall be selected well in advance of the time that materials will be required in the work. Test results from samples shall be submitted for approval not less than [30] [___] days before material is required for the work.

Unconfined compression tests shall be conducted in accordance with ASTM D 1633. Three tests shall be conducted for each mix design tested. In addition to the requirements of ASTM D 1633, stress-strain curves shall be obtained for [one third] [_____] of the tests to at least 5% strain. Samples shall be cured at a constant moisture content and temperature for 28 days.

[Wet-dry tests shall be conducted in accordance with [AASHTO T 135] [ASTM D 559].] [Freeze-thaw tests shall be conducted in accordance with [AASHTO T 136] [ASTM D 560].] Three tests shall be conducted for each mix design tested. Scratch portion of the test shall be omitted.

Results of laboratory tests for quality control purposes shall be submitted to the Contracting Officer and approved prior to using the material.

Copies of field test results shall be submitted within [24] [___] hours after the tests are performed.

Calibration curves and related test results shall be submitted prior to using the device or equipment being calibrated.

Certified copies of manufacturer's test results indicating compliance of bituminous material with applicable specified requirements shall be submitted to the contracting Officer not less than [30] [___] days before the material is required in the work.

1.9 STOCKPILING MATERIALS

****

NOTE: This paragraph will be deleted when select material is not required or when small quantities do not justify the inclusion of select material.

****

Select material, including approved material available from excavation and grading, shall be stockpiled in the manner and at the locations designated. Before stockpiling material, storage sites shall be cleared and sloped to drain. Materials obtained from different sources shall be stockpiled separately.

1.10 PLANT, EQUIPMENT, MACHINES, AND TOOLS

1.10.1 General Requirements

Plant, equipment, machines, and tools used in the work shall be subject to approval and shall be maintained in satisfactory working condition at all times. Other compacting equipment may be used in lieu of that specified, where it can be demonstrated that the results are equivalent. The equipment shall be adequate and have the capability of producing the results specified. Protective equipment, apparel, and barriers shall be provided to protect the eyes, respiratory system, and the skin of workers exposed to contact with [lime] [cement] dust or slurry.

****

NOTE: Types of equipment specified but not required in this type of course will be deleted, and other items of equipment not listed will be added as appropriate.

****

1.10.2 Steel-Wheeled Rollers

Steel-wheeled rollers shall be the self-propelled type weighing not less than 10 tons, with a minimum weight of 300 pounds per inch-width of rear wheel. Wheels of the rollers shall be equipped with adjustable scrapers. The use of vibratory rollers is optional.

1.10.3 Pneumatic-Tired Rollers

Pneumatic-tired rollers shall have four or more tires, each loaded to a minimum of [   ] pounds and inflated to a minimum pressure of [   ] psi. The loading shall be equally distributed to all wheels, and the tires shall be uniformly inflated. Towing equipment shall also be pneumatic-tired.

1.10.4 Mechanical Spreader

Mechanical spreaders shall be self-propelled or attached to a propelling unit capable of moving the spreader and material truck. The device shall be steerable and shall have variable speeds forward and reverse. The spreader and propelling unit shall be carried on tracks, rubber tires, or drum-type steel rollers that will not disturb the underlying material. The spreader shall contain a hopper, an adjustable screed, and outboard bumper rolls and be designed to have a uniform, steady flow of material from the hopper. The spreader shall be capable of laying material without segregation across the full width of the lane to a uniform thickness and to a uniform loose density so that when compacted, the layer or layers shall conform to thickness and grade requirements indicated. The Contracting Officer may require a demonstration of the spreader prior to approving use in performance of the work.

1.10.5 Sprinkling Equipment

Sprinkling equipment shall consist of tank trucks, pressure distributors, or other approved equipment designed to apply controlled quantities of water uniformly over variable widths of surface.

1.10.6 Tampers

Tampers shall be of an approved mechanical type, operated by either pneumatic pressure or internal combustion, and shall have sufficient weight and striking power to produce the compaction required.

1.10.7 Mixers

Soil, fibers, water [and cement] [and lime] shall be mixed [in place] [in a central mixing plant and transported to the site]. The mixer used will be a [traveling mixing machine of the [flat-transverse-shaft type with a [single-shaft] [multiple-shaft]] [windrow-type pugmill]] [Central mixing plant of the [continuous-flow-type] [batch-type pugmill] [rotary drum mixer type]]. The soil shall be sufficiently pulverized and uniformly mixed with the specified amounts of fibers and water [and cement] [and lime].

1.10.8 Straightedge

The Contractor shall furnish and maintain at the site, in good condition, at least one [10-] [12-] foot straightedge for use in the testing of the finished surface. Straightedge shall be made available for Government use. Straightedges shall be constructed of aluminum or other lightweight metal and shall have blades of box or box-girder cross section with flat bottom reinforced to insure rigidity and accuracy. Straightedges shall have handles to facilitate movement on pavement.

1.11 WEATHER LIMITATIONS

Work on the course shall not be performed during freezing temperatures. When the temperature is below 40 degrees F, the completed course shall be protected against freezing by a sufficient covering of straw, or by other approved methods, until weather permits continuation of the work. If the composite contains a chemical additive, the completed portion shall be protected from rain after each day's work by covering of an impermeable membrane such as polypropylene sheeting or other suitable material. Any areas of completed course that are damaged by freezing, rainfall, or other weather conditions shall be brought to a satisfactory condition in conformance with this specification without additional cost to the Government. If the composite design contains chemical additives, construction shall not be conducted when the atmospheric temperature is less than 40 degrees F. Fibers [and chemical additives] shall not be added to soils that are frozen or contain frost, or when the underlying material is frozen.

PART 2 PRODUCTS

2.1 MATERIALS

2.1.1 Fibers

The individual fibers shall consist of discrete fibrillated polyolefin and shall be [__ mil diameter] [____ denier] fibers with a length of [1] [___] inch.

2.1.2 Lime

****

NOTE: This section shall be deleted if lime stabilization is not included in the composite.

Type of lime desired will be selected. The second term in brackets will be deleted when quicklime is specified, and the first term in brackets will be deleted when hydrated lime is specified.

****

Lime shall be a standard brand of [quicklime] [hydrated lime] conforming to the following physical and chemical requirements:

a. Lime shall be of such gradation that 99-1/2 percent passes a No. 20 sieve and a minimum of 85 percent passes a No. 100 sieve.

b. Combined calcium oxide and magnesium oxide shall be not less than [92 percent] [70 percent].

2.1.3 Cement

****
NOTE: This section shall be deleted if cement stabilization is not included in the composite.
****

Cement shall conform to [AASHTO M 85 or ASTM C 150, Type I, IA, II, or IIA] [AASHTO M 240 or ASTM C 595, Type IS or IS(A)].

2.1.4 Material to be Stabilized

****
NOTE: For base courses for airfield pavements delete requirements for in-place materials, traveling plant, and in-place mix method. Specify a select material conforming to AASHTO M 147 or ASTM D 1241 and central plant mixing method.
****

The material to be stabilized shall consist of [in-place material] [select material conforming to AASHTO M 147 or ASTM D 1241, Grading [B] [C] [or] [D]]. Stones retained on a 2-inch sieve and deleterious substances such as sticks, debris, and organic matter shall be removed. [When the in-place material consists primarily of soil having high plasticity, the course shall be constructed to produce fully hardened soil cement as determined by AASHTO T 135 and AASHTO T 136 or ASTM D 559 and ASTM D 560; not more than 45 percent of the material should be retained on the No. 4 sieve.]

2.1.5 Bituminous Material

****
NOTE: Asphalt of one grade or type will be specified.
****

Material shall conform to one of the following:

2.1.5.1 Cutback Asphalt

[AASHTO M 81] [AASHTO M 82] [ASTM D 2027] [ASTM D 2028], Grade {RC-250] [RC-800] [MC-250] [MC-800].

2.1.5.2 Emulsified Asphalt

[AASHTO M 140] [ASTM D 977], Type [RS-1] [RS-2].

2.1.6 Water

Water shall be clean, fresh, and free from injurious amounts of oil, acid, salt, alkali, organic matter, and other substances potentially deleterious to the composite, and shall be subject to approval.

2.2 SAMPLING AND TESTING

2.2.1 General Requirements

Sampling and testing shall be performed by an approved [commercial testing laboratory] [facility furnished by the contractor]. No work requiring testing shall be permitted until the facilities have been inspected and approved. The first inspection shall be at the expense of the Government. Cost incurred for any subsequent inspection required because of failure of the facilities to pass the first inspection will be charged to the Contractor. Tests shall be performed in sufficient numbers and as specified to insure that materials and compaction meet specified requirements.

2.2.2 Test Results

Results shall verify that materials comply with the specification. [When a material source is changed, the new material will be tested for compliance.] When deficiencies are found, the initial analysis shall be repeated and the material already placed shall be retested to determine the extent of unacceptable material. All in-place unacceptable material shall be replaced or repaired to conform to the contract requirements at no additional cost to the Government.

2.2.3 Samples

Specimens to be used for unconfined compression tests shall be prepared in accordance with ASTM D 1632 except that a 4-inch diameter by 8-inch high mold shall be used to prepare specimens when more than 35 percent of the material is retained on the No. 4 sieve.

2.2.4 Initial Sampling and Testing

2.2.4.1 Sieve Analysis

****

NOTE: Delete reference to source of material when select material is not required.

****

A minimum of one sieve analysis shall be performed for each [1000] [____] tons of material to be stabilized, with a minimum of three analyses for each day's run until the course is completed. When [the source of materials is changed [and][or]] deficiencies are found, the analysis shall be repeated and the material already placed shall be retested to determine the extent of unacceptable material. All in-place unacceptable material shall be replaced at no additional cost to the Government.

2.2.4.2 Liquid Limit and Plasticity Index

One liquid limit and plasticity index shall be performed for each sieve analysis. Liquid limit and plasticity index shall be in accordance with AASHTO T 89 and AASHTO T 90 or ASTM D 4318.

2.2.4.3 Laboratory Density

Moisture-density tests shall be conducted in accordance with the procedure contained in AASHTO T 134 or ASTM D 558; however the apparatus and procedures outlined in Methods A or D, depending on gradation of the mix, of AASHTO T 180 or ASTM D 1557 shall be used to compact the soil-cement mixture.

2.2.4.4 Unconfined Compression Testing

Unconfined compression tests shall be conducted in accordance with ASTM D 1633. Three tests shall be conducted for each mix design tested. Samples shall be cured at a constant design moisture content and a constant temperature for 7 days.

2.2.4.5 Durability Tests

****

NOTE: Where the soil aggregate mixture is an approved select material conforming to AASHTO M 147 or ASTM D 1241, Grading B, C, or D, the use of the test procedures conforming to AASHTO T 135 and AASHTO T 136 or ASTM D 559 and ASTM D 560 may be waived.

****

[Wet-dry tests shall be conducted in accordance with AASHTO T 135 or ASTM D 559.] [Freeze-thaw tests shall be conducted in accordance with AASHTO T 136 or ASTM D 560.] Three tests shall be conducted for each mix design tested.

2.2.5 Sampling and Testing During Construction

Quality control sampling and testing during construction shall be performed as required in paragraph "FIELD QUALITY CONTROL."

PART 3 EXECUTION

3.1 GENERAL REQUIREMENTS

After mixing is completed, the proportions of the mixture shall be in accordance with the approved mix design. When application of water and mixing are completed, on the basis of dry weight, moisture shall not be below the optimum moisture content of the mixture nor shall it be more than 2 percent above the optimum moisture content. When the stabilized course is constructed in more than one layer, the previously constructed layer shall be cleaned of loose and foreign matter by sweeping with power sweepers or power brooms, except that hand brooms may be used in areas where power cleaning is not practicable. Adequate drainage shall be provided during the entire construction period to prevent water from collecting or standing on the areas to be stabilized or on pulverized, mixed, or partially mixed material. Line and grade stakes shall be provided as necessary for control. Grade stakes shall be placed in lines parallel to the centerline of the area under construction and suitably spaced for string lining.

3.2 OPERATION OF BORROW PITS

****

NOTE: Paragraph will be deleted when select material is not required or when small quantities do not justify the inclusion of select material.

****

[Borrow pits shall be cleared, stripped and excavated to working depth in a manner that produces excavation faces that are as nearly vertical as practicable for the materials being excavated. Strata of unsuitable materials overlying or occurring in the deposit shall be wasted. Methods of operating the pits and the processing and blending of the materials may be changed or modified if necessary to obtain material conforming to the specified requirements. Upon completion of the work, pits shall be conditioned to drain readily.] [Borrow material shall be obtained from approved off-site sources.]

3.3 PREPARATION OF AREA TO BE STABILIZED

****

NOTE: Inapplicable paragraph will be deleted.

****

3.3.1 General Requirements

Area shall be cleaned of debris. It shall be tested for adequate compaction and shall be capable of withstanding without displacement the compaction specified for the stabilized mixture.

Debris and removed unsatisfactory in-place material shall be disposed of as specified.

3.3.2 In-Place Material to be Stabilized

The entire area shall be graded and shaped to conform to the lines, grades, and cross sections shown in the plans prior to being processed. Soft or yielding areas shall be made stable before construction is begun.

3.3.3 In-Place Materials to Receive Stabilized Course

****
NOTE: If this paragraph is retained, inapplicable portions will be deleted.
****

[Soft, yielding areas and ruts or other irregularities in the surface shall be corrected. Material in the affected areas shall be loosened and unsatisfactory material removed. Approved select material shall be added where directed. The area shall then be shaped to line, grade, and cross section, and shall be compacted to the specified density.] [Subgrade shall conform to Section 02230 EXCAVATION, EMBANKMENT, AND PREPARATION OF SUBGRADE.] [Subbase course shall conform to Section [02232 SELECT-MATERIAL SUBBASE COURSE] [02234 SUBBASE COURSE].]

3.3.4 Select Material

****
NOTE: Delete if select material is not required.
****

Sufficient select material shall be utilized to provide the required thickness of the composite layer after compaction and shall be processed to meet the requirements specified before stabilization is undertaken.

3.3.5 Grade Control

Underlying material shall be excavated to sufficient depth for the required stabilized-course thickness so that the finished stabilized course with the subsequent surface course will meet the fixed grade. Finished and completed stabilized area shall conform to the lines, grades, cross section, and dimensions indicated.

3.4 INSTALLATION

3.4.1 Mixed-In-Place Method

3.4.1.1 Scarifying and Pulverizing of Soil

Prior to application of fibers [and lime] [and cement] the soil shall be scarified and pulverized [to the depth shown] [to a depth of [____] inches]. Scarification shall be carefully controlled so that the layer beneath the layer to be treated is not disturbed. Depth of pulverizing shall not exceed the depth of scarification.

3.4.1.2 Application of Additives

Pulverized material shall be shaped to approximately the cross section indicated. Fibers [and lime] [and cement] shall be applied so that when uniformly mixed with the soil, the specified fiber [and lime] [and cement] content is obtained, and a sufficient quantity of treated soil is produced to construct a compacted composite course conforming to the lines, grades, and cross section indicated. If fibers [[and] [or] lime] [[and] [or] cement] is spread by hand, the bundled raw materials shall be spotted accurately on the area being stabilized so that the material is spread uniformly on the area being processed. No equipment except that used in spreading and mixing shall pass over the freshly applied fibers [and lime] [and cement].

3.4.1.3 Mixing

Immediately after the fibers [and lime] [and cement] have been distributed, mixing shall commence. Mixing shall be sufficient to alleviate any dusting or wetting of the additives that might occur in the event of wind or rainstorms.

3.4.1.4 Water Application and Moist Mixing

Moisture content of the mixture will be determined in preparation for final mixing. Moisture in the mixture following final mixing shall not be less than the water content determined to be optimum based on dry weight of soil and shall not exceed the optimum water content by more than [2] [___] percentage points. Water may be added in increments as large as the equipment will permit; however, such increment of water shall be partially incorporated in the mix to avoid concentration of water near the surface. After the last increment of water has been added, mixing shall be continued until the water is uniformly distributed throughout the full depth of the mixture. Particular care shall be taken to ensure satisfactory moisture distribution along the edges of the section.

3.4.2 Edges of the Stabilized Course

Approved material shall be placed along the edges of the stabilized course in such quantity as will compact to the thickness of the course being constructed, or to the thickness of each layer in a multiple-layer course, allowing at least a 1 foot width of the shoulder to be rolled and compacted simultaneously with the rolling and compacting of each layer of the stabilized course.

3.4.3 Central-Plant Method

****

NOTE: Central plant will be specified for mixing select material for subbase or base course construction.

****

Plant shall be capable of producing a uniform fiber [and lime] [and cement] treated mixture at the specified additive percentages and moisture content. Mixture shall be hauled to the job in trucks equipped with protective covers. Underlying course shall be thoroughly moistened and the mixture then placed on the prepared area in a uniform layer with mechanical spreaders. The layer shall be uniform in thickness and surface contour and in such quantity that the completed layer will conform to the required grade and cross section.

3.4.4 Traveling-Plant Method

****

NOTE: Traveling plant will be specified for mixing in-place material for subbase and base course construction.

****

Traveling plant shall move at a uniform rate of speed and shall accomplish thorough mixing of the materials in ____ passes. Water and fibers [and lime] [and cement] shall be delivered from supply trucks or bins at a predetermined rate. Windrows of prepared mixture shall be of sufficient size to cover a predetermined width to the indicated compacted thickness.

3.4.5 Layer Thickness

Compacted thickness of the stabilized course shall be [as indicated] [______ inches]. No layer shall be more than 8 inches or less than 3 inches in compacted thickness.

3.4.6 Compaction

****
NOTE: Density will be based on the material being stabilized.
****

Before compaction operations are started and as a continuation of the mixing operation, the mixture shall be thoroughly loosened and pulverized to the full depth. Compaction shall be started immediately after mixing is completed. During final compaction, the surface shall be moistened, if necessary, and shaped to the required lines, grades, and cross section. Density of compacted mixture shall be at least [90] [___] percent of laboratory maximum density. Rolling shall begin at the outside edge of the surface and proceed to the center, overlapping on successive trips at least one-half the width of the roller. Alternate trips of the roller shall be slightly different lengths. The speed of the roller at all times shall be such that displacement of the mixture does not occur. Areas inaccessible to the rollers shall be compacted with mechanical tampers, and shall be shaped and finished by hand methods.

3.4.7 Finishing

The surface of the top layer shall be finished to the grade and cross section shown. The surface shall be of uniform texture. Light blading during rolling may be necessary for the finished surface to conform to the lines, grades, and cross sections. Should the surface for any reason become rough, corrugated, uneven in texture, or traffic-marked prior to completion, such unsatisfactory portions shall be scarified, relaid, or replaced as directed. Should any portion of the course, when laid, become watersoaked for any reason, that portion shall be removed immediately, and the mix placed in a windrow and aerated until a moisture content within the limits specified is obtained, and then spread, shaped, and rolled as specified above.

3.4.8 Curing and Protection

****
NOTE: It may be advantageous to specify that the bituminous seal coat be placed immediately after final finishing for curing purposes. In this case, the first sentence in the paragraph will be modified accordingly. This specification section must be coordinated with other sections covering the various components of the pavement structure.
****

Immediately after the soil composite area has been finished as specified above, the surface shall be protected against rapid drying for 7 days [by one of the methods specified below].

3.4.8.1 Moist Curing

The area shall be moistened by sprinkling and shall be kept moist for the 7-day curing period.

3.4.8.2 Bituminous Material

****

NOTE: The application temperatures will be selected from the following table and inserted in the blanks:

	Degrees F
Cutback asphalt:	
RC-250, MC-250	145-220
RC-800, MC-800	180-255
Emulsified asphalt:	
RS-1	75-130
RS-2	110-160

****

Bituminous material shall be uniformly applied by means of a bituminous distributor within a temperature range of [____] degrees F to [____] degrees F. Bituminous material shall be applied in quantities of not less than 0.1 gallon per square yard nor more than 0.25 gallon per square yard. Areas inaccessible to or missed by the distributor shall be properly treated using the manually operated hose attachment. Bituminous material shall be applied only to the top layer. At the time the bituminous material is applied, the surface of the area shall be free of loose or foreign matter and shall contain sufficient moisture to prevent excessive penetration of the bituminous material. When necessary, the area shall be sprinkled with water immediately before the bituminous material is applied. [Treated surface shall be sanded or dusted to prevent the bituminous material from being picked up by traffic.]

3.4.9 Construction Joints

At the end of each day's construction, a straight transverse construction joint shall be formed by cutting back into the completed work to form a vertical face.

Composite treatment for large, wide areas shall be built in a series of parallel lanes of convenient length [not more than ___ feet nor less than ___ feet] and width [not more than ___ feet nor less than ___ feet]. Straight longitudinal joints shall be formed at the edge of each day's construction by cutting back into the completed construction to form a vertical face free of loose or shattered material.

3.5 FIELD QUALITY CONTROL

3.5.1 General

Results of field quality control testing shall verify that materials comply with this specification. [When a material source is changed, the new material shall be tested for compliance.] When deficiencies are found, the initial analysis shall be repeated and the material already placed shall be retested to determine the extent of unacceptable material. All in-place unacceptable material shall be replaced or repaired, as directed by the Contracting Officer, at no additional cost to the Government.

3.5.2 Thickness Control

****

NOTE: When applied courses are constructed less than 6 inches in total thickness, a deficiency of 1/2 inch in thickness is considered excessive. Applicable to job conditions, thickness tolerance provisions may be modified as required, restricting all deficiencies to not over 1/4 inch.

****

Completed thicknesses of the stabilized course shall be within 1/2 inch of the thickness indicated. Where the measured thickness of the stabilized course is more than 1/2 inch deficient, such areas shall be corrected by scarifying, adding mixture of proper gradation, reblading, and recompacting as directed. Where the measured thickness of the stabilized course is more than 1/2 inch thicker than indicated, it shall be considered as conforming to the specified thickness requirement. Average job thickness shall be the average of all thickness measurements taken for the job, but shall be within 1/4 inch of the thickness indicated. Thickness of the stabilized course shall be measured at intervals in such a manner as to ensure one measurement for each [500] [____] square yards of stabilized course. Measurements shall be made in 3-inch diameter test holes penetrating the stabilized course.

3.5.3 Field Density

Field in-place density shall be determined in accordance with [ASTM D 1556] [ASTM D 2167] [ASTM D 2922] [AASHTO T 191] [AASHTO T 205] [AASHTO T 238]. [When [ASTM D 2922] [AASHTO T 238] is used, the calibration curves shall be checked, and adjusted if necessary, using the sand cone method as described in paragraph "Calibration" of the [ASTM] [AASHTO] publication.] [ASTM D 2922] [AASHTO T 238] results in a wet unit weight of soil and when using this method, [ASTM D 3017] [AASHTO T 239] shall be used to determine the moisture content of the soil. The calibration curves furnished with the moisture gauges shall be checked along with density calibration checks as described in [ASTM D 3017] [AASHTO T 238]. If [AASHTO T 238] [ASTM D 2922] is used, in-place densities shall be checked by [AASHTO T 191] [ASTM D 1556] at least once per lift for each [___] square yards of stabilized material. Calibration curves and calibration tests results shall be furnished to the Contracting Officer within 24 hours of conclusion of the tests. At least one field density test shall be performed for each [250] [___] square yards of each layer of base material.

3.5.4 Smoothness Test

****

NOTE: For subgrade and subbase stabilization, this paragraph should be deleted.

****

The surface of a stabilized layer shall show no deviations in excess of 3/8 inch when tested with the [10-] [12-] foot straightedge. Deviations exceeding this amount shall be corrected by removing material and replacing with new material, or by reworking existing material and compacting, as directed. Measurements for deviation from grade and cross section shown shall be taken in successive positions parallel to the road centerline with a [10-] [12-] foot straightedge. Measurements shall also be taken perpendicular to the road centerline at [50-] [___] foot intervals.

3.6 TRAFFIC

Completed portions of the treated soil area may be opened immediately to light traffic provided the curing is not impaired. After the curing period has elapsed, completed areas may be opened to all traffic, provided the stabilized course has hardened sufficiently to prevent marring or distorting of the surface by equipment or traffic. Heavy equipment shall not be permitted on the area during the curing period. Lime and water may be hauled over the completed area with pneumatic-tired equipment if approved. Finished portions of composite-stabilized soil that are traveled by construction equipment, shall be protected in a manner to prevent equipment from marring or damaging completed work.

3.7 MAINTENANCE

Stabilized area shall be maintained in a satisfactory condition until the completed work is accepted. Maintenance shall include immediate repairs of any defects and shall be repeated as often as necessary to keep the area intact. Defects shall be corrected as specified herein.

3.8 DISPOSAL OF UNSATISFACTORY MATERIALS

Removed materials that are unsuitable for stabilization shall be disposed of [as directed] [in waste disposal areas indicated].

****

ADDITIONAL NOTES

NOTE A: For additional information on the use of all CEGS, see CEGS-01000 CEGS GENERAL NOTES.

****

-- End of Section --

REPORT DOCUMENTATION PAGE

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Stabilization of High Plasticity Clay and Silty Sand by Inclusion of Discrete Fibrillated Polypropylene Fibers for Use in Pavement Subgrades

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13. ABSTRACT *(Maximum 200 words)*

The U.S. Army Engineer Waterways Experiment Station (WES) and Synthetic Industries, Chattanooga, TN, in a joint research effort investigated the advantages of adding discrete fibrillated polypropylene fibers to a silty sand and a high plasticity clay for enhancement of engineering properties. The investigation centered on the use of the materials in pavement layers; however, other applications such as slope stabilization have been successfully completed by Synthetic Industries. Various combinations of fibers with raw soils and chemically stabilized soils were placed in test track sections and subjected to trafficking of a single-axle dual-wheel vehicle. Progressive damage due to trafficking was monitored, and various field and laboratory tests were conducted to determine performance of the test sections. Performance of fiber-reinforced sections was determined based on comparison with the performance of sections without fiber added.

The trafficking tests showed a definite improvement in strength and durability for the soil materials with fiber added. Uniaxial laboratory tests also reflected improvement in modulus, peak strength, and strain energy density with addition of fibers.

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