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Contingency Airfield Construction: Mechanical Stabilization Using Monofilament and Fibrillated Fibers

by Randy C. Ahlrich, Lee E. Tidwell
Geotechnical Laboratory

Prepared for U.S. Air Force Wright Laboratory

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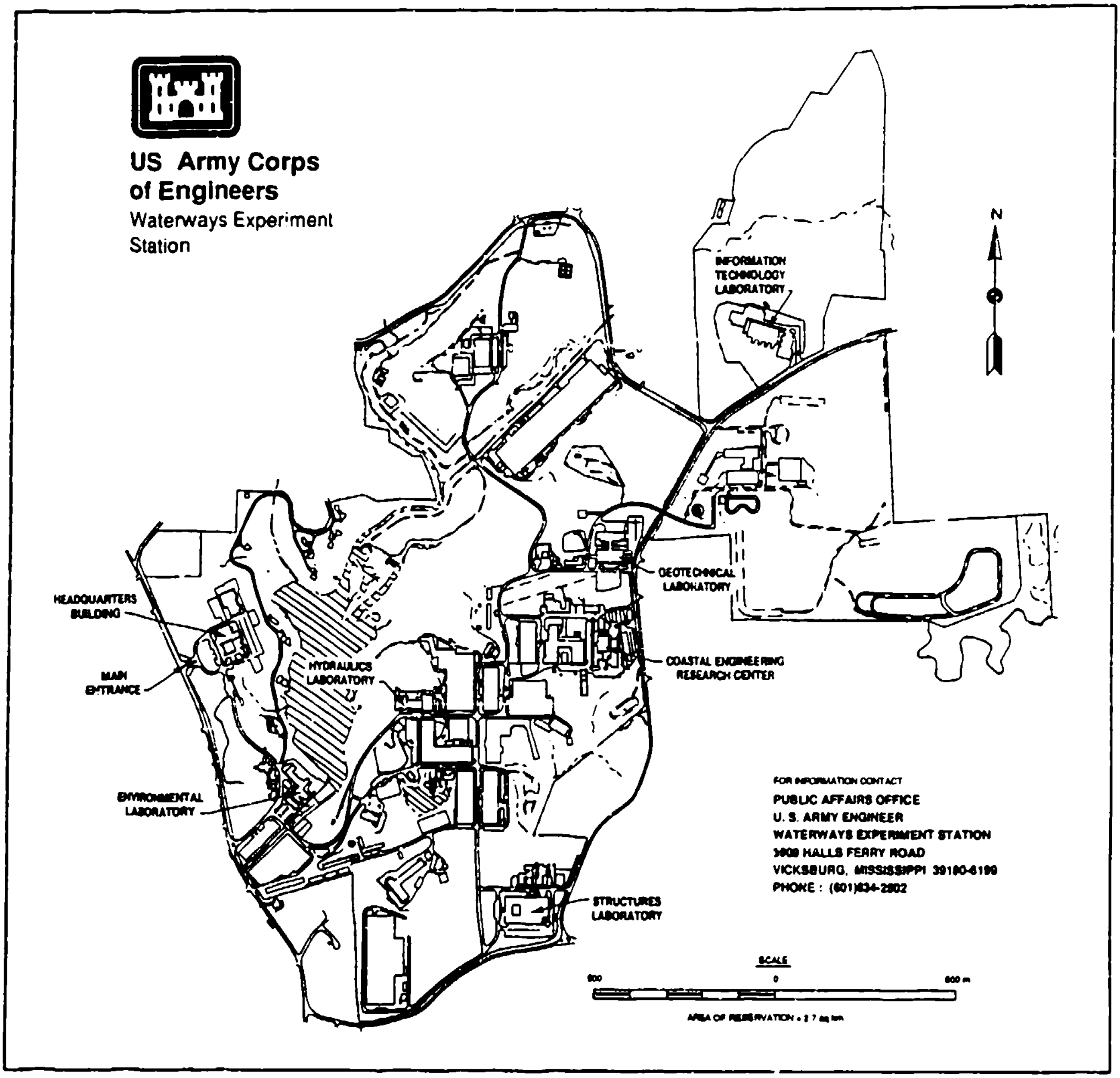

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Preface

The investigation documented in this report was sponsored by the U.S. Air Force Wright Laboratory, Flight Dynamics Directorate, Airbase Systems Branch, Tyndall AFB, Florida. The work was conducted under Military Interdepartmental Purchase Request Number 93-12, Project "Rapid Airfield Stabilization." Technical Monitors for this study were CPT Chris Foreman and Mr. James Murfee, WL/FIVCO, Tyndall AFB, Florida.

This study was conducted by personnel of the Pavement Systems Division (PSD) and the Soil and Rock Mechanics Division (SRMD), Geotechnical Laboratory (GL) at the U.S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi, from October 1992 through September 1993. Mr. Randy C. Ahlrich and Ms. Lee E. Tidwell were the Principal Investigators and authors of the report. PSD and SRMD personnel engaged in the laboratory testing included Messrs. Bill Burke, Charles Carter, Perrin Griffing, Herbert McKnight, and Joey Simmons.

This study was conducted under the general supervision of Dr. W. F. Marcuson III, Director, GL. Direct supervision was provided by Dr. G. M. Hammitt II, Chief, PSD, and Mr. T. W. Vollor, Chief, Materials Research and Construction Technology Branch.

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

Conversion Factors, Non-SI to SI Units of Measurement

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

Multiply	By	To Obtain
inches	2.54	centimeters
pounds (force) per square inch	6.894757	kilopascals
pounds (mass) per cubic foot	16.01846	kilograms per cubic meter

1 Introduction

Background

Contingency airfields constructed by military engineers generally fall into one of three categories: unsurfaced airstrips, landing mat surfaced airfields, or chemically stabilized soil airstrips without surfacing. Bare soil airstrips require the least construction effort but the in situ soil strength may vary considerably with varying material types and moisture contents. Landing mat airfields are easy to construct and offer maximum all-weather structural support but the weight and volume involved in transporting the matting is extremely large and the cost of the matting is comparatively high. Chemically stabilized airstrips are inexpensive from a material standpoint and they are durable but the construction effort involved is time consuming and labor intensive. There is a need for a soil stabilization technology that is low cost, easily transportable, can be rapidly installed, and can maintain structural stability for long periods of time. Mechanical stabilization systems which can be intermixed into a soil mass to provide increased soil strength and long-term stability appear to offer high potential.

Objective

The objective of this research study is to evaluate monofilament and fibrillated fibers for the mechanical stabilization of low-strength soils and to provide guidance on fiber type, length, and dosage rate to produce stabilized soils for contingency airfield construction.

Scope

The scope of this research study included a review of available literature and existing data, a two-phase laboratory study on laboratory-produced samples, and an analysis of the data. The soil materials used in the laboratory evaluation included a high plasticity clay (CH) and a beach sand (SP). Each soil was tested according to MIL STD 621A, Method 100 (Department of Defense 1964), to determine the optimum moisture content and maximum dry density using the CE 55 compactive effort. CBR strength values were also determined for each soil type using MIL STD 621A, Method 101. The clay and sand materials were then stabilized with monofilament and fibrillated polypropylene fibers of various lengths (0.5, 1.0, and 2.0 in.) and dosages (0.5, 1.0, 2.0 percent by weight). These stabilized soils were compacted and evaluated with the Corps of Engineers Gyratory Testing Machine (GTM) to determine gyratory shear strength properties. The stabilized soils that indicated an increase in gyratory shear strength were also evaluated with the laboratory CBR procedure (MIL STD 621A, Method 101) to determine the as-molded (unsoaked) and soaked CBR strength values.

2 Literature Review

Several searches of literature were conducted through the WES Information Technology Laboratory (ITL). Approximately 500 literature summaries were reviewed that discussed the use of geosynthetics in pavement design. Articles that provided "state-of-the-art" or otherwise noteworthy information were acquired by the WES library. The literature findings reported will be limited to those describing the use of geofibers for subgrade reinforcement and pavement design.

Description of Geofibers

Geofibers come in three forms: filaments, staple fibers, and slit films. A continuous filament has infinite length and is produced by extruding melted polymer through dies or spinnerets. After extrusion, the filament is usually stretched to longitudinally orient its molecules, resulting in greater tensile strength. Two or more filaments may be aligned to form a multifilament yarn. Staple fibers are made by cutting filaments in lengths of 1 to 4 in. A spun yarn is made by interlacing and twisting together staple fibers. Slit film fibers are generally cut from extruded sheets and then drawn. A fibrillated yarn is a slit film fiber which has been partially slit to produce a series of still-connected fibers, and then twisted (Dass 1992).

Research Studies using Geofibers

Numerous studies have been conducted to investigate the benefits of fiber-reinforced soil. A summary of several studies is discussed below:

WES and Synthetic Industries (Grogan and Johnson 1993) conducted a joint research study under the Construction Productivity Advancement Research (CPAR) Program to evaluate discrete fibrillated polypropylene fibers as a stabilizing additive in pavement layers. This study involved constructing and trafficking a fiber-reinforced test strip at College Station, Texas. The objective of this research study was to determine if the fibers could be adequately mixed into the in situ soils and to evaluate the structural benefits of fibers when added to a silty sand, a lime-stabilized CH clay, and a cement-stabilized sand.

The fibers used in these test sections were nominally 1-in. long discrete fibrillated polypropylene fibers mixed at dosage rates between 0.0 and 0.5 percent by weight. The sand-based sections were constructed and evaluated using four methods; fiber stabilized, cement stabilized, fiber and cement stabilized, and no treatment. The CH clay sections were constructed and evaluated using three methods; lime stabilized, fiber and lime stabilized, and no treatment.

The test results showed that the addition of these fibers in both the lime stabilized clay and cement stabilized sand improved the strength and durability of the field test sections. The fibers slowed the rutting process during trafficking tests and reduced the effects of cracking in the chemically stabilized materials. The sand material stabilized with 0.5 percent fibers and 5 percent cement increased the amount of traffic to failure by 60 percent in the 6-in. thick section when compared with the sand section without fibers. The clay material stabilized with 0.3 percent fibers and 5 percent lime increased the amount of traffic to failure by 90 percent in the 6-in. thick section when compared with the clay section with 5 percent lime.

A fiber-reinforced test strip was constructed at WES in 1991 as a part of the Rapid Airfield Stabilization Project to determine the feasibility of mixing discrete fibrillated polypropylene fibers into in situ soils using field mixing equipment (rotary mixer) and to evaluate the effect of different fiber lengths on mixing consistency. A high-plasticity clay (CH) was used with a water content of 29 percent and a fiber content of 0.5 percent. This was considered a "worst case condition" for mixing fibers with a CH soil. The discrete fibrillated polypropylene fibers were successfully blended into the stiff clay and the shorter fibers (1 in.) were better distributed into the CH clay material. The shorter fibers (1 in.) were mixed and distributed more consistently into the CH clay than the longer fibers (2 in. and 4 in.) (Brabston 1991).

A research study was conducted by Fletcher and Humphries (1991) to determine the effect of blending discrete polypropylene fibers with a cohesive material on CBR values. The soil evaluated was a residual silt (ML) derived from the in-place weathering of rock (gneiss). The fiber tested was a 50-denier monofilament polypropylene cut to lengths of 1 in. The fiber dosage rates tested were 0.5, 1.0, and 1.5 percent by weight of the dry soil. The moisture-density relationship showed that an increase in fiber dosage caused a modest increase in maximum dry density as well as a slight decrease in optimum moisture content. The test results showed that the CBR values of the micaceous silt were significantly enhanced by the addition of fibers. There was a 133 percent increase in CBR values using a 50 denier, 1-in. long monofilament fiber at a dosage rate of 1.0 percent (Fletcher and Humphries 1991).

A study was conducted by Gray to determine the response of sands reinforced with discrete, randomly distributed fibers. Laboratory triaxial compression, resonant column, and torsional shear tests were used to measure the stress-deformation response and to observe the influence of various fiber properties, soil properties, and other test variables on constitutive behavior. Randomly distributed fiber inclusions significantly increased the ultimate strength and stiffness of sands under the action of static loads in triaxial compression tests. The increase in strength and stiffness was a function of sand granulometry (i.e., gradation, particle size, and shape) and fiber properties (e.g., weight fraction, aspect ratio, and modulus). The following observations were found from the study (Gray 1988):

a. The failure surface in a triaxial compression test of randomly distributed, fiber-reinforced sand is planar and oriented in the same manner as predicted by the Coulomb theory. This finding suggests an isotropic reinforcing action with no development of preferred planes of weakness or strength.

b. The failure envelopes in the tests were either curved-linear or bilinear with the transition or break occurring at a confining stress denoted as the "critical confining stress."

c. An increase in fiber aspect ratio, L/D, resulted in a lower critical confining stress and more effective fiber contribution to increased shear strength.

d. An increase in fiber amount had no effect on the critical confining stress, but it did influence strength significantly.

e. Shear strength increases approximately linearly with increasing amounts of fiber and then approaches an asymptotic upper limit that is governed mainly by confining stress and fiber aspect ratio.

f. Very low modulus fibers (e.g., rubber) contribute little to increased strength in spite of superior pullout resistance.

g. An increase in the soils coefficient of uniformity, Cu, resulted in a lower critical confining pressure, and higher fiber contribution to strength (all other factors constant).

h. An increase in particle sphericity resulted in a higher critical confining stress, and lower fiber contribution to strength (all other factors constant).

i. An increase in soil grain size, D_{50}, had no effect on critical confining stress, however, it reduced the fiber contribution strength (all other factors constant).

Al-Refeai (1991) conducted a laboratory study to evaluate the effects of adding glass fibers to a fine dune sand with subrounded particles and a medium wadi sand with subangular particles. The principal objective of this study was to investigate the load-deformation behavior of the two types of sands reinforced with randomly oriented fiber inclusions. Triaxial tests at various confining pressures were performed on the modified sand specimens with fiber lengths of 0.5 in. to 4 in. and dosage rates ranging from 0.3 percent to 2 percent by weight.

The test results indicated that short fibers required a greater confining stress to prevent bond failure for both sand types. The authors stated that longer fibers had a greater effect on the two types of sands because the load could be fully mobilized along the length of the reinforcement. A fiber length of 3 in. was found to be the optimum in maximizing the strength and stiffness of the two fiber-reinforced sands. This study showed that fine sand with subrounded particles showed a better response to fiber reinforcement than the medium wadi sand with subangular particles (Al-Refeai 1991).

In France, the Texsol process has been used extensively for soil reinforcement (Leflaive 1986). The Texsol process is produced by blowing soil, usually sand, through a pneumatic system and simultaneously projecting numerous continuous yarns. The flow of soil and yarn must have adequate relative movements to produce an appropriate distribution of yarn in the soil. The geofibers used in the Texsol process are multiple continuous threads that are added at rates of 0.1 to 0.2 percent by weight. Specially designed equipment is used to produce Texsol and this process is patented by the French Bridges and Roads Research Laboratory (LCPC).

Triaxial tests performed on Texsol samples show that the measured angle of internal friction of Texsol is higher than that of the original material and that an additional apparent cohesion exists due to the fiber. A conservative figure for this cohesive property is 14.5 psi for 0.1 percent of fiber. Another significant feature of Texsol is that its strain at failure is about twice that of sand (Khay, Gigan, and Ledelliou 1990). In structures where the hydraulic properties are important, it is noted that the permeability of Texsol is the same as the permeability of the soil material, since the yarn only occupies about 1/100 of the volume of the voids of the soil. The yarn entanglement may improve the hydraulic internal stability of the soil if used as a filter.

3 Laboratory Study

General

The purpose of this laboratory study was to determine the effects of monofilament and fibrillated fibers on the stability of low strength soils. Laboratory tests were conducted on both the natural soil materials and the mechanically stabilized materials to determine the influence of the stabilizing fibers. The main focus of this laboratory study was to determine the change in strength of stabilized soils when evaluated with the Corps of Engineers Gyratory Testing Machine and the laboratory CBR test.

Materials

Two types of fibers (monofilament and fibrillated) and two types of soils (a high plasticity clay and a beach sand) were selected for use in this study. The monofilament fibers were 50 denier (0.08-mm) polypropylene fibers cut in lengths of 0.5, 1.0, and 2.0 in. The fibrillated fibers were 1000 denier (0.21-mm) polypropylene fibers cut in lengths of 0.5, 1.0, and 2.0 in. Both fibers had a specific gravity of 0.91 and are shown in Figures 1 and 2.

The basic soil classification properties, sieve analysis and Atterburg limits, were tested according to American Society for Testing and Materials (ASTM) 1993a, 1993b, and 1993c. The test results for the high plasticity clay and the beach sand are shown in Figures 3 and 4, respectively.

Moisture-Density Relationship of Natural Materials

The moisture-density relationships of the high plasticity clay and the beach sand were determined according to MIL STD 621A, Method 100, (Department of Defense 1964), using the CE55 compactive effort. The moisture-density test results for the high plasticity clay are shown in Figure 5. The optimum moisture content was 15.3 percent with a maximum dry density of 112.2 pcf. The moisture-density test results for the beach sand are shown in Figure 6. The optimum moisture content was 9.1 percent with a maximum dry density of 101.5 pcf.

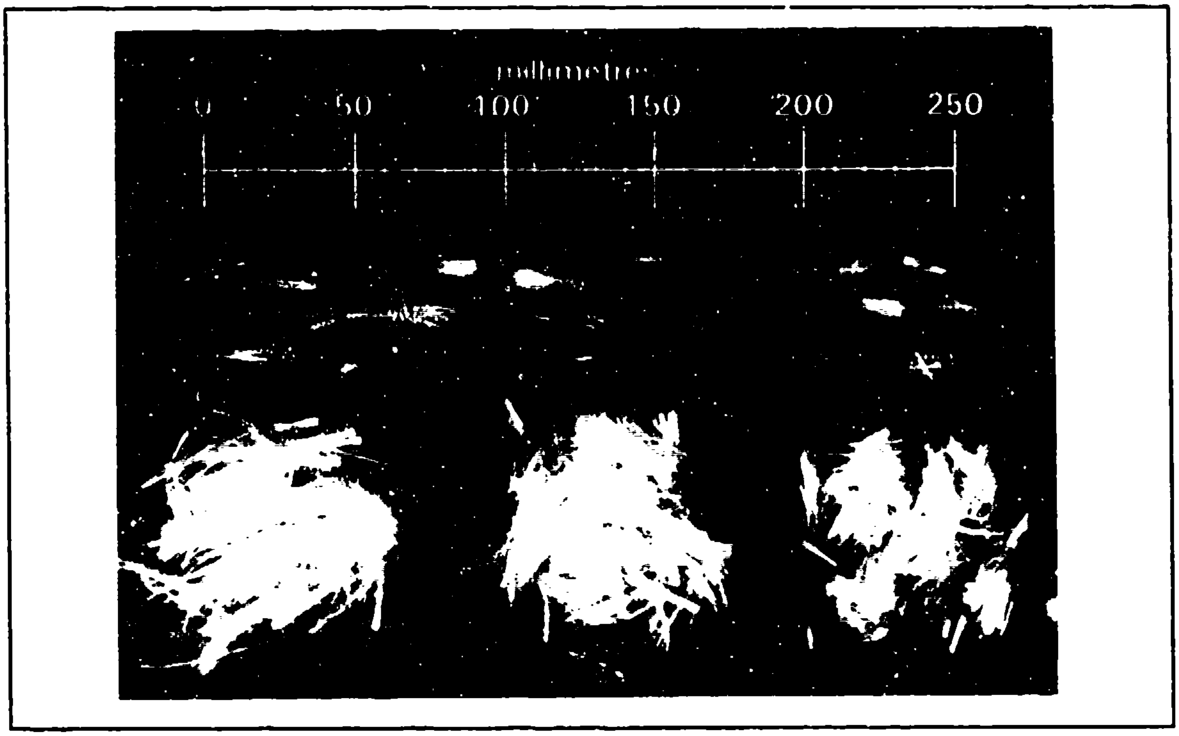

Figure 1. Monofilament fibers

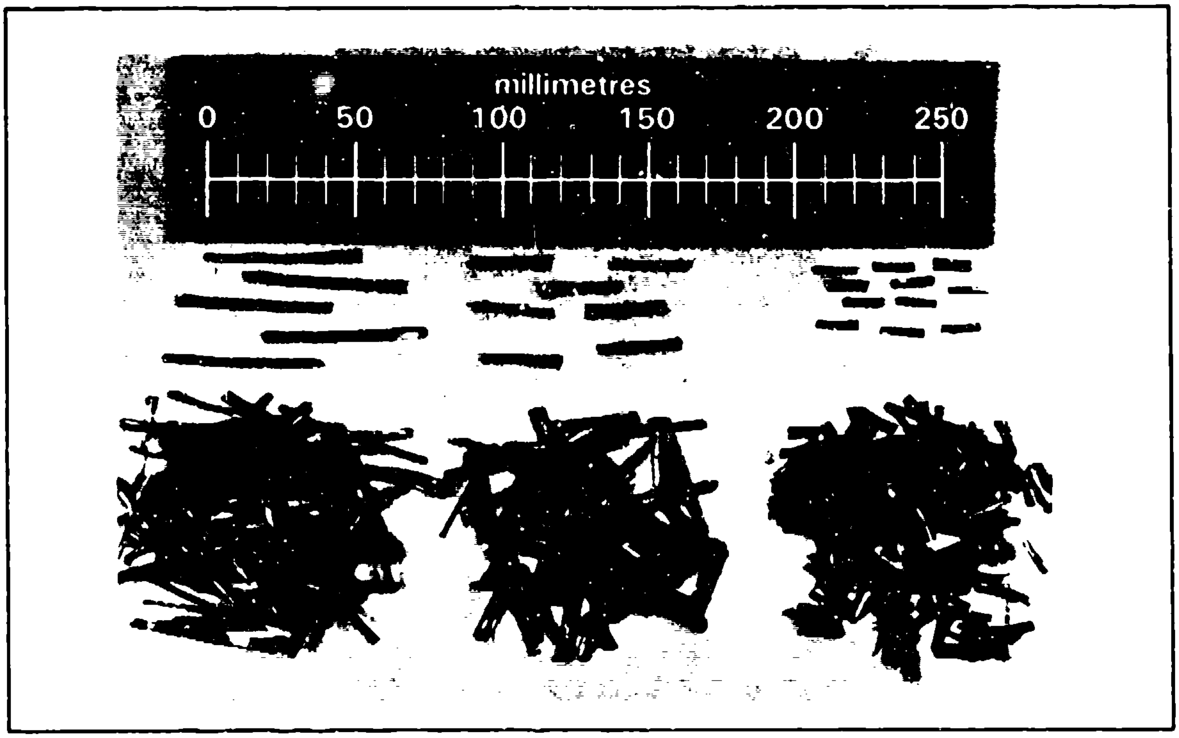

Figure 2. Fibrillated fibers

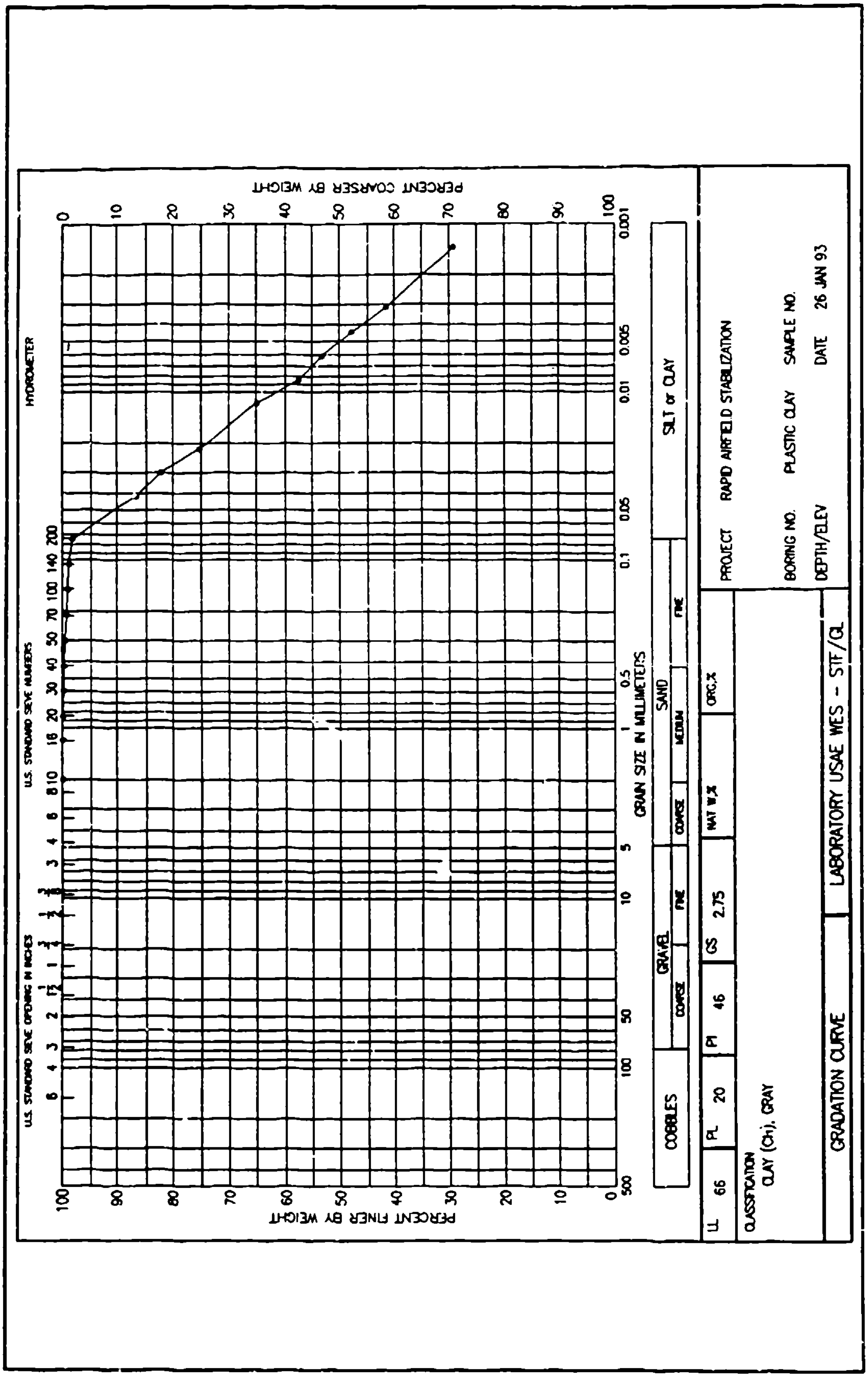

Figure 3. Sieve analysis and Atterberg limits for high plasticity clay (CH)

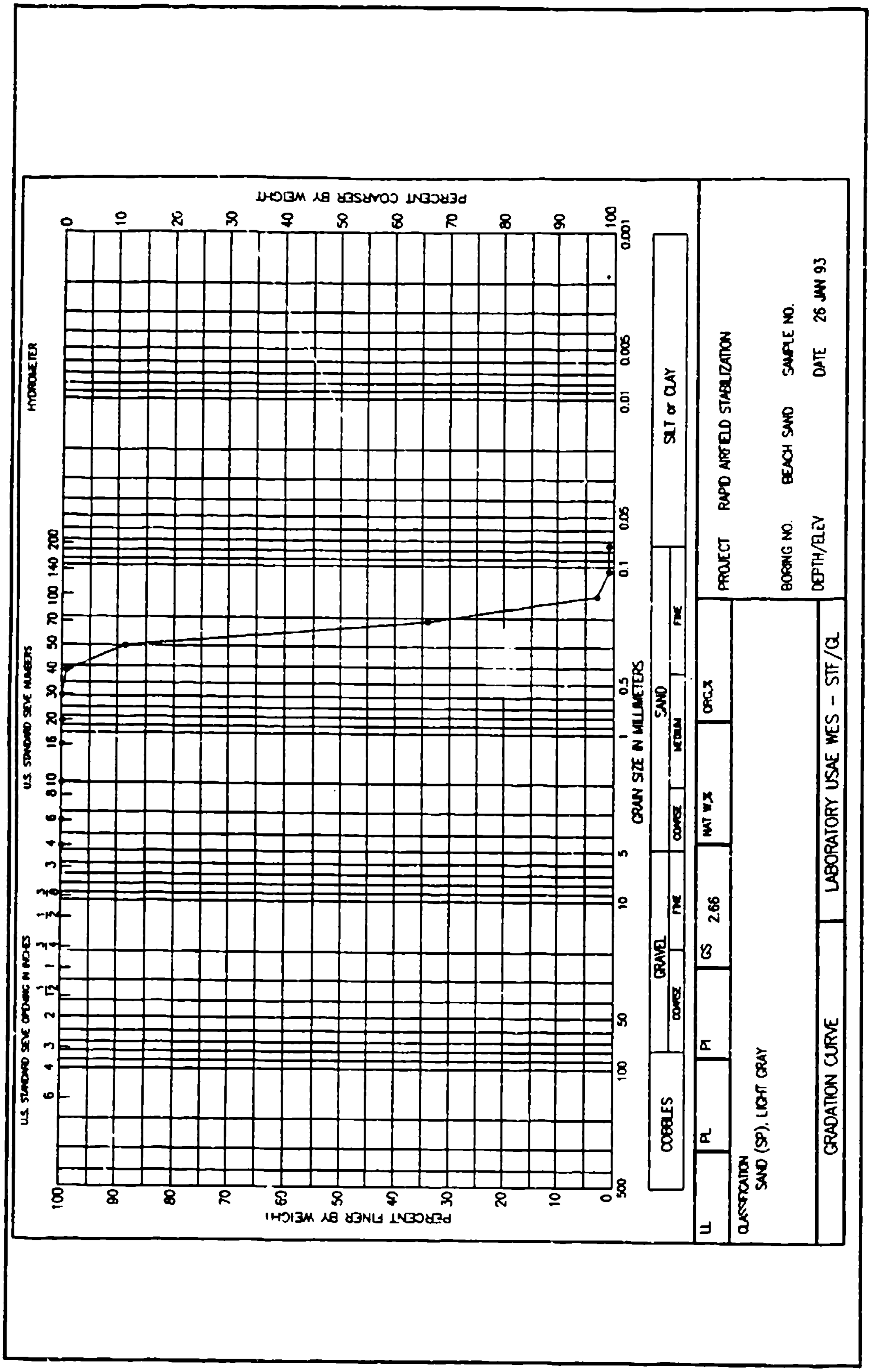

Figure 4. Sieve analysis for beach sand

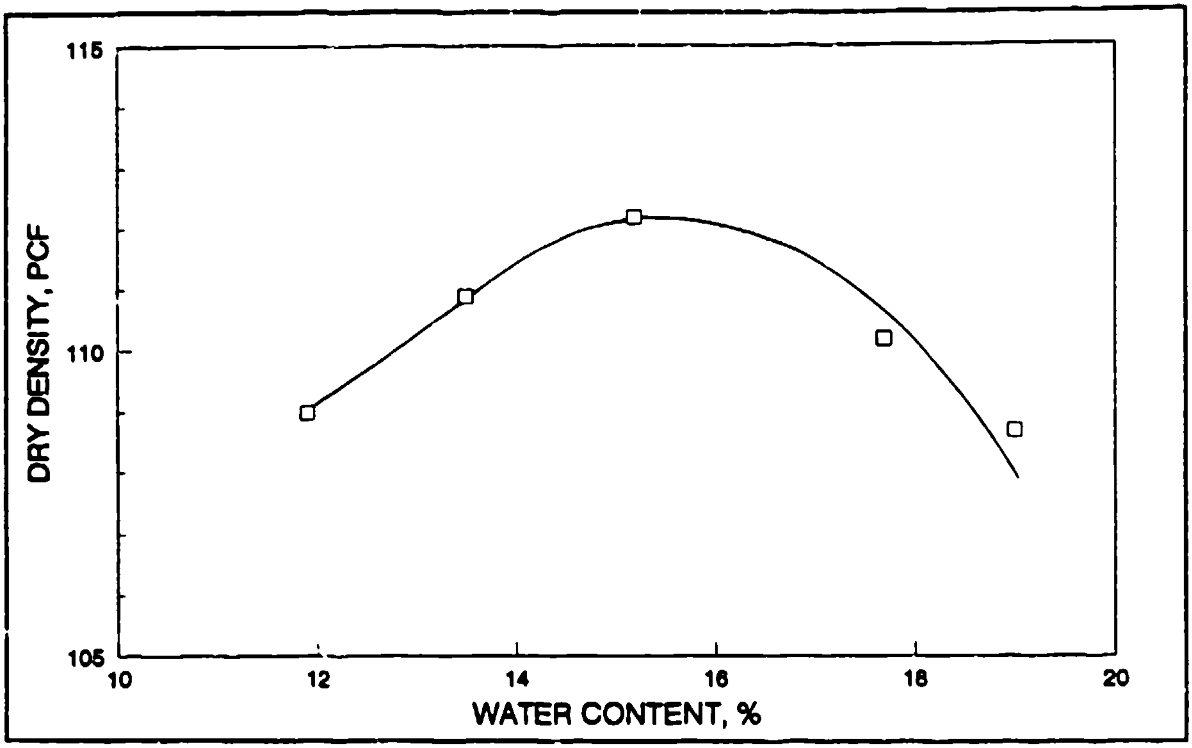

Figure 5. Moisture-density curve for high plasticity clay

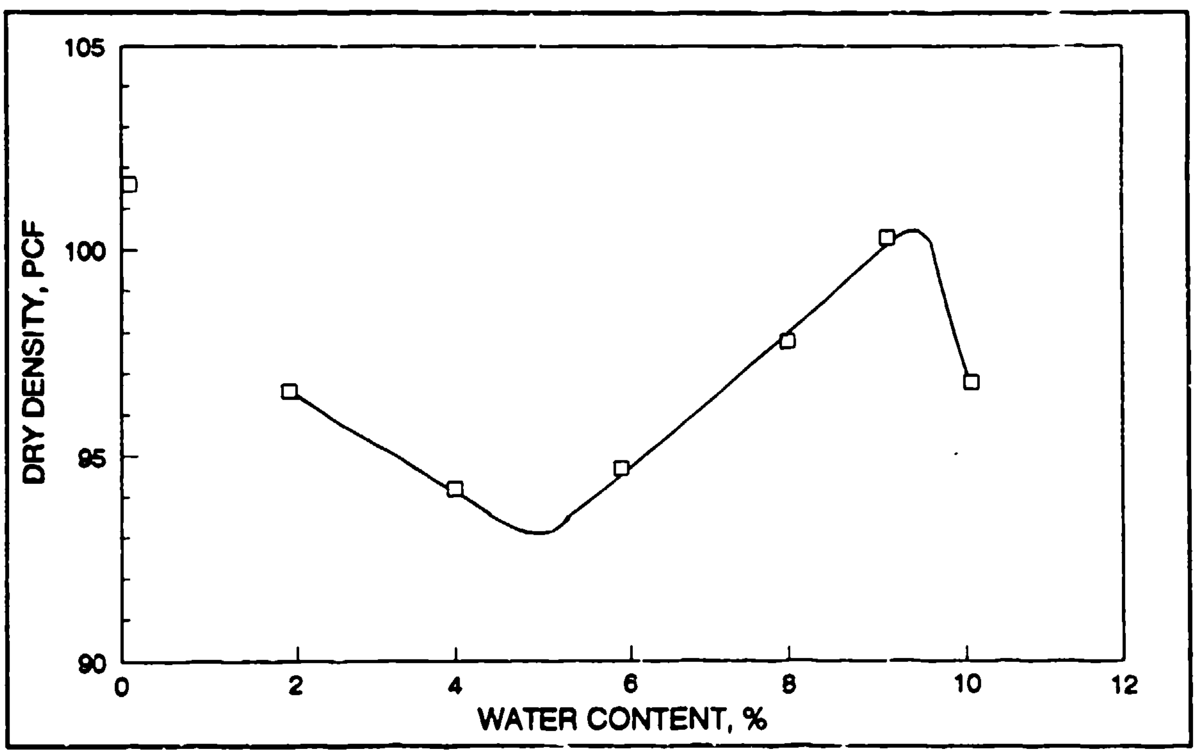

Figure 6. Moisture-density curve for beach sand

Gyratory Test Results

Gyratory testing machine

The Corps of Engineers gyratory testing machine (GTM) is a compaction device and a plane strain, simple shear testing device. The GTM is used to compact and test soils, subgrade materials, base course materials, and asphalt concrete mixtures. Compaction of pavement materials using the gyratory method applies normal forces to both the top and bottom faces of the material confined in cylindrically-shaped molds. Normal forces at designated pressures are supplemented with a kneading action or gyratory motion to compact the pavement materials into a denser configuration while totally confined. The U.S. Army Corps of Engineers and ASTM have established procedures and equipment standards for using this compaction process (Department of Defense 1966 and ASTM D3387 1993).

The gyratory compaction method involves placing the paving materials into a 4-in.-diameter mold and loading the GTM to a prescribed normal stress level (pressure). The paving material and mold are then rotated through a 1-degree gyration angle for a specified number of revolutions of the roller assembly. Figure 7 is a schematic of the gyratory compaction process. All fiber stabilized soils were compacted and tested in the Model 8A/6B/4C GTM (Figure 8).

High-plasticity clay, natural soil

Gyratory shear tests were conducted on the natural high plasticity clay as a baseline to compare with the fiber-stabilized high plasticity clay. It was determined that a compactive effort of 200 psi ram pressure and 100 revolutions would yield sample densities equivalent to that obtained by the CE55 compactive effort. Two samples of processed clay were tested in the gyratory machine at that compactive effort. In addition, two samples of the processed clay were compacted in the gyratory machine with a compactive effort of 100-psi ram pressure and 100 revolutions. The average results of these tests are given in Table 1.

At 100-psi ram pressure and 100 revolutions, the average dry density was 107.1 pcf. At 200-psi ram pressure and 100 revolutions, the average dry density was 113.5 pcf. The higher compactive effort increased the dry density by 6.4 pcf (6 percent).

High-plasticity clay, stabilized with monofilament fibers

Gyratory shear tests were conducted on the monofilament fiber stabilized high plasticity clay at both compactive efforts described above. Thirty-six clay samples were tested to examine the effect of fiber length and fiber dosage on the gyratory shear strength. The monofilament fiber stabilized high plasticity clay consisted of three fiber lengths (0.5, 1.0, and 2.0 in.) at three

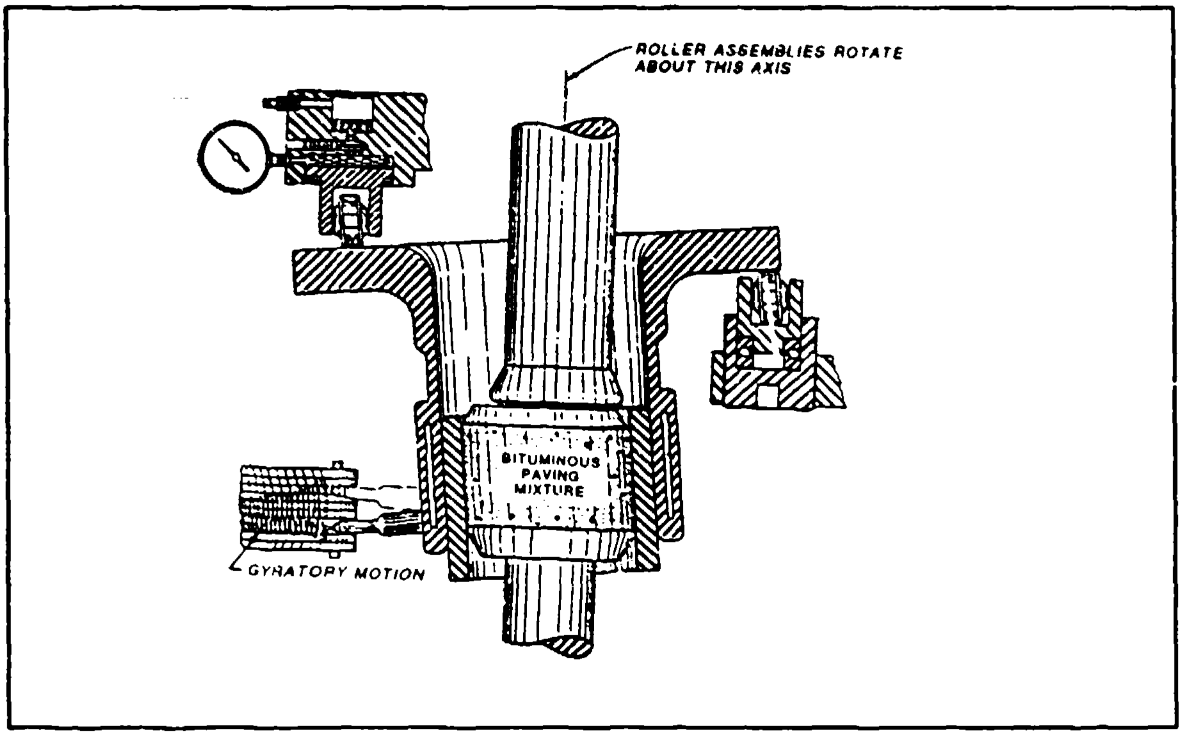

Figure 7. Schematic of gyratory compaction process

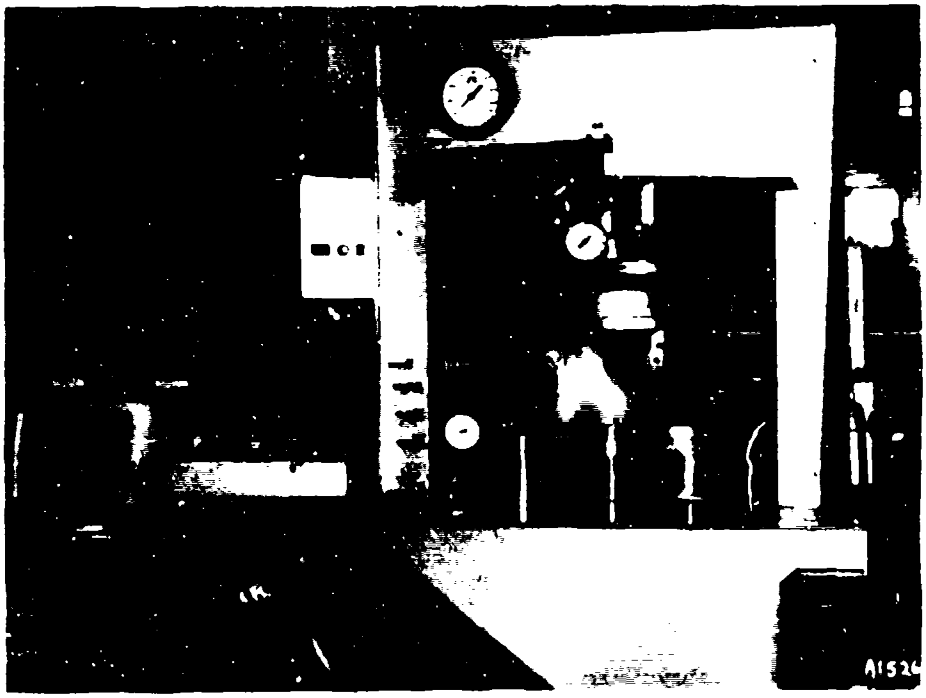

Figure 8. Model 8A/6B/4C gyratory testing machine

Table 1
Density Values for Various Compaction Efforts

Procedure	Compaction Efforts	Soil Type	Optimum Moisture Content, percent	Density, pcf
MIL STD 621A Method 100	CE 55	Clay	15.3	112.2
MIL STD 621A Method 100	CE 55	Sand	9.1	101.5
GTM	200 psi 100 rev	Clay	15.3	113.0 114.0 113.5 AVG
GTM	100 psi 100 rev	Clay	15.3	106.4 107.8 107.1 AVG
GTM	200 psi 100 rev	Sand	9.1	101.5 102.4 102.0 AVG

fiber dosages (0.5, 1.0, and 2.0 percent by weight). Table 2 and Figure 9 show the data obtained from the samples when the gyratory machine was set on 200-psi ram pressure and 100 revolutions. Table 3 and Figure 10 show the data obtained from the samples at 100-psi ram pressure and 100 revolutions.

The average dry density and gyratory shear strengths of the stabilized samples were compared with the average values obtained from the nonstabilized samples. This type of analysis provided the data necessary to determine whether fibers substantially improve soil strength. At 200-psi ram pressure and 100 revolutions, the nonstabilized sample's average dry density and gyratory shear strength was 113.5 pcf and 137.3 psi, respectively. The stabilized samples average dry density ranged from 105.4 pcf to 115.2 pcf and the average gyratory shear strength ranged from 93.4 psi to 138.3 psi. Only one set of samples showed an increase in gyratory shear strength (2-in. length at 1 percent dosage rate) and the strength increase (0.7 percent) was insignificant.

At 100-psi ram pressure and 100 revolutions, the nonstabilized sample average dry density and gyratory shear strength was 107.1 pcf and 56.6 psi, respectively. The stabilized samples average dry density ranged from 92.2 pcf to 102.0 pcf and the average gyratory shear strengths ranged from 32.4 psi to 52.3 psi. The gyratory shear strengths of all stabilized samples were less than the shear strength of the nonstabilized samples.

Table 2
Results of High-Plasticity Clay Stabilized with Monofilament Fibers at 200-psi Ram Pressure and 100 Revolutions

Fiber Length, in.	Fiber Dosage, percent	Dry Density, pcf	Gyratory Shear Strength S_g, psi	Difference in S_g, percent
0.0	0.0	113.5	137.3	–
0.5	0.5	113.9	97.3	- 29.1
0.5	1.0	113.1	107.9	- 21.4
0.5	2.0	110.7	97.5	- 29.0
1.0	0.5	115.2	93.4	- 32.0
1.0	1.0	113.8	106.5	- 22.4
1.0	2.0	111.3	113.5	- 17.3
2.0	0.5	108.0	122.9	- 10.5
2.0	1.0	107.6	138.3	+ 0.7
2.0	2.0	105.4	105.9	- 22.9

Table 3
Results of High-Plasticity Clay Stabilized with Monofilament Fibers at 100-psi Ram Pressure and 100 Revolutions

Fiber Length, in.	Fiber Dosage, percent	Dry Density, pcf	Gyratory Shear Strength S_g, psi	Difference in S_g, percent
0.0	0.0	107.1	56.6	–
0.5	0.5	102.0	42.8	- 24.4
0.5	1.0	100.8	43.7	- 22.8
0.5	2.0	100.2	52.3	- 7.6
1.0	0.5	101.5	46.6	- 17.7
1.0	1.0	101.3	36.1	- 36.2
1.0	2.0	96.9	37.6	- 33.6
2.0	0.5	101.4	50.9	- 10.1
2.0	1.0	98.1	32.4	- 42.8
2.0	2.0	92.2	44.8	- 20.8

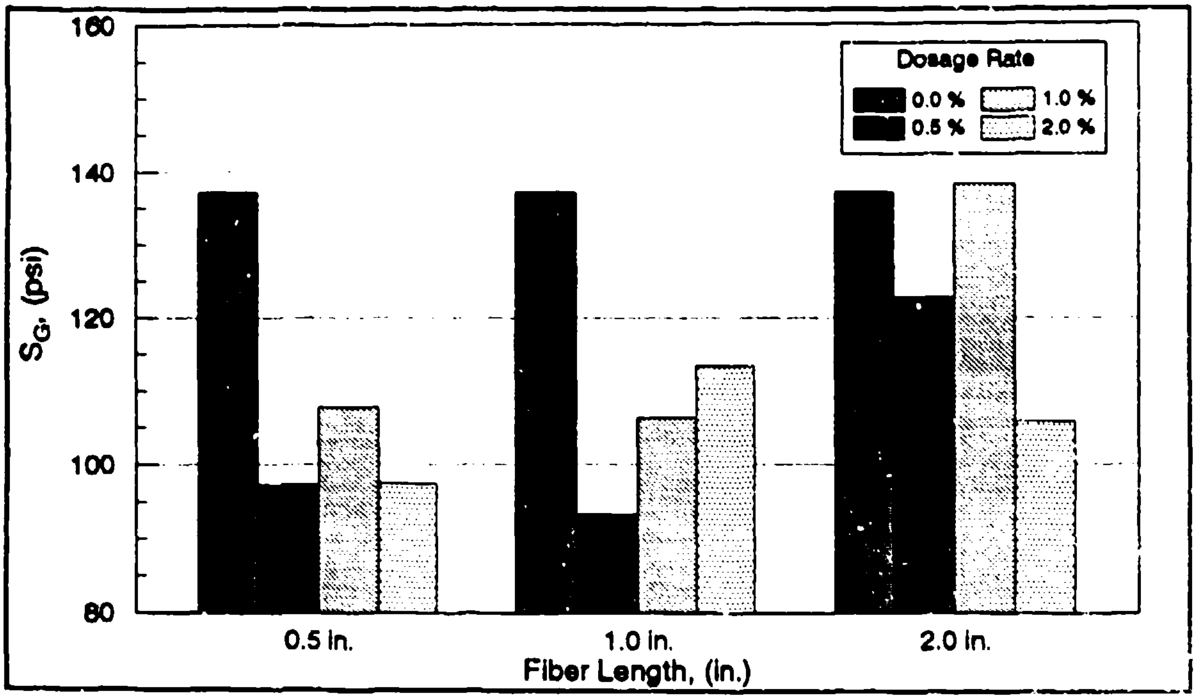

Figure 9. Gyratory shear strength values for high plasticity clay stabilized with monofilament fibers (200 psi pressure)

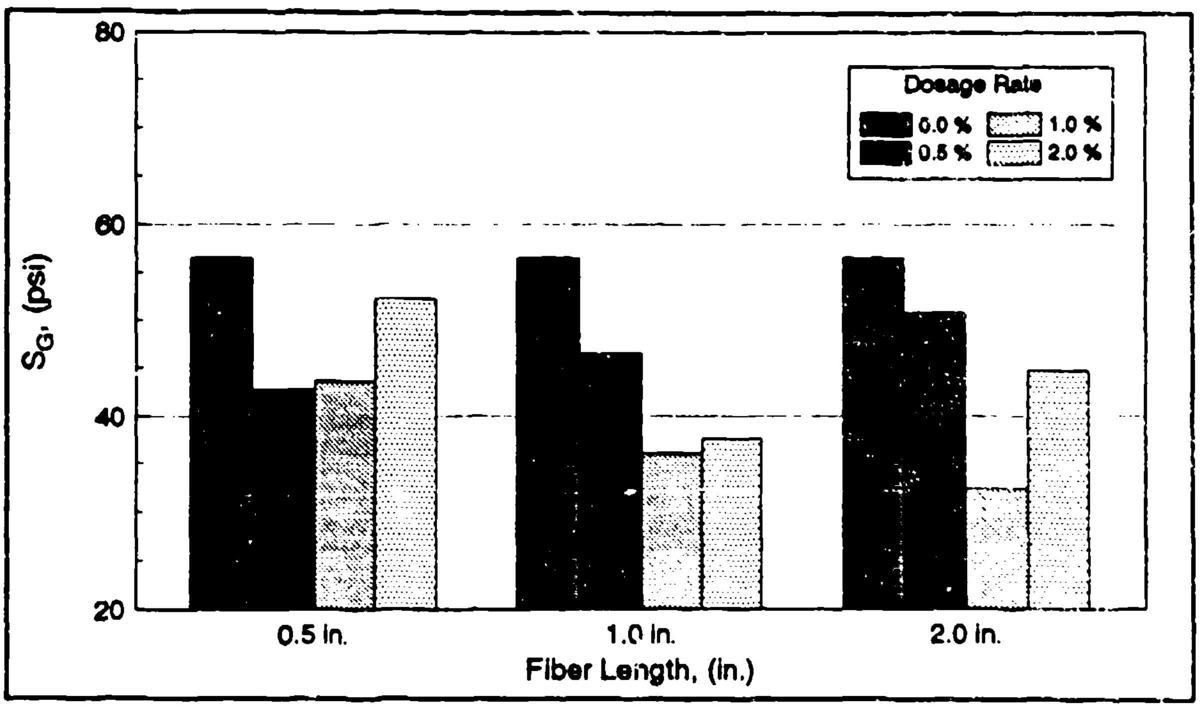

Figure 10. Gyratory shear strength values for high plasticity clay stabilized with monofilament fibers (100 psi pressure)

High-plasticity clay, stabilized with fibrillated fibers

Gyratory shear tests were conducted on the fibrillated fiber stabilized high plasticity clay at both 100-psi and 200-psi ram pressures. Forty clay samples were tested to examine the effect of fiber length and fiber dosage on the gyratory shear strength. The fibrillated fiber stabilized high plasticity clay consisted of three fiber lengths (0.5, 1.0, and 2.0 in.) and three fiber dosages (0.5, 1.0, and 2.0 percent). Table 4 and Figure 11 show the data when the gyratory machine was set on 200-psi ram pressure and 100 revolutions. Table 5 and Figure 12 show the data obtained from the samples at 100-psi ram pressure and 100 revolutions.

The average dry density and gyratory shear strengths of the stabilized samples were compared to the average values obtained from the nonstabilized samples. At 100 revolutions and 200-psi ram pressure the nonstabilized sample average dry density and gyratory shear strength was 113.5 pcf and 137.3 psi, respectively. The fibrillated fiber stabilized samples average dry density ranged from 105.5 pcf to 113.8 pcf and the gyratory shear strengths ranged from 93.2 psi to 143.6 psi. The only fiber stabilized combination that produced an increase in strength was the 0.5 in. fiber at 0.5 percent dosage rate. The increase was only 4.6 percent while the majority of the fiber stabilized combinations produced a decrease in strength.

At 100-psi ram pressure and 100 revolutions, the nonstabilized sample average dry density and gyratory shear strength was 107.1 pcf and 56.6 psi, respectively. The fibrillated fiber stabilized samples average dry density ranged from 93.0 pcf to 104.3 pcf and the average gyratory shear strengths ranged from 34.4 psi to 68.5 psi. The gyratory shear strengths of the 0.5-in. fiber at 0.5 percent and 1.0 percent stabilized materials were the only samples that produced an increase in strength. The increase in gyratory strength was 13.6 percent and 21.0 percent, respectively.

Beach sand, natural soil

Gyratory shear tests were conducted on the natural beach sand as a baseline to compare to the stabilized beach sand. It was determined that a compactive effort of 200-psi ram pressure and 100 revolutions would yield sample densities equivalent to that obtained by the CE55 compactive effort. Two samples of processed beach sand were compacted and tested in the gyratory machine at that compactive effort. The results of these tests are given in Table 1. The average dry density was 102.0 pcf and the average gyratory shear strength was 176.1 psi.

Beach sand, stabilized with monofilament fibers

Gyratory shear tests were conducted on the monofilament fiber stabilized beach sand at the compactive effort described above. Twenty-nine beach sand samples were tested to examine the effect of fiber length and fiber dosage on

Table 4
Results of High-Plasticity Clay Stabilized with Fibrillated Fibers at 200-psi Ram Pressure and 100 Revolutions

Fiber Length, in.	Fiber Dosage, percent	Dry Density, pcf	Gyratory Shear Strength S_e, psi	Difference in S_e, percent
0.0	0.0	113.5	137.3	–
0.5	0.5	112.2	143.6	+ 4.6
0.5	1.0	110.0	134.7	- 1.9
0.5	2.0	108.3	132.9	- 3.2
1.0	0.5	109.3	112.4	- 18.1
1.0	1.0	108.2	100.1	- 27.1
1.0	2.0	105.5	96.2	- 29.9
2.0	0.5	113.8	111.6	- 18.7
2.0	1.0	112.3	107.8	- 21.5
2.0	2.0	109.9	93.2	- 32.1

Table 5
Results of High-Plasticity Clay Stabilized with Fibrillated Fibers at 100-psi Ram Pressure and 100 Revolutions

Fiber Length, in.	Fiber Dosage, percent	Dry Density, pcf	Gyratory Shear Strength S_e, psi	Difference in S_e, percent
0.0	0.0	107.1	56.6	–
0.5	0.5	101.7	64.3	+ 13.6
0.5	1.0	100.1	68.5	+ 21.0
0.5	2.0	97.7	53.7	- 5.1
1.0	0.5	104.3	39.5	- 30.2
1.0	1.0	101.4	47.5	- 16.1
1.0	2.0	99.9	51.6	- 8.8
2.0	0.5	103.6	34.4	- 39.2
2.0	1.0	100.9	38.0	- 32.9
2.0	2.0	93.0	47.3	- 16.4

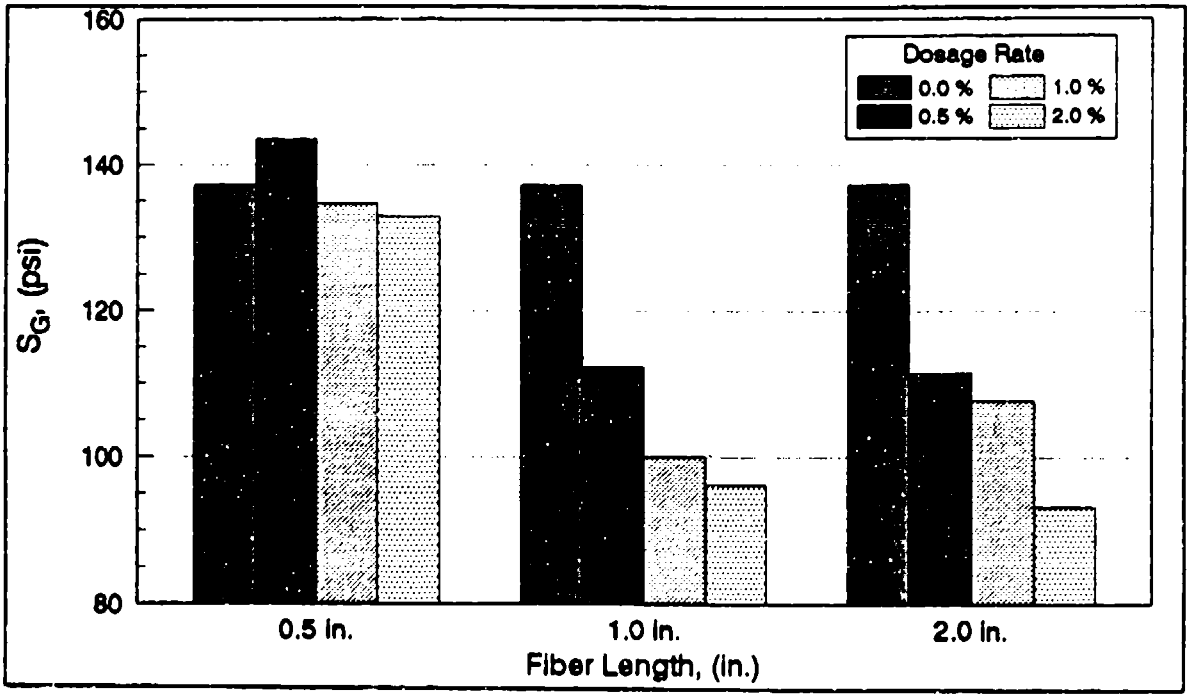

Figure 11. Gyratory shear strength values for high-plasticity clay stabilized with fibrillated fibers (200-psi pressure)

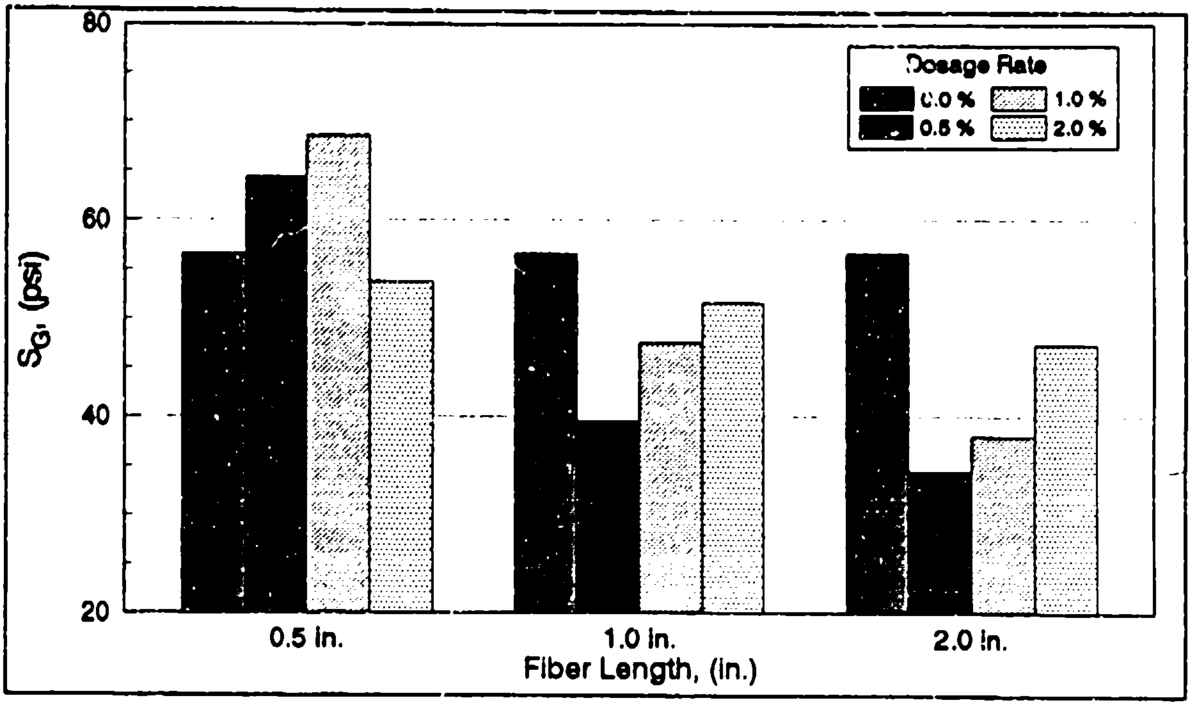

Figure 12. Gyratory shear strength values for high-plasticity clay stabilized with fibrillated fibers (100-psi pressure)

the gyratory shear strength. The monofilament fiber-stabilized beach sand consisted of three fiber lengths (0.5, 1.0, and 2.0 in.) and three fiber dosages (0.5, 1.0, and 2.0 percent). The results of these tests are shown in Table 6 and Figure 13.

Table 6
Results of Beach Sand Stabilized with Monofilament Fibers at 200-psi Ram Pressure and 100 Revolutions

Fiber Length, in.	Fiber Dosage, percent	Dry Density, pcf	Gyratory Shear Strength S_G, psi	Difference in S_G, percent
0.0	0.0	102.0	176.1	0.0
0.5	0.5	100.7	179.0	+ 1.6
0.5	1.0	97.9	188.2	+ 6.9
0.5	2.0	98.2	205.5	+ 16.7
1.0	0.5	100.8	192.4	+ 9.3
1.0	1.0	98.4	207.0	+ 17.5
1.0	2.0	97.8	194.9	+ 10.7
2.0	0.5	99.4	225.9	+ 28.3
2.0	1.0	99.1	206.0	+ 17.0
2.0	2.0	98.0	197.9	+ 12.4

The average dry density and gyratory shear strengths of the monofilament stabilized beach sand samples were compared to the average values obtained from the nonstabilized beach sand samples. At 200-psi ram pressure and 100 revolutions, the nonstabilized samples average dry density and gyratory shear strength was 102 pcf and 176.1 psi, respectively. The monofilament fiber stabilized samples average dry density ranged from 97.8 pcf to 100.8 pcf and the gyratory shear strengths ranged from 179.0 psi to 225.9 psi. The monofilament fiber stabilization of the beach sand produced the greatest effect on the gyratory shear strength value. The data showed that the fiber length and dosage rate affected the gyratory shear strength values. As the fiber length increased, the optimum dosage-rate decreased in order to produce the largest increase in gyratory shear strength. All monofilament fiber stabilized samples had a higher gyratory shear strength than the natural sand material. The highest gyratory strength value was achieved by stabilizing the beach sand with 2.0 in. fibers at a 0.5 percent dosage rate. This stabilization increased the gyratory shear strength by 28.3 percent.

Beach sand, stabilized with fibrillated fibers

Gyratory shear tests were conducted on the fibrillated fiber stabilized beach sand at the same compactive effort as with the monofilament fibers. Twenty-one beach sand samples were tested to examine the effect of fiber length and fiber dosage on the dry density and gyratory shear strength. The fibrillated fiber stabilized beach sand consisted of three fiber lengths (0.5, 1.0, and 2.0 in.) and three fiber dosages (0.5, 1.0, 2.0 percent). The results of these tests are shown in Table 7 and Figure 14.

Table 7
Results of Beach Sand Stabilized with Fibrillated Fibers at 200-psi Ram Pressure and 100 Revolutions

Fiber Length, in.	Fiber Dosage, percent	Dry Density, pcf	Gyratory Shear Strength S_G, psi	Difference in S_G, percent
0.0	0.0	102.0	176.1	0.0
0.5	0.5	100.4	182.3	+ 3.5
0.5	1.0	98.9	153.8	- 12.7
0.5	2.0	97.4	139.2	- 21.0
1.0	0.5	100.9	152.8	- 13.2
1.0	1.0	99.4	153.8	- 12.6
1.0	2.0	97.2	151.0	- 14.3
2.0	0.5	100.0	152.5	- 13.4
2.0	1.0	100.0	143.8	- 18.3
2.0	2.0	96.8	113.0	- 35.8

The average dry density and gyratory shear strengths of the fibrillated fiber stabilized beach sand samples were compared with the average values obtained from the nonstabilized beach sand samples. At 200-psi ram pressure and 100 revolutions, the nonstabilized samples average dry density and gyratory shear strength was 102 pcf and 176.1 psi, respectively. The fibrillated fiber stabilized samples average dry density ranged from 96.8 pcf to 100.9 pcf and the gyratory shear strengths ranged from 113.0 psi to 182.3 psi. Only one set of fibrillated fiber stabilized samples (0.5 in. length at 0.5 percent dosage) had a higher gyratory shear strength than the nonstabilized samples and the strength increase (3.5 percent) from that sample was insignificant.

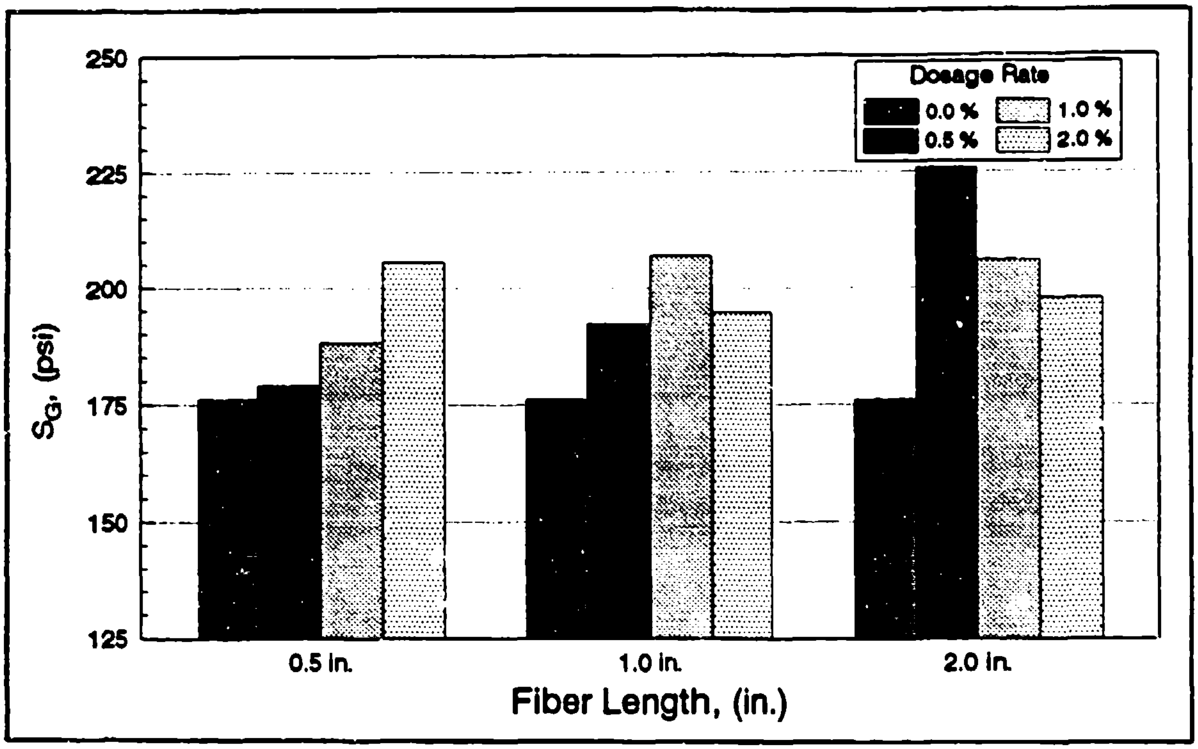

Figure 13. Gyratory shear strength values for beach sand stabilized with monofilament fibers

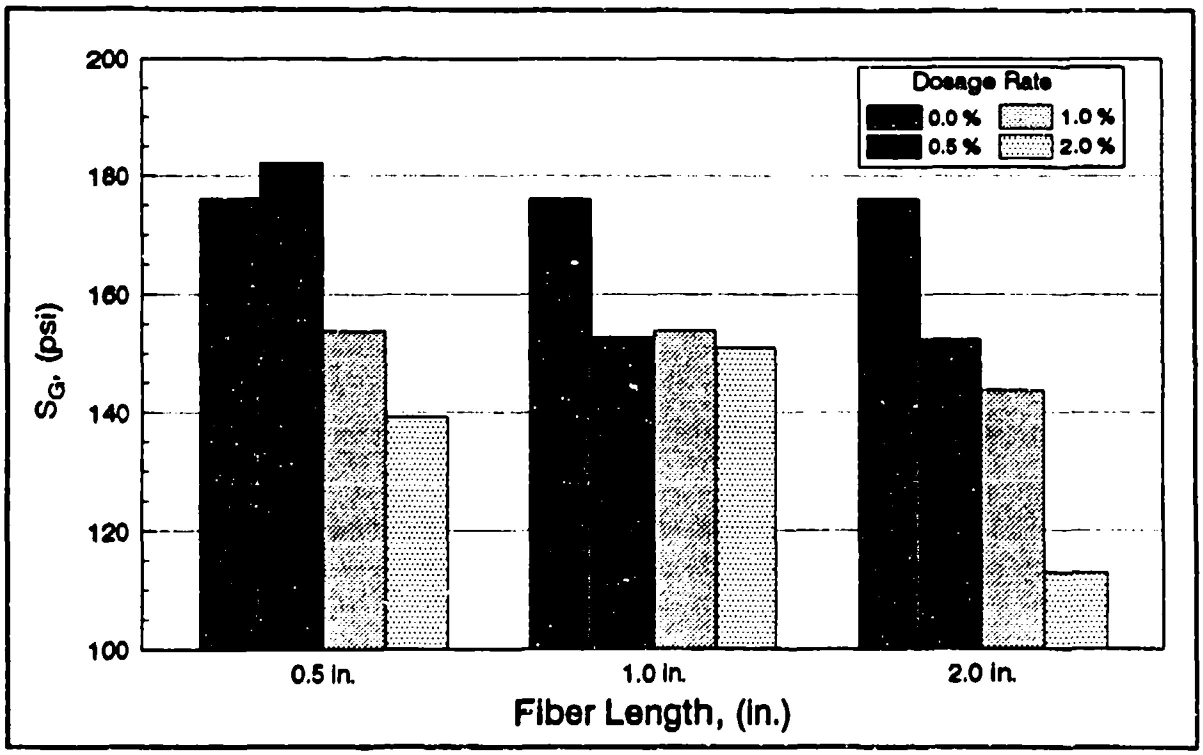

Figure 14. Gyratory shear strength values for beach sand stabilized with fibrillated fibers

CBR Test Results

CBR data for natural materials

The laboratory CBR test procedure was conducted on the high plasticity clay and the beach sand according to MIL STD 621A, Method 101. A CBR value was determined for each material in both the unsoaked (as molded) and soaked (4 day) conditions. The relationships between CBR values and moisture contents for the high plasticity clay are shown in Figures 15 and 16. The CBR value for the as-molded condition was 63.0 at an optimum moisture content of 15.7 percent. The CBR value for the soaked condition was 2.0 at an optimum moisture content of 15.3 percent. The relationship between the CBR values and moisture contents for the beach sand are shown in Figures 17 and 18. The CBR value for the as-molded condition was 53.3 at an optimum moisture content of 9.5 percent. The CBR for the soaked condition was 72.5 at an optimum moisture content of 9.1 percent.

CBR data for stabilized materials

Based on the results from the gyratory testing machine, the selected stabilized materials that produced an increase in the gyratory shear strength value were further evaluated with the laboratory CBR procedure. The stabilized materials that produced an increase in strength properties included both natural soil materials. The increased gyratory shear strength was produced in samples stabilized with various fiber types, lengths, and dosage rates. The specific parameters for these fiber stabilized materials are listed in Table 8. These fiber stabilized materials were evaluated at various moisture contents in the as-molded condition and at the optimum moisture content in the soaked condition.

As previously mentioned, the stabilization of a high plasticity clay with monofilament fibers did not produce a significant increase in the gyratory shear strength values. The only combination of fiber stabilization that did improve the strength property was a 2-in. fiber at a dosage rate of 1.0 percent. The results of the CBR tests for this fiber stabilization are listed in Tables 9 and 10 and shown in Figure 19.

The monofilament fiber had little effect on the soaked CBR values and decreased the as-molded CBR value at the optimum moisture content. The CBR values for the soaked conditions were approximately 2.0 for both the natural clay and the stabilized clay materials. The as-molded CBR value for the fiber stabilized clay was 43.0, compared with 63.0 for the natural clay material. The monofilament fiber did not improve the CBR strength value for the high plasticity clay.

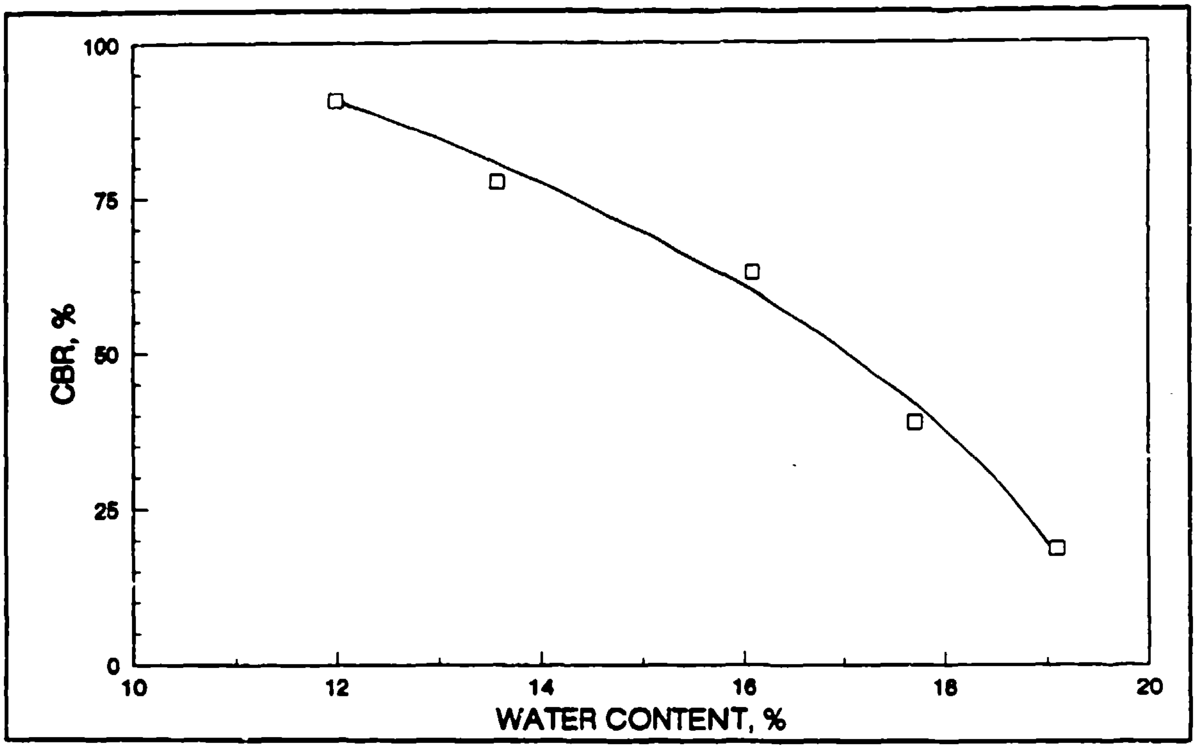

Figure 15. CBR curve for high plasticity clay (as molded)

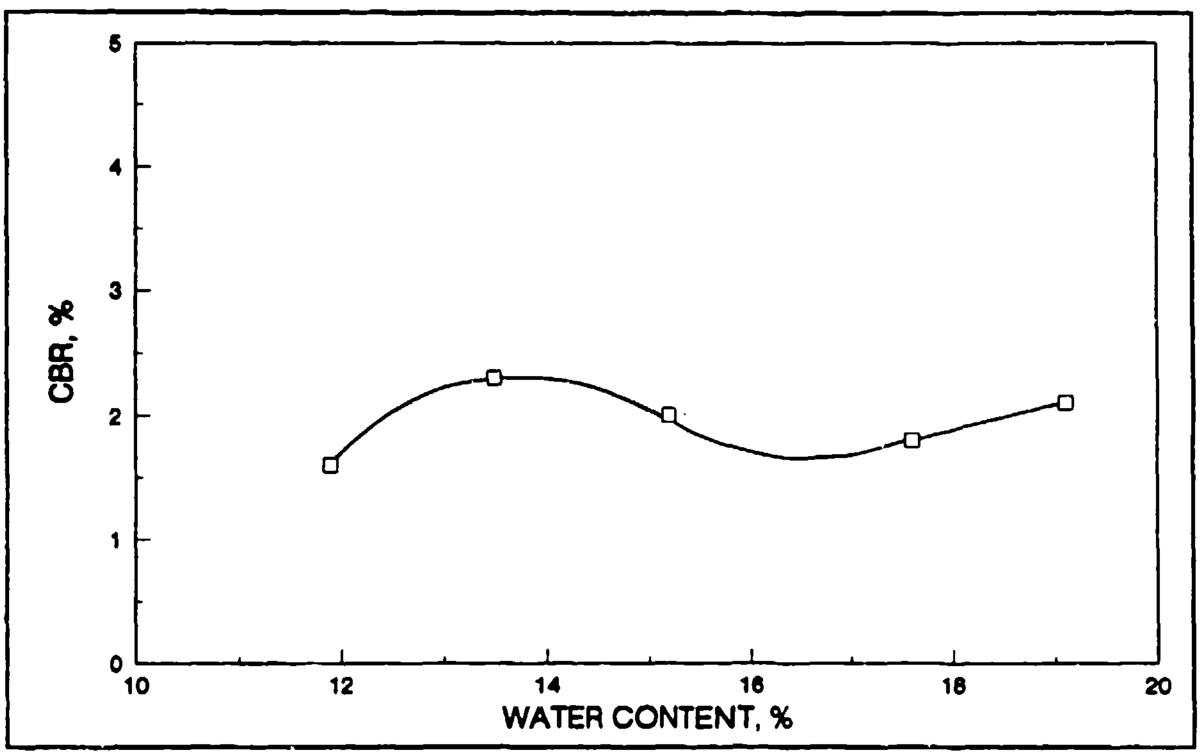

Figure 16. CBR curve for high plasticity clay (soaked)

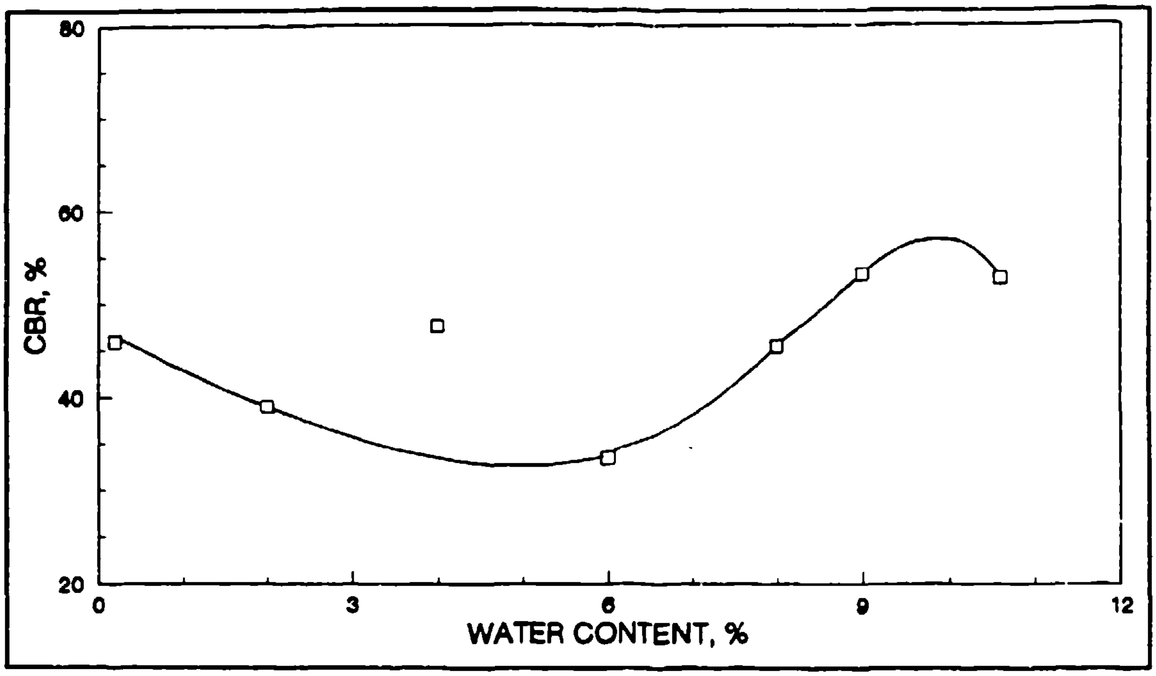

Figure 17. CBR curve for beach sand (as molded)

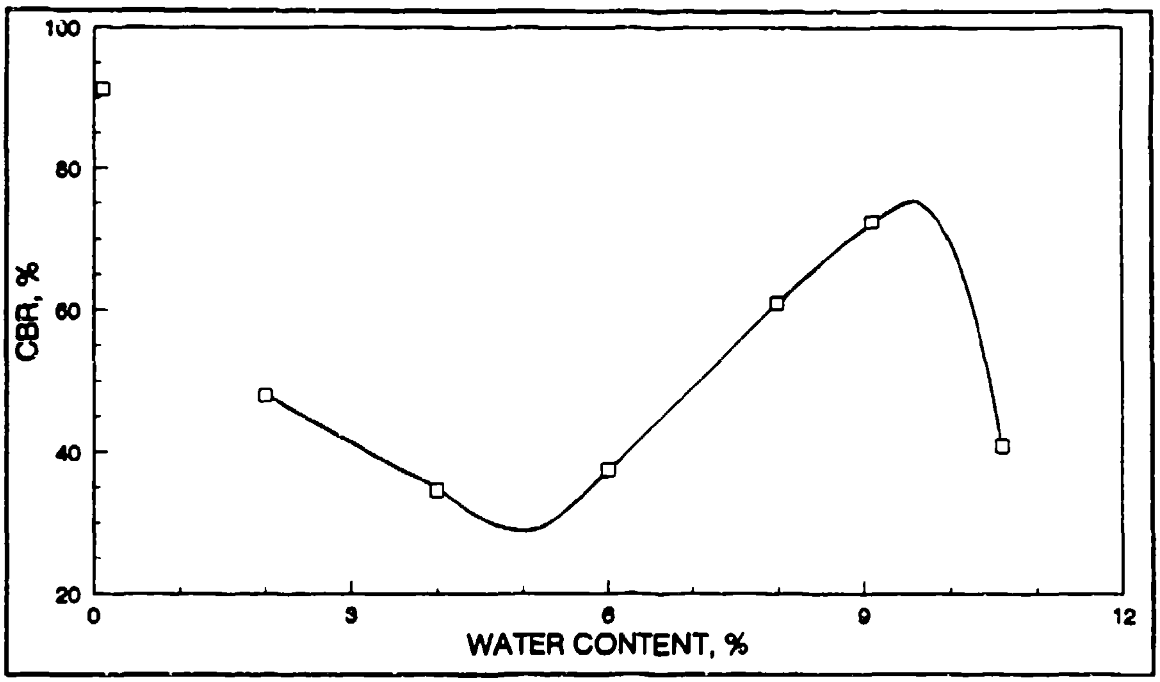

Figure 18. CBR curve for beach sand (soaked)

Table 8
Stabilized Materials Evaluated with CBR Procedure

Soil Type	Fiber Type	Fiber Length, in.	Fiber Dosage, percent
High plasticity clay	Fibrillated	0.5	0.5
	Fibrillated	0.5	1.0
	Fibrillated	0.5	2.0
	Monofilament	2.0	1.0
Beach sand	Fibrillated	0.5	0.5
	Monofilament	0.5	1.0
	Monofilament	0.5	2.0
	Monofilament	1.0	1.0
	Monofilament	2.0	0.5
	Monofilament	2.0	1.0

Stabilization of the high plasticity clay with fibrillated fibers had little effect and did not produce a significant increase in the gyratory shear strength values. The only positive or equivalent gyratory strength values were obtained with the 0.5-in. fibers. These fibers were evaluated with the CBR test at dosage rates of 0.5, 1.0, and 2.0 percent. The results of the CBR tests are listed in Tables 9 and 10 and shown in Figures 20-22.

The fibrillated fibers produced a decrease in the as-molded CBR values for the high plasticity clay. The CBR values decreased from 12 to 30 percent with the addition of fibrillated fibers. These fibrillated fibers also had little effect on the soaked CBR values. The CBR values for the soaked conditions were approximately 2.0 for both the stabilized and natural materials. The general trend of the fibrillated fiber stabilization in the high plasticity clay was a decrease in CBR strength with an increase in dosage rate.

The stabilization of the beach sand with monofilament fibers had the greatest positive effect on the gyratory shear strength values of any fiber stabilization. All fiber stabilized materials had an increase in strength. Multiple fiber lengths and dosage rates were evaluated with the CBR test. The results of the CBR tests are listed in Tables 9 and 10 and shown in Figures 23-27.

The monofilament fibers decreased the soaked CBR values for stabilized materials. The natural beach sand had a CBR value of 72.5 compared with the stabilized sand materials that ranged from 40.9 to 60.2. The monofilament fibers produced both a positive and negative effect on the as molded CBR values. The CBR value increased beyond the natural soil strength when a

2.0-in. fiber was used at a dosage rate of 1.0 percent. The general trend for beach sand stabilized with monofilament fibers was that the CBR value increased with fiber length and dosage rate. A minimum fiber length of 1.0 in. and a dosage rate of 1.0 percent appeared to be adequate to produce greater CBR values when compared with natural beach sand values.

The stabilization of the beach sand with fibrillated fibers had an insignificant effect on the gyratory strength values. The only combination of fiber stabilization that did improve the gyratory strength property was the 0.5-in. fiber at 0.5 percent dosage rate. The results of the CBR tests for this fiber stabilization are listed in Tables 9 and 10 and shown in Figure 28.

The fibrillated fibers decreased the as-molded and soaked CBR values in the stabilized beach sand. The as-molded CBR value decreased from 52.0 for the natural beach sand to 42.0 for the stabilized materials, a 20 percent decrease. The soaked CBR value decreased from 72.5 for the natural beach sand to 39.7 for the stabilized material, a 44 percent decrease.

The raw data of the CBR test also produced an interesting trend for the CBR values. It was found that the 0.2-in. penetration readings produced a higher CBR value than the 0.1-in. penetration readings in the beach sand materials stabilized with monofilament fibers. This increase in CBR values at the 0.2-in. reading did not occur in the natural sand CBR test results. One possible explanation for this increase in strength at a larger deformation; would be that the fibers began to carry the load after the sample had been stressed. This may imply that the CBR test is not totally evaluating the effectiveness of the fibers.

Table 9
CBR Test Results at Optimum Moisture Content (As-Molded)

Soil Type	Fiber Type	Fiber Length, in.	Fiber Dosage, percent	Optimum Moisture, percent	Density, pcf	CBR
Clay	–	–	–	15.7	111.4	63.0
	Fibrillated	0.5	0.5	15.8	110.3	55.3
	Fibrillated	0.5	1.0	15.7	108.6	53.1
	Fibrillated	0.5	2.0	18.2	107.2	44.5
	Monofilament	2.0	1.0	17.3	107.7	43.0
Beach Sand	–	–	–	9.5	100.7	53.3
	Fibrillated	0.5	0.5	8.1	94.1	42.0
	Monofilament	0.5	1.0	7.8	94.8	48.0
	Monofilament	0.5	2.0	7.0	92.8	50.0
	Monofilament	1.0	1.0	6.1	94.1	49.2
	Monofilament	2.0	0.5	6.1	95.6	38.7
	Monofilament	2.0	1.0	7.1	95.2	56.5

Table 10
CBR Test Results at Optimum Moisture Content (Soaked)

Soil Type	Fiber Type	Fiber Length, in.	Fiber Dosage, percent	Optimum Moisture, percent	Density, pcf	CBR
Clay	–	–	–	15.3	112.2	2.0
	Fibrillated	0.5	0.5	15.8	110.3	2.4
	Fibrillated	0.5	1.0	15.7	108.6	2.3
	Fibrillated	0.5	2.0	18.2	107.2	1.8
	Monofilament	2.0	1.0	17.3	107.7	2.2
Beach Sand	–	–	–	9.1	101.4	72.5
	Fibrillated	0.5	0.5	8.1	94.1	39.7
	Monofilament	0.5	1.0	7.8	94.8	40.9
	Monofilament	0.5	2.0	7.0	92.8	42.6
	Monofilament	1.0	1.0	6.1	94.1	60.2
	Monofilament	2.0	0.5	6.1	95.6	53.8
	Monofilament	2.0	1.0	7.1	95.2	57.4

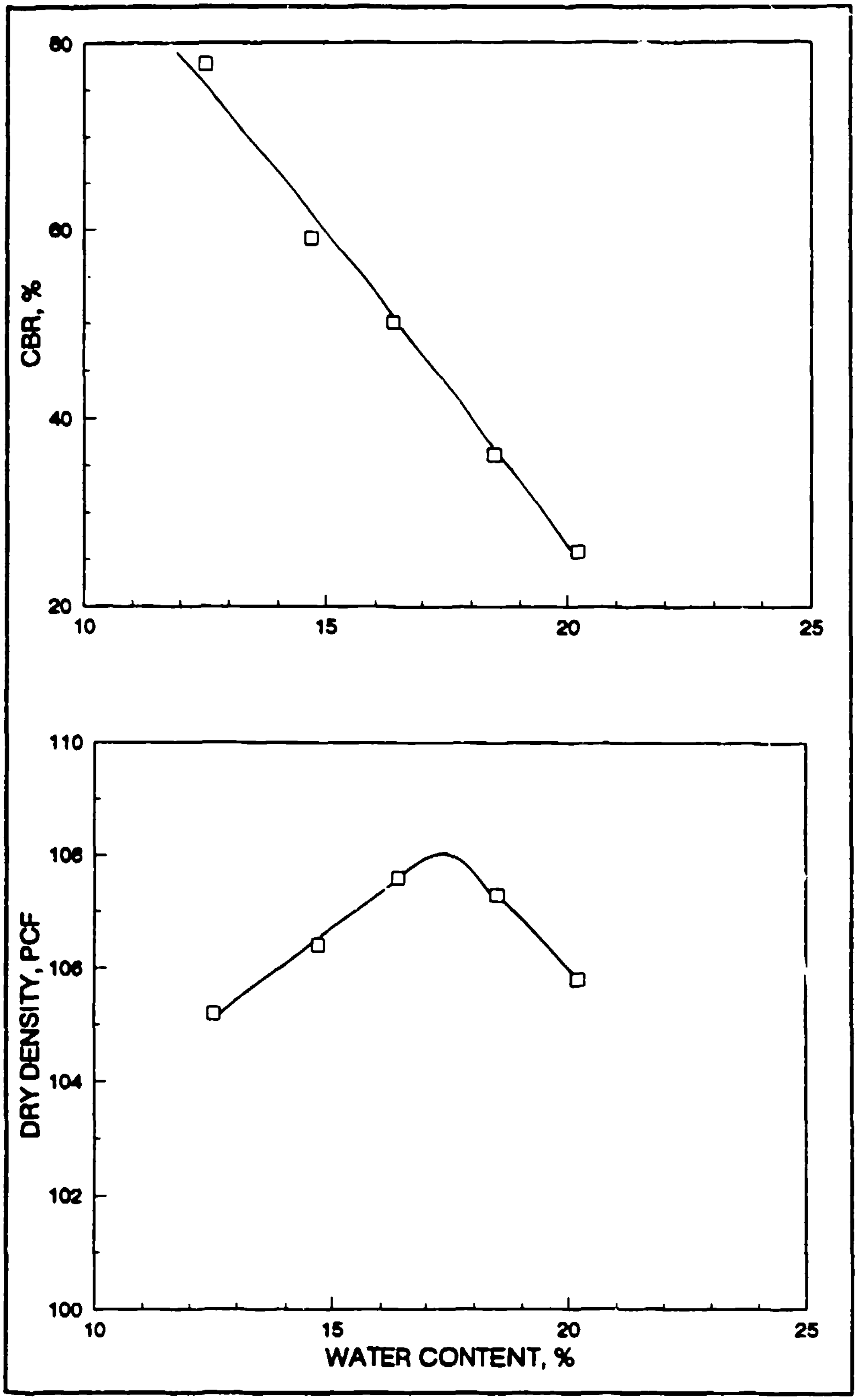

Figure 19. CBR, density and moisture content data for high-plasticity clay stabilized with monofilament fibers - 2 in. at 1.0 percent (as molded)

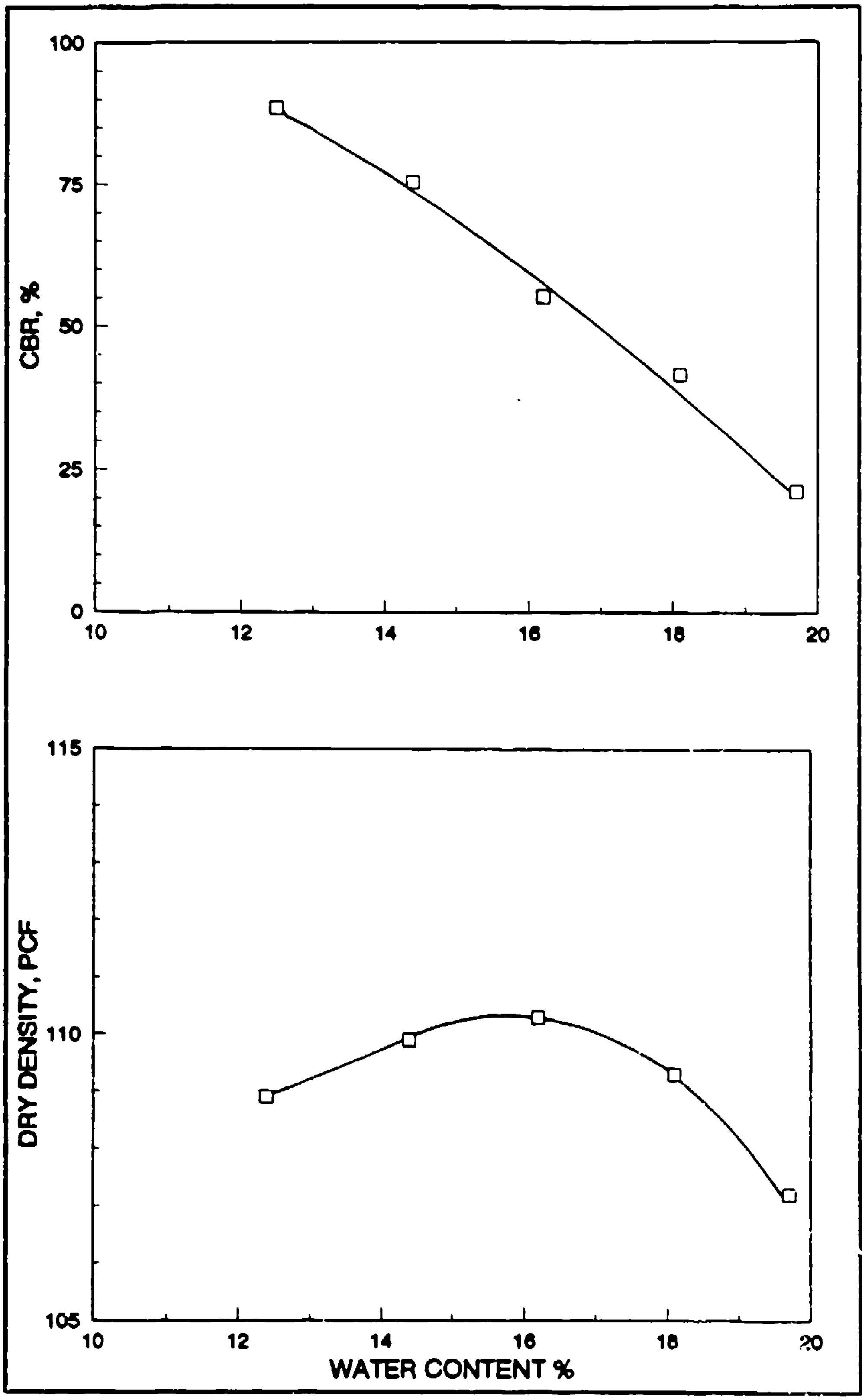

Figure 20. CBR, density and moisture content data for high-plasticity clay stabilized with fibrillated fibers - 0.5 in. at 0.5 percent (as molded)

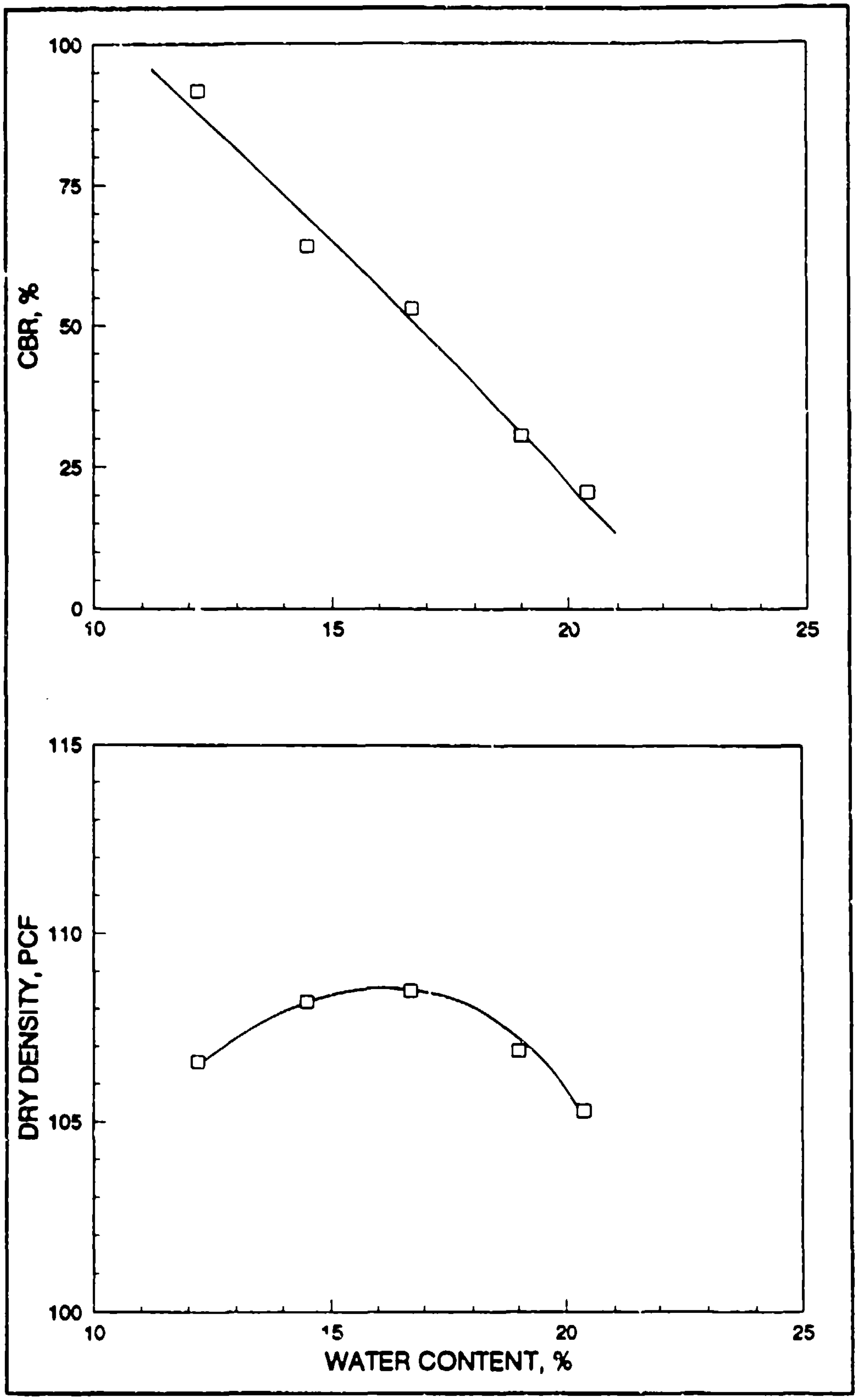

Figure 21. CBR, density and moisture content data for high-plasticity clay stabilized with fibrillated fibers - 0.5 in. at 1.0 percent (as molded)

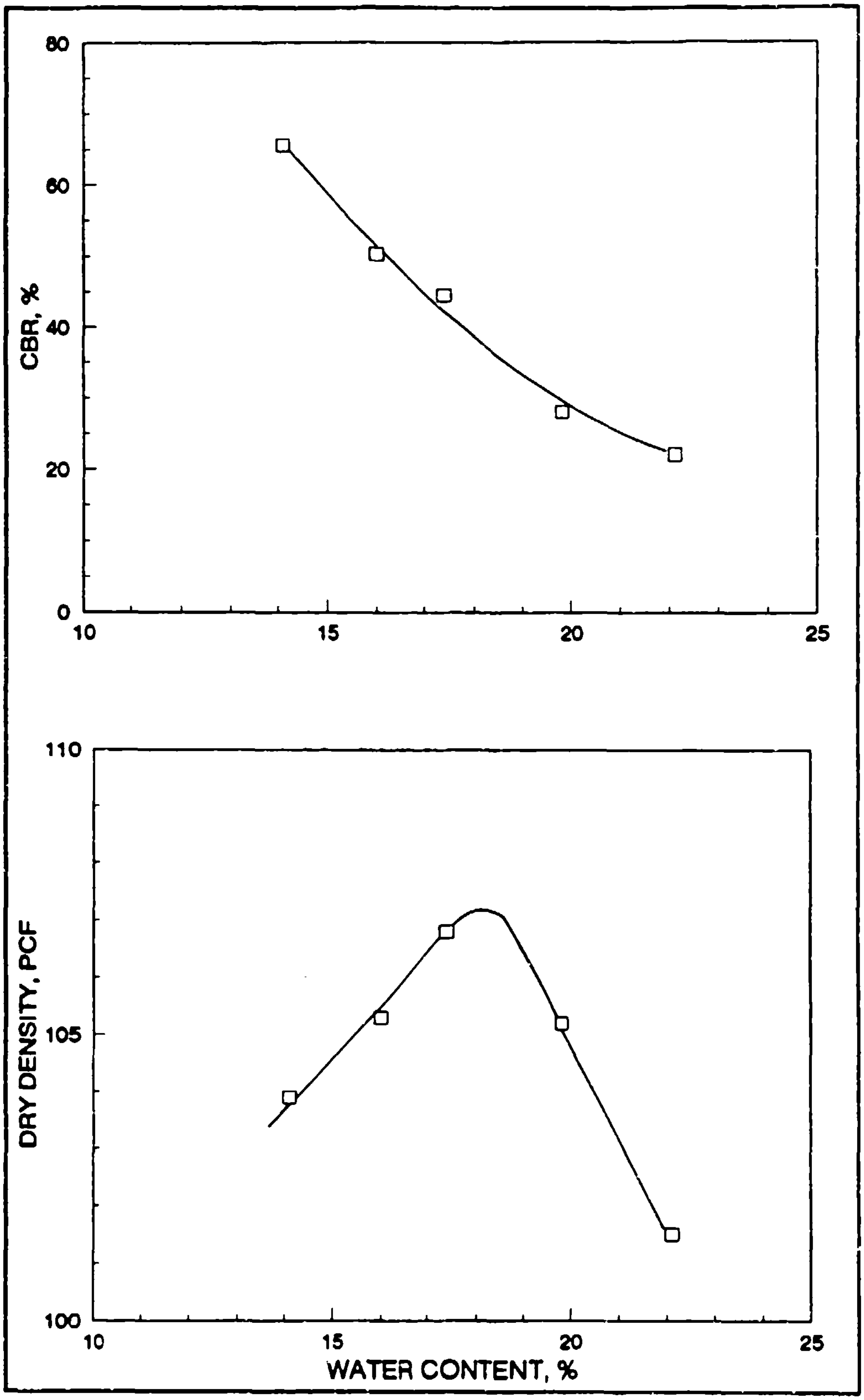

Figure 22. CBR, density and moisture content data for high-plasticity clay stabilized with fibrillated fibers - 0.5 in. at 2.0 percent (as molded)

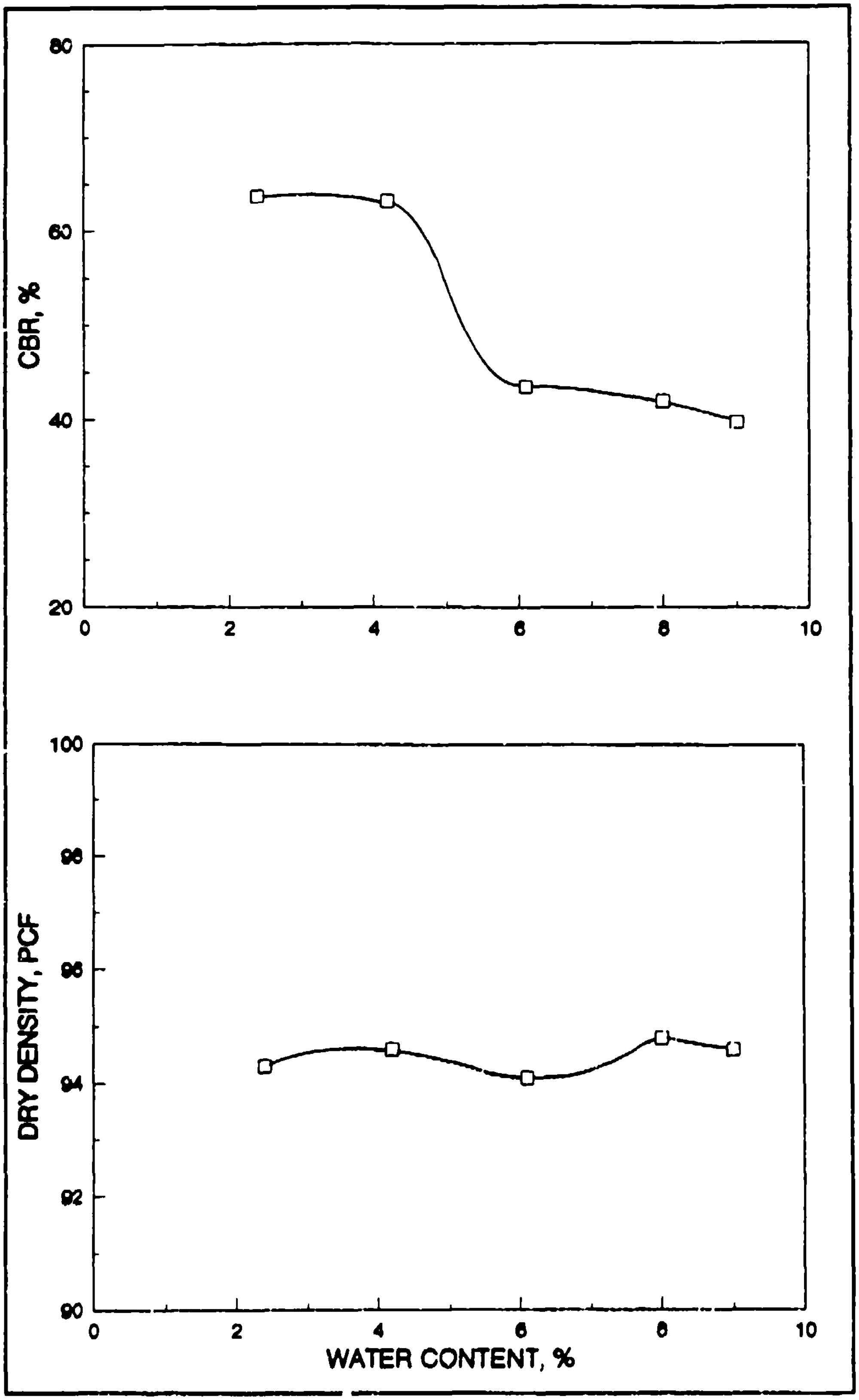

Figure 23. CBR, density and moisture content data for beach sand stabilized with monofilament fibers - 0.5 in. at 1.0 percent (as molded)

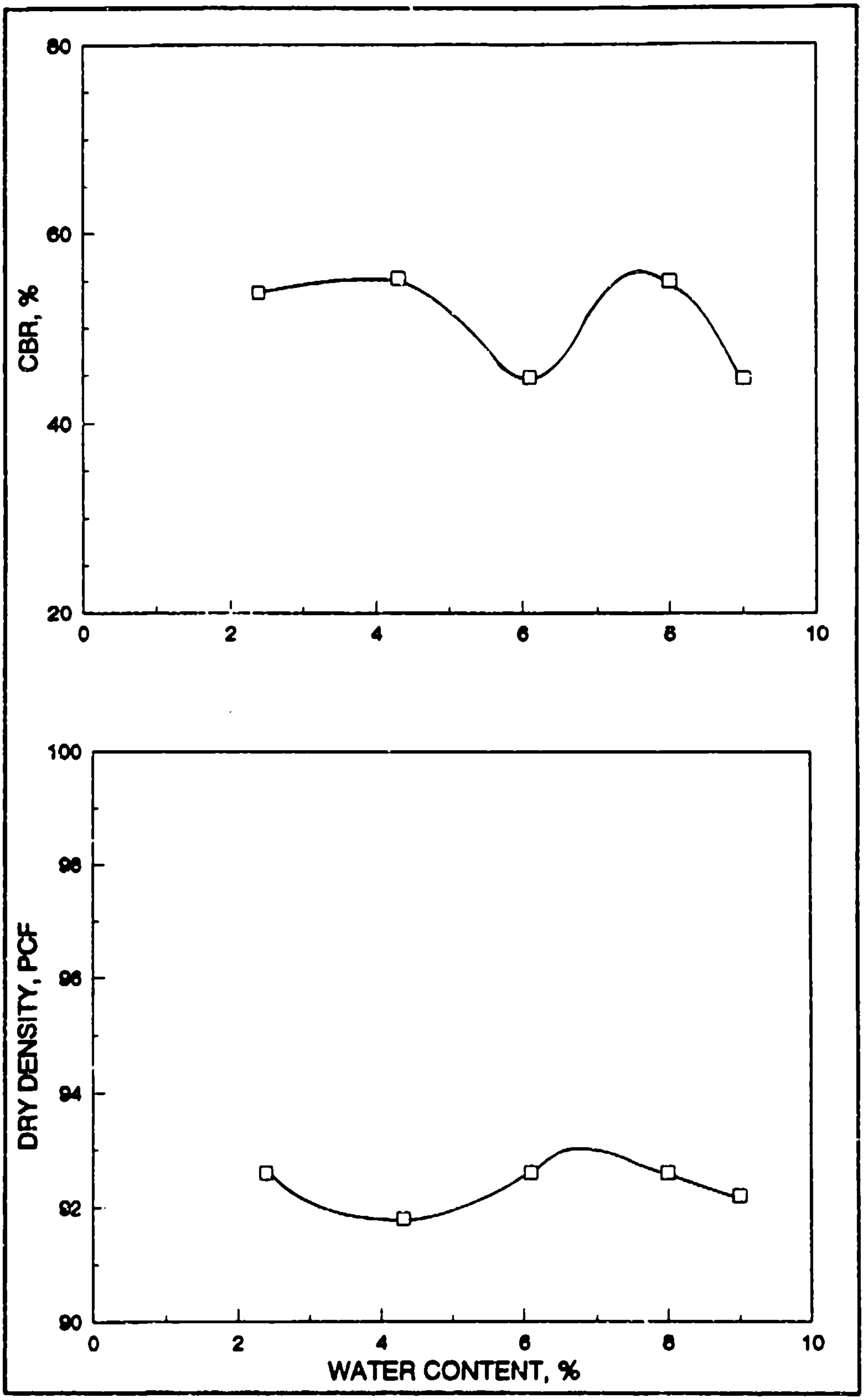

Figure 24. CBR, density and moisture content data for beach sand stabilized with monofilament fibers - 0.5 in. at 2.0 percent (as molded)

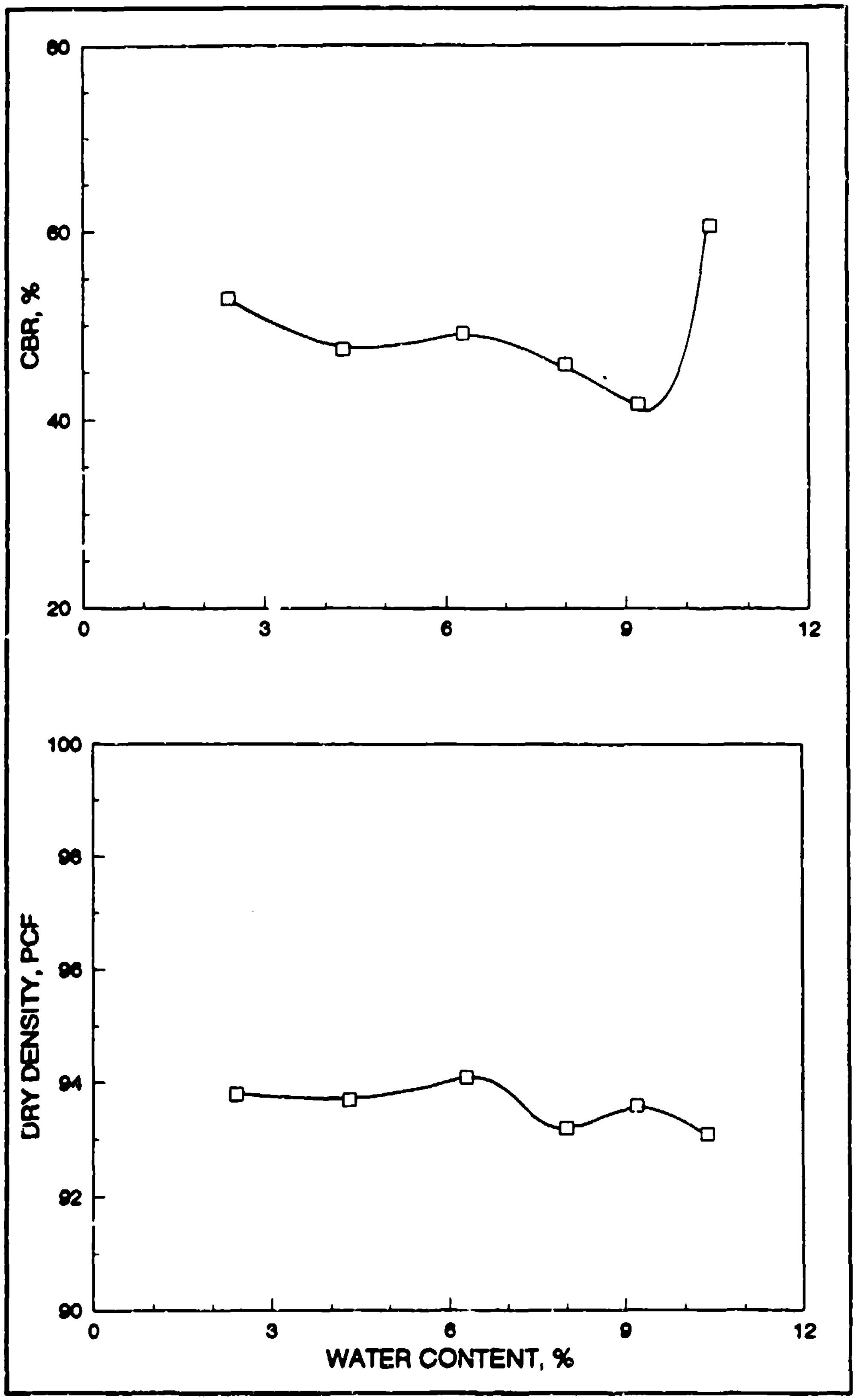

Figure 25. CBR, density and moisture content data for beach sand stabilized with monofilament fibers - 1 in. at 1 percent (as molded)

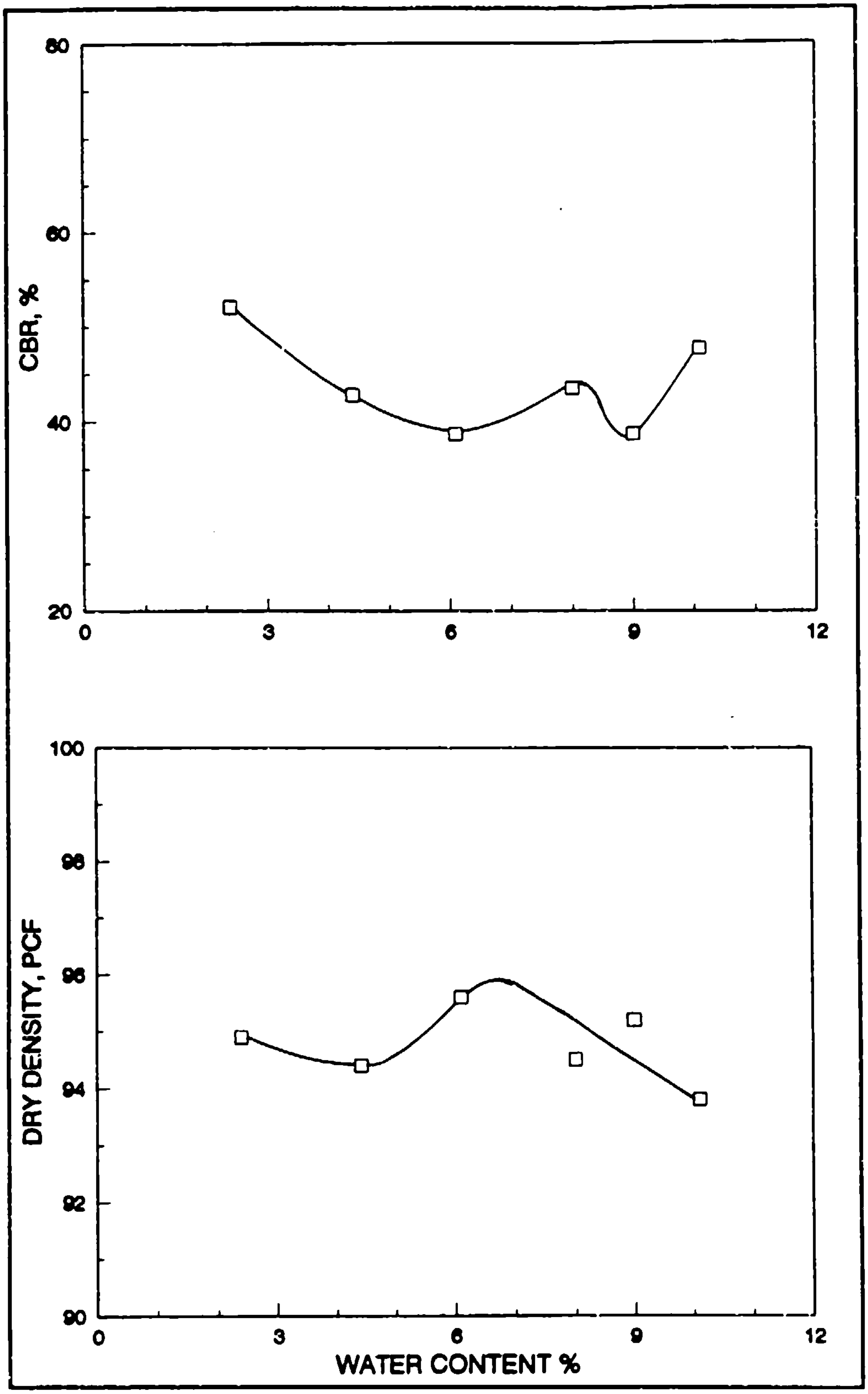

Figure 26. CBR, density and moisture content data for beach sand stabilized with monofilament fibers - 2 in. at 0.5 percent (as molded)

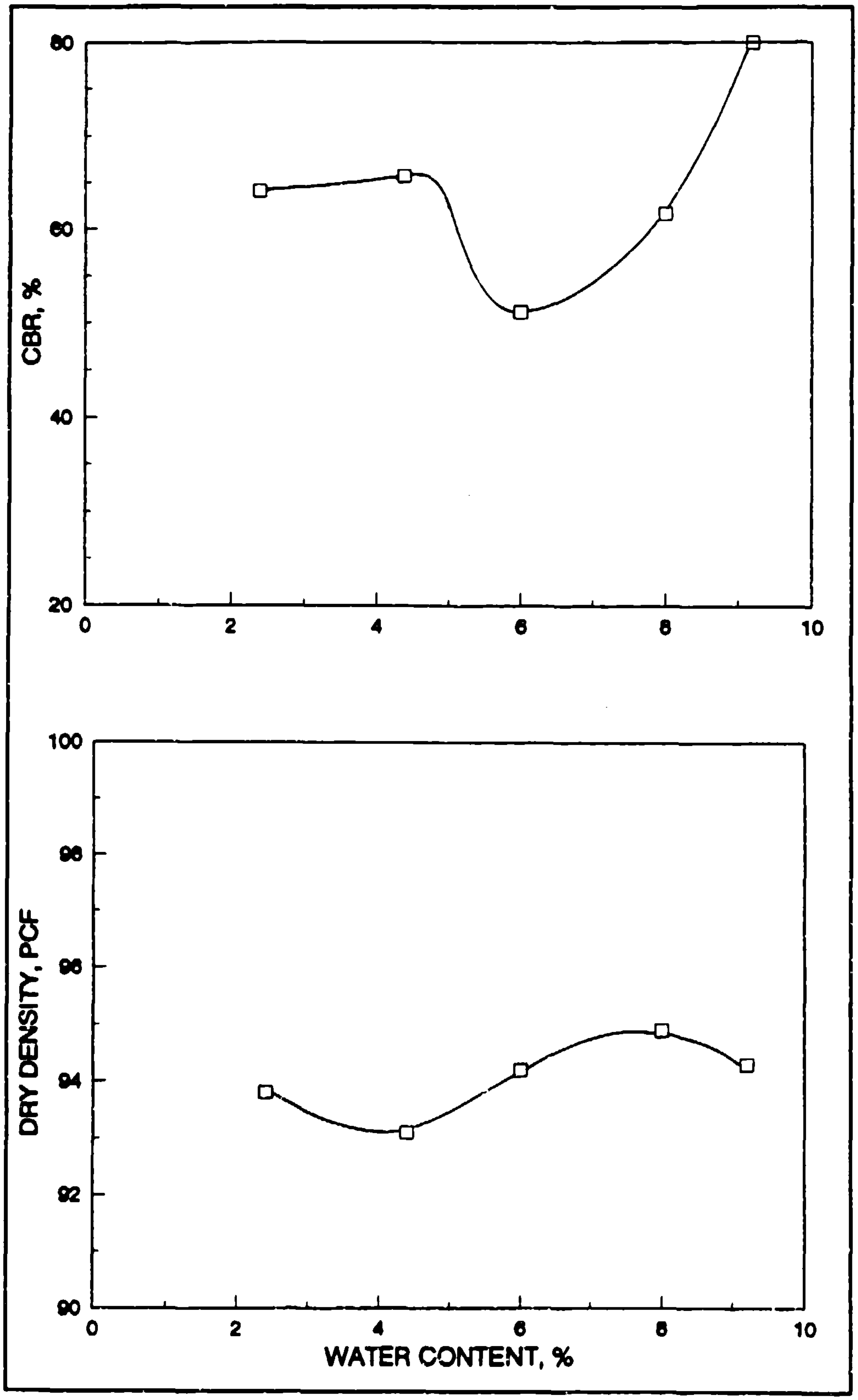

Figure 27. CBR, density and moisture content data for beach sand stabilized with monofilament fibers - 2 in. at 1.0 percent (as molded)

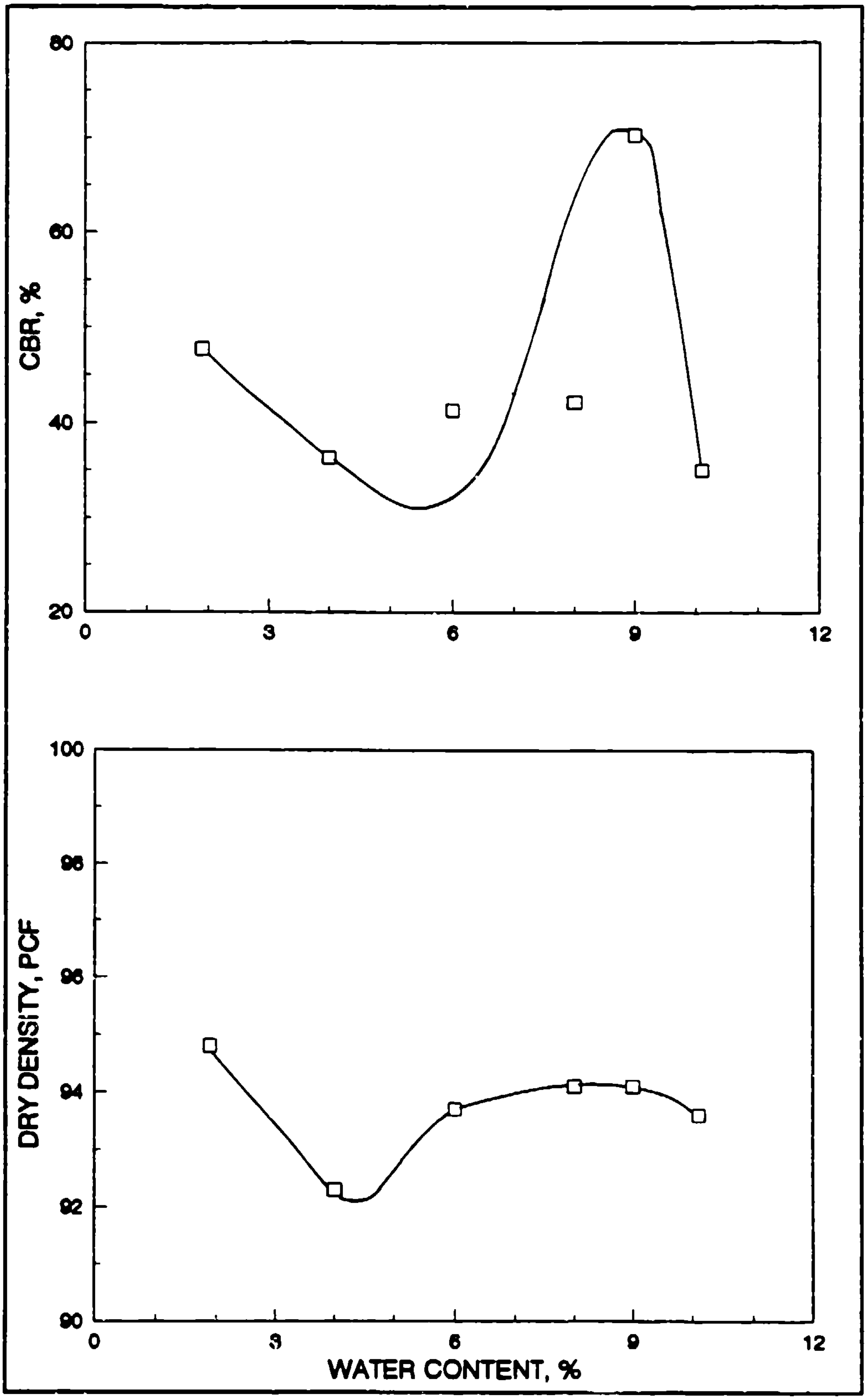

Figure 28. CBR, density and moisture content data for beach sand stabilized with fibrillated fibers - 0.5 in. at 0.5 percent (as molded)

4 Conclusions and Recommendations

Conclusions

Based on the findings of the literature review, the following conclusions were made on the effects of fiber stabilized high plasticity clay and fiber stabilized beach sand:

a. In test section studies, fibrillated fibers have been found to improve the performance of a lime-modified clay and a cement stabilized sand by reducing the amount of rutting and cracking.

b. Discrete fibrillated polypropylene can be adequately mixed into clay soils; fibers 1 in. and less in length are mixed and distributed more consistently than longer fibers.

c. Fiber inclusions significantly increased the ultimate strength and stiffness of sands in triaxial compression tests.

d. Long glass fibers had a greater effect than short glass fibers on load deformation behavior of sands; optimum length was 3 in.

Based on the results of the laboratory study, the following conclusions were made on the effects of fiber stabilized high plasticity clay and fiber stabilized beach sand:

a. In most cases of the laboratory study, the dry density of a clay or sand stabilized material decreased with the addition of fibers.

b. In all but one case, monofilament fiber stabilized high plasticity clay exhibited a lower gyratory shear strength than the nonstabilized high plasticity clay.

c. In most cases, fibrillated fiber stabilized high plasticity clay exhibited a lower gyratory shear strength than the nonstabilized soil. Very slight increases in gyratory shear strength were obtained in a few samples.

d. At the lower compactive effort, the fibrillated fiber produced an increase in gyratory shear strength. These fibers had a greater effect at the 100-psi compactive effort than at the 200-psi compactive effort.

e. The monofilament fiber stabilized beach sand exhibited a higher gyratory shear strength in all cases. A 2-in. fiber at 0.5 percent dosage gave the highest strength value.

f. For the monofilament stabilized beach sand, the gyratory shear strength of the samples increased with fiber length up to a length of 2 in.

g. For the beach sand stabilized with 0.5-in. monofilament fibers, the gyratory shear strength increased with an increase in fiber dosage.

h. For the beach sand stabilized with 2-in. monofilament fibers, the gyratory shear strength decreased with an increase in fiber dosage.

i. The fibrillated fiber stabilized beach sand exhibited lower gyratory shear strength values than the nonstabilized sand in all but one case (0.5-in. fibers at 0.5 percent dosage). At that fiber dosage the increase in strength was not significant.

j. The stabilization of the high plasticity clay with monofilament fibers did not improve the CBR strength value.

k. The fibrillated fibers produced a decrease in as-molded CBR values and had little effect on the soaked CBR values for the high plasticity clay. The CBR value of the stabilized clay decreased as the fiber dosage increased.

l. The monofilament fibers produced both positive and negative effects on the CBR values for the beach sand. The fibers decreased the soaked CBR values but produced an increase in the as-molded CBR values. The trend for the beach sand was that the CBR value increased as the fiber length and dosage rate increased.

m. The stabilization of the beach with fibrillated fibers produced a decrease in the CBR values.

n. CBR tests may not effectively evaluate the effectiveness of fiber stabilization.

Recommendations

Based on the conclusions derived from the results of this study, the following recommendations are made.

a. Use monofilament fibers to improve strength values of beach sand. Maximum strength increases can be produced with a 2-in. fiber at a dosage rate of 0.5 percent.

b. Use fibrillated fibers to improve strength values of high plasticity clay at low compactive efforts. Optimum fiber stabilization is 0.5-in. fiber at a dosage rate of 1.0 percent.

c. Need additional triaxial tests to evaluate the effects of fibers in a confined state.

d. Need more research to determine the effect of fiber stabilization with lime modification of clays and cement stabilization of sands.

e. Need field tests to evaluate the performance of fiber stabilization under actual traffic loadings.

f. Need more research to determine the potential of the TEXSOL process.

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13. ABSTRACT *(Maximum 200 words)*

This report documents a laboratory study that evaluated the effectiveness of mechanically stabilizing low-strength soils with monofilament and fibrillated fibers. The study provides guidance on fiber type, length, and dosage rate to produce stabilized soils for contingency airfield construction. This study included a review of available literature and a two-phase laboratory test program.

The basis of this study was to determine the feasibility of using fibers to significantly enhance the strength of low-strength soils. The soil materials used in the laboratory study were a high plasticity clay (CH) and a beach sand (SP). Each soil was tested to determine the optimum moisture content, maximum dry density, soaked and as-molded CBR strengths. The clay and sand materials were then stabilized with monofilament and fibrillated fibers at various lengths and dosages. These stabilized materials were then evaluated with the Corps of Engineers Gyratory Testing Machine to determine gyratory shear strength properties. The stabilized soils that indicated an increase in gyratory shear strength were evaluated with the laboratory CBR procedure to determine the soaked and as-molded CBR strength values.

The findings of this study indicated that the monofilament fibers can improve strength values of beach sand and the fibrillated fibers can improve the strength values of a high plasticity clay. This laboratory study also indicated that the CBR test may not evaluate the effectiveness of fiber stabilization.

14. SUBJECT TERMS

Airfield construction	Fiber reinforcement	Gyratory testing machine
CBR tests	Fibrillated fibers	Mechanical stabilization
Contingency pavements	Gyratory shear strength	Monofilament fibers

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