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Fiber Reinforcement for Rapid Stabilization of Soft Clay Soils

Susan D. Rafalko, Thomas L. Brandon, George M. Filz,
and James K. Mitchell

Since World War II, the military has sought methods for rapid stabilization of weak soils for support of its missions worldwide. Over the past 60 years, cement and lime have been the most effective stabilizers for road and airfield applications, although recent developments show promise from nontraditional stabilizers, such as reinforcing fibers. The benefits derived from fibers may depend on whether they are used alone or in combination with chemical stabilizers. The ability of stabilizers to increase the strength of two soft clay soils within 72 h to support C-17 and C-130 aircraft traffic on contingency airfields was investigated. Laboratory test results showed that longer fibers increased the strength and toughness the most for a clay treated only with fibers. For a clay treated with fibers in addition to a chemical stabilizer, shorter fibers increased toughness the most, but the fibers had little effect on strength. Higher dosage rates of fibers had increasing effectiveness, but mixing became difficult for fiber contents above 1%. Poly(vinyl) alcohol fibers were anticipated to perform better than other inert fibers because of hydrogen bonding between the fibers and clay minerals, but these fibers performed similarly to other fibers.

Since World War II, the military has had a need to stabilize weak soils to support overseas operations and, as a result, has initiated research programs on rapid soil stabilization. The goal was to find a stabilizer that could be quickly and easily mixed into weak soil to create a pavement that could support traffic from military vehicles. Over the past 60 years, progress has been made, but a magic juice has not yet been found that has the ability to convert a weak soil to a strong material with little effort and in a matter of hours. Cement and lime are still among the most effective stabilizers in use today, although many claims have been made for nontraditional stabilizers, such as reinforcing fibers. The benefits derived from fibers may depend on whether they are used alone or in combination with chemical stabilizers, such as cement and lime.

The purpose of this research was to determine the most effective stabilizer to increase the strength of wet and soft clay soils within 72 h for contingency airfields. The Air Force Research Laboratory (AFRL) objective was to develop a method that would be suitable for stabilizing soils with a California bearing ratio (CBR) as low as 2, which represents a very poor subgrade condition. After treatment, the stabilized soil must sustain aircraft traffic from Globemaster

C-17s and Hercules C-130s. For added strength, the stabilized soil may be covered with a lightweight prefabricated aluminum grid or crushed aggregate, depending on availability.

The study discussed in this paper is part of a comprehensive project that used unconfined compression strength (UCS) tests to screen and compare the effectiveness of different stabilizers at a constant dosage rate of 5% by dry weight of soil. This dosage rate was selected because it is within a typical and reasonable range used in the field for soil stabilization. Once the most effective stabilizers were determined, the clay was treated using various dosage rates of stabilizers and evaluated with both UCS and CBR tests in a follow-up study. Details of the complete project are discussed and summarized elsewhere (1). A similar study, currently being performed by the U.S. Army Corps of Engineers at its Engineering Research and Development Center, is focusing on soil stabilization of silty sand and clay (2, 3) for unsurfaced airfields (4, 5) as part of the Joint Rapid Airfield Construction program (6).

This paper reviews a number of different fiber types and their potential for stabilizing soft clay soil. The results of UCS tests performed on two clays treated with fibers and chemical stabilizers are presented and discussed.

LITERATURE REVIEW

Polypropylene Fibers

Polypropylene is a common material used for fiber reinforcement of soils. It is manufactured in two forms: monofilament and fibrillated. Monofilament fibers are individual, cylindrical fibers. Fibrillated fibers are flat, tape-like fibers that can be described as a latticework of "stems and webs" as the fibers break apart during mixing and compaction (7).

Nylon Fibers

Nylon fibers are used as reinforcement in concrete to increase ductility, durability, and toughness. When nylon fibers are used in concrete, they can absorb water, allowing the fibers to cure the concrete from the inside out (8). This absorbed water also contributes to adhesion between the fibers and concrete. Although scant research has been done on the use of nylon fibers with soil, these fibers may mechanically and chemically stabilize soil, especially when combined with cement.

Poly(vinyl) Alcohol Fibers

Poly(vinyl) alcohol (PVA) fibers also are used as reinforcement in concrete to increase ductility, durability, and toughness because

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hydrogen bonds form between the hydroxyl groups of the PVA fibers and cement particles (9). Occasionally, the hydrogen bonding between the PVA fibers and concrete is so strong that the PVA fibers rupture instead of pulling out of the cement matrix. If the PVA fibers do rupture, this fiber-reinforced concrete may be too brittle for a particular application. To counteract this phenomenon, some PVA fibers are coated with an oiling agent so that the PVA fibers will pull out of the cement matrix instead of rupturing.

Clay has been stabilized with PVA solution where hydrogen bonds also have formed between the hydroxyl groups of the PVA molecules and the silicate sheets of the clay (10). However, stabilization using PVA fibers has not been investigated previously. It might be anticipated that the hydroxyl groups of the PVA fibers may form hydrogen bonds with the silicate sheets of the clay and could be effective in stabilizing the clay soil both chemically and mechanically. If the soil is treated with cement in addition to PVA fibers, the fibers may bond better to a clay–cement mixture than clay alone, because bonding between fibers and cement has been verified.

Portland Cement and Lime

Portland cement and lime have long been used for soil stabilization, and their chemistry and effects in soil have been well described in the literature (11–14).

Calcium Carbide

When calcium carbide reacts with water, the end products are acetylene gas and hydrated lime, with production of quicklime during an intermediate step. More water is consumed in these chemical reactions, and more water is evaporated by the higher heat at which these reactions take place than in quicklime hydration alone. This suggests that calcium carbide might have the potential for use as a soil stabilizer and could be more effective than lime. Furthermore, if the acetylene gas were captured and combusted, even more water could be driven off.

Calcium carbide is most commonly used for the speedy moisture test [ASTM D4944 (15)] but apparently has not been used for soil stabilization.

MATERIALS AND METHODS

The following sections describe index properties of the two clays, test procedures used to determine the UCS of the soil-stabilizer mixtures, and properties of the stabilizers.

In this study, stabilizers were categorized as primary or secondary stabilizers. The primary stabilizers were applied at a dosage rate of 5% chemical stabilizer or 0.05% to 1% fibers by dry weight of soil. As secondary stabilizers, fibers were used in addition to primary chemical stabilizers. All of the fibers used as secondary stabilizers were applied at a dosage rate of 1% by dry weight of soil.

Testing Program

Soil Characterization

ASTM standard methods were used to determine the classification, Atterberg limits, particle size distribution, specific gravity, and

organic content of two clays; Staunton clay and Vicksburg Buckshot clay (VBC). Mineralogical analyses were performed also.

Initial Water Contents

Water contents of both soils were adjusted to produce the same initial untreated strength, as represented by a CBR of approximately 2. This value was selected by the ARFL because it represents a very poor subgrade condition. CBR values were determined for both soils according to ASTM D1883 (15) at various water contents using standard Proctor effort [ASTM D698 (15)]. Once a well-defined curve of CBR versus water content was established, the required water content for a CBR of 2 could be determined. The required initial water contents for the Staunton clay and VBC to achieve a CBR of 2 were determined to be 33.5% and 44.2%, which compare with liquid limit values of 53 and 84, respectively.

Sample Preparation and Testing

To ensure uniformity, the unprocessed soil was air dried, broken down to particle sizes that could pass a #4 sieve, and then hydrated to the appropriate water content. The appropriate amount of stabilizer was added according to the desired percentage by dry weight of soil necessary for each batch. Kitchen stand mixers were used to mix the stabilizers into the clay for a mixing time of 5 to 10 min. When fibers were used, some fibers tended to cluster and bunch up during mixing, but the majority of the fibers did not segregate from the wet clays used in this research. More difficulties with mixing and segregation may occur in drier soils.

The soil was then compacted into four plastic tubes with an internal diameter of 2 in. (50 mm) and height of 4 in. (100 mm). To compact the samples, a machined aluminum stand was used to hold the mold in place, and a small drop hammer was used for compaction (16). The soil was placed in five lifts, and each lift was compacted to produce the same density as produced by ASTM D698 (15) at the same water content.

After compaction, both ends of the sample were leveled using a metal screed, capped with a plastic lid, and sealed using electrical tape. The samples for each batch were then stored in a humid room for curing times of 1, 3, 7, and 28 days, after which the samples were removed and carefully extruded from the molds. UCS tests were run according to ASTM D2166 (15) at a strain rate of 1% per minute.

Two batches were prepared and tested to determine the 3-day UCS for each stabilizer or combination of stabilizers. The UCS was plotted against curing time for both batches, and the 3-day UCS was calculated from a trend line that best fit the data. This process mitigates the effect of scatter in the data.

Stabilizers

Polypropylene Fibers

Two types of polypropylene fibers were used. The fibrillated polypropylene (FP) fibers are flat, tape-like fibers that are 0.001 in. (0.025 mm) thick, variable in width, and 0.75 in. (19 mm) long, with a specific gravity of 0.91. The FP fibers have a tensile strength of 97 ksi (0.67 GPa) and a Young's modulus of 580 ksi (4 GPa). The monofilament polypropylene (MP) fibers are 0.75 in. (19 mm) long and have a nominal diameter of 0.002 in. (0.051 mm). The

MP fibers have a specific gravity of 0.92 and a Young's Modulus of 550 ksi (3.8 GPa).

Nylon Fibers

The nylon fibers are 0.75 in. (19 mm) long and 0.0013 in. (0.033 mm) in diameter with a specific gravity of 1.16. These fibers have a tensile strength of 130 ksi (0.9 GPa) and a Young's modulus of 750 ksi (5.2 GPa). The nylon fibers can absorb up to 4.5% of their weight in water.

PVA Fibers

Two types of PVA fibers were used. The PVA1 fibers are 0.33 in. (8.4 mm) long and 0.0016 in. (0.041 mm) in diameter with a specific gravity of 1.3. The PVA1 fibers have a tensile strength of 203 ksi (1.4 GPa). The PVA2 fibers are 0.50 in. (13 mm) long and 0.004 in. (0.1 mm) in diameter with a specific gravity of 1.3. The PVA2 fibers have a tensile strength of 160 ksi (1.1 GPa) and a Young's modulus of 4,210 ksi (29 GPa). Both fibers are resin bundled for easier mixing. According to the distributor, the PVA2 fibers are coated by an oiling agent, whereas the PVA1 fibers are not.

Portland Cement

Both Type I/II and Type III cement were used. ASTM C 150 (17) specifies that the composition of both Type I and Type III cement has a maximum of 55% to 56% C₃S, 19% C₂S, 10% C₃A, and 7% C₄AF, whereas the composition of Type II cement has a maximum of 51% C₃S, 24% C₂S, 6% C₃A, and 11% C₄AF. Type I/II cement must meet both of the compositional requirements for Type I and Type II cements (18).

Lime

Pelletized and pulverized quicklimes were used. The pelletized quicklime contains more than 90% CaO and has particles less than 0.125 in. (3.2 mm) in size. The pulverized quicklime contains more than 90% CaO and has particles less than 0.0058 in. (0.15 mm) in size.

Calcium Carbide

The calcium carbide used in this study contains 75% to 85% calcium carbide and 10% to 20% calcium oxide.

TABLE 1 Clay Fractions

Mineral	Staunton	
	Clay (%)	VBC (%)
Kaolinite	45	10
Montmorillonite	20	60
Mica	10	10
Vermiculite	10	15
Hydroxyl interlayered vermiculite	4	—
Gibbsite	1	—
Quartz	10	5

RESULTS

Soil Characterization

For the mineralogical analyses, the quantity of kaolinite in each clay fraction was first determined by thermogravimetric analysis (TGA) using Georgia kaolinite as a standard (Lucian Zelazny, unpublished data). The remaining percentages of minerals were then determined by X-ray diffraction using the TGA-determined kaolinite as an internal standard. Based on these analyses, the clay fraction is shown in Table 1.

The percentage of kaolinite, gibbsite, and quartz may have an error margin of approximately 2% to 3%, and the remaining minerals may have an error margin up to 5%. Although amorphous material was not detected, up to 2% to 3% may be present. The index properties of the clays are shown in Table 2. Even though both clays are classified as highly plastic, they have quite different compositions and properties.

Unconfined Compressive Strength Tests

Staunton Clay

Fibers as Primary Stabilizers Figure 1 shows the 3-day normalized UCS and 3-day UCS for Staunton clay treated with the indicated fiber types and dosages. The normalization is by the untreated Staunton clay's 3-day UCS of 16 psi (110 kPa).

In addition to increasing strength, fibers are known for increasing toughness, which is the amount of energy a material can absorb. Toughness is important because chemically treated soils without fibers exhibit brittle stress-strain curves and have relatively little toughness, which may cause the treated soil to crack and fail suddenly.

TABLE 2 Summary of Soil Index Properties

Soil Name	USCS Soil Type	Group Name	Atterberg Limits			Fines (<#200) (%)	Max. Dry Unit Weight ^a (pcf) ^b	Opt. Moisture Content ^a (%)	Specific Gravity
			LL	PL	PI				
Staunton clay	CH	Fat clay	53	25	28	81	92.0	26.0	2.74
VBC	CH	Fat clay	84	35	49	>95	89.8	27.8	2.79

^aStandard compactive effort (ASTM D698).

^b1 pcf = 0.1571 kN/m³.

USCS = Uniform Soil Classification System, LL = liquid limit, PL = plastic limit, PI = plasticity index.

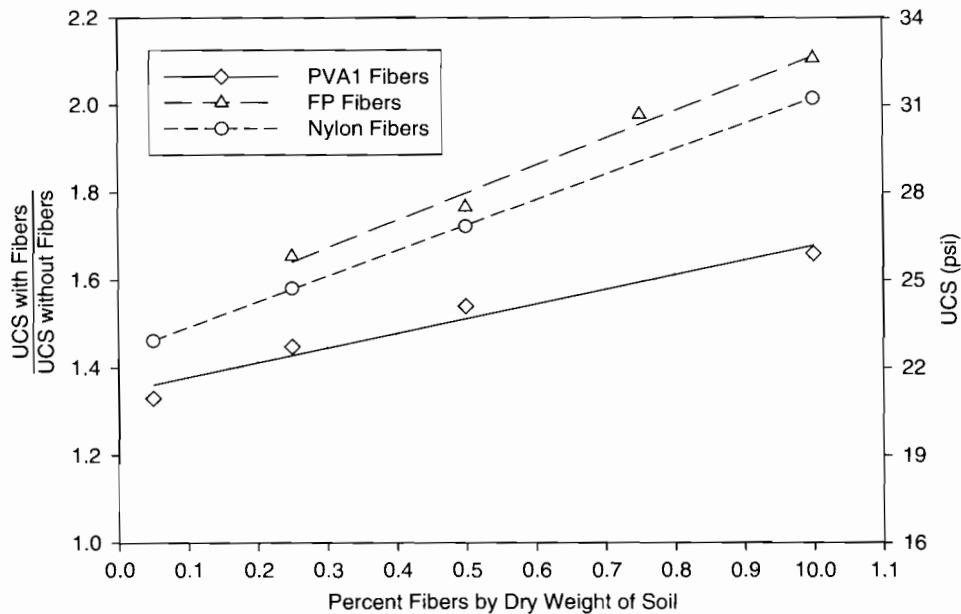


FIGURE 1 Three-day normalized UCS and 3-day UCS versus percentage fibers by dry weight of Staunton clay.

Not only will a runway fail more quickly but also this sudden cracking and failure can create foreign object debris on a runway surface, which fibers have been found to reduce (2). An increase in toughness is desirable, because the longevity of the airfield would be expected to increase with increasing toughness.

Toughness can be evaluated by calculating the area underneath the stress-strain curve. Figure 2 shows the 3-day normalized toughness and 3-day toughness calculated at 15% strain for Staunton clay treated with the same fiber types and dosages as in Figure 1. The

normalization in Figure 2 is by the 3-day toughness of 2.0 in.-lb/in.³ (13.8 kJ/m³) for the untreated Staunton clay. For both untreated and treated Staunton clay, the UCS did not increase with curing time, and failure occurred at high strains around 10% and greater.

Figures 1 and 2 show that the FP fibers increased strength and toughness the most, followed by the nylon fibers, and then the PVA1 fibers. Based on these results, the longer FP and nylon fibers consistently performed better than the shorter PVA1 fibers. Although strength and toughness increased with increasing fiber content, the

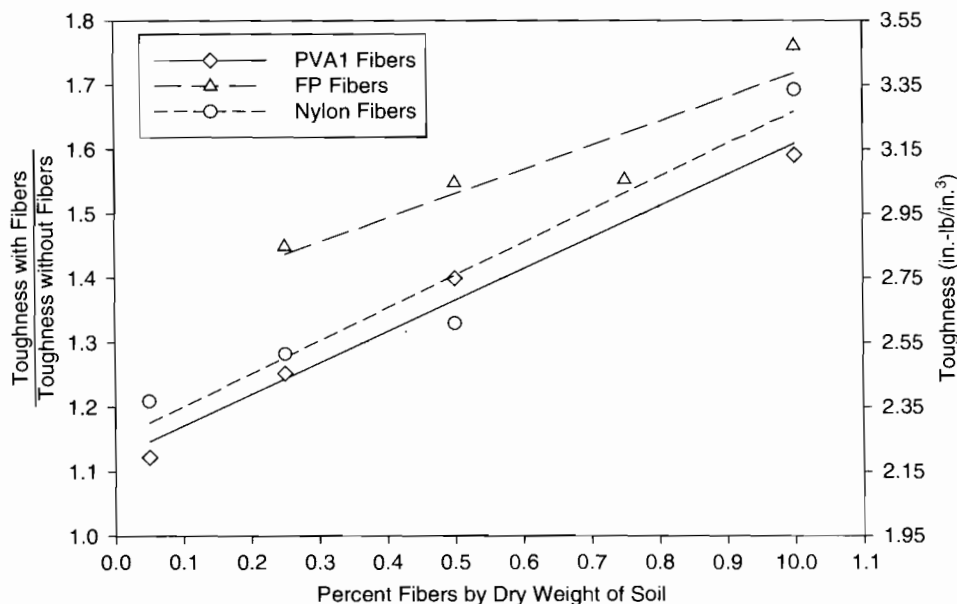


FIGURE 2 Three-day normalized toughness and 3-day toughness calculated at 15% strain versus percentage fibers by dry weight of Staunton clay.

TABLE 3 Three-Day UCS for Staunton Clay Treated with 5% Primary Stabilizer and 1% Fibers by Dry Weight of Soil

Fiber Type	UCS			
	No Primary Stabilizer (psi)	Type I/II Cement (psi)	Type III Cement (psi)	Calcium Carbide (psi)
No fibers	16	284	266	129
PVA1 fibers	26	258	275	148
PVA2 fibers	— ^a	240	235	—
FP fibers	33	205	212	—
Nylon fibers	31	174	190	157

1 psi = 6.89 kPa.

^aTests not conducted.**TABLE 4** Three-Day Toughness Calculated at 2% Strain for Staunton Clay Treated with 5% Primary Stabilizer and 1% Fibers by Dry Weight of Soil

Fiber Type	Toughness			
	No Primary Stabilizer (in.-lb/in. ³)	Type I/II Cement (in.-lb/in. ³)	Type III Cement (in.-lb/in. ³)	Calcium Carbide (in.-lb/in. ³)
No fibers	0.104	2.8	3.1	1.85
PVA1 fibers	0.151	4.2	4.7	2.3
PVA2 fibers	— ^a	3.5	3.6	—
FP fibers	0.169	3.4	3.3	—
Nylon fibers	0.152	3.0	2.5	1.86

1 in.-lb/in.³ = 6.89 kJ/m³.^aTests not conducted.

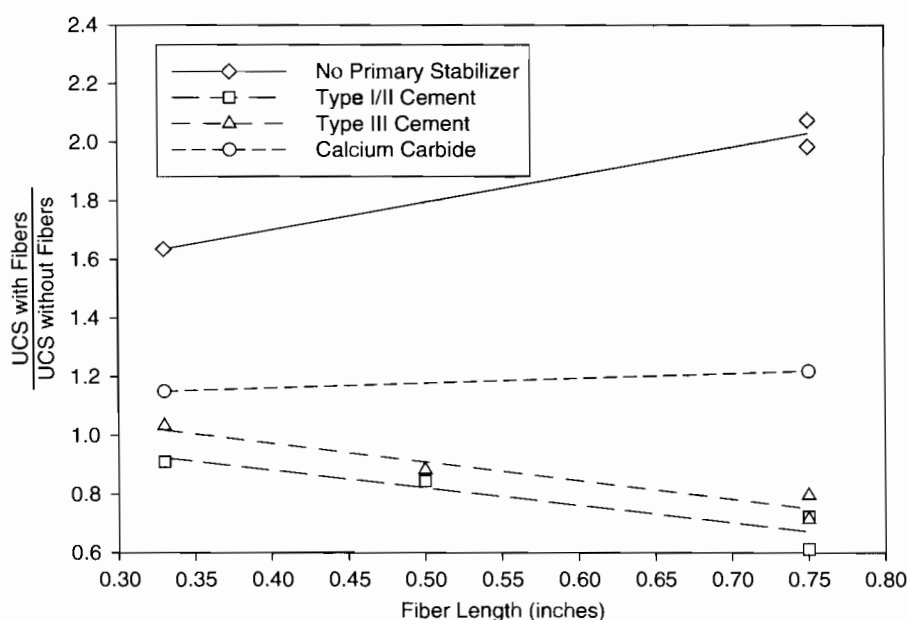
maximum dosage rate was limited to 1% of dry weight of soil because mixing became difficult at greater dosage rates.

Fibers as Secondary Stabilizers Table 3 shows the 3-day UCS for Staunton clay treated with 5% primary stabilizer without fibers and with 1% fibers by dry weight of soil. In general, the addition of fibers decreased the maximum strength gain of the cement-treated clay, and more decrease occurred with longer fibers. This is shown in Figure 3, where the 3-day UCS values with fibers are normalized by the 3-day UCS values without fibers. The 0.33-in.-long PVA1 fibers had little effect on the strength of the cement-treated clay, the 0.5-in.-long PVA2 fibers reduced the strength slightly, the 0.75-in.-long FP fibers reduced the strength more, and the 0.75-in.-long nylon fibers reduced the strength the most. The effect of fiber diameter on normalized strength also was evaluated, but the results were inconsistent, possibly because of simultaneous variations in other factors that may have had a greater influence on strength, such as fiber shape and length.

Table 3 and Figure 3 also show that the addition of fibers to calcium carbide-treated Staunton clay increased the maximum strength of the mixture compared with treating Staunton clay with calcium carbide alone, which is the opposite effect that fibers had on cement-treated Staunton clay. However, when nylon fibers were added to calcium carbide-treated Staunton clay, the maximum strength occurred at high strains near 15%, which was unlike the cement- and fiber-treated Staunton clay specimens, which reached their maximum strength at around 1% strain.

For reference, Figure 3 also shows that fiber treatment increased the strength of the Staunton clay without chemical stabilizers. In this case again, the maximum strength occurred at strains greater than 10%.

The addition of fibers tended to increase the toughness of the Staunton clay treated with 5% primary stabilizer. Table 4 shows the 3-day toughness values for the Staunton clay treated with 5% primary stabilizer without fibers and with 1% fibers by dry weight of soil. In

**FIGURE 3** Three-day normalized UCS versus fiber length for Staunton clay treated with 5% primary stabilizer and 1% fibers by dry weight of soil (1 in. = 25.4 mm).

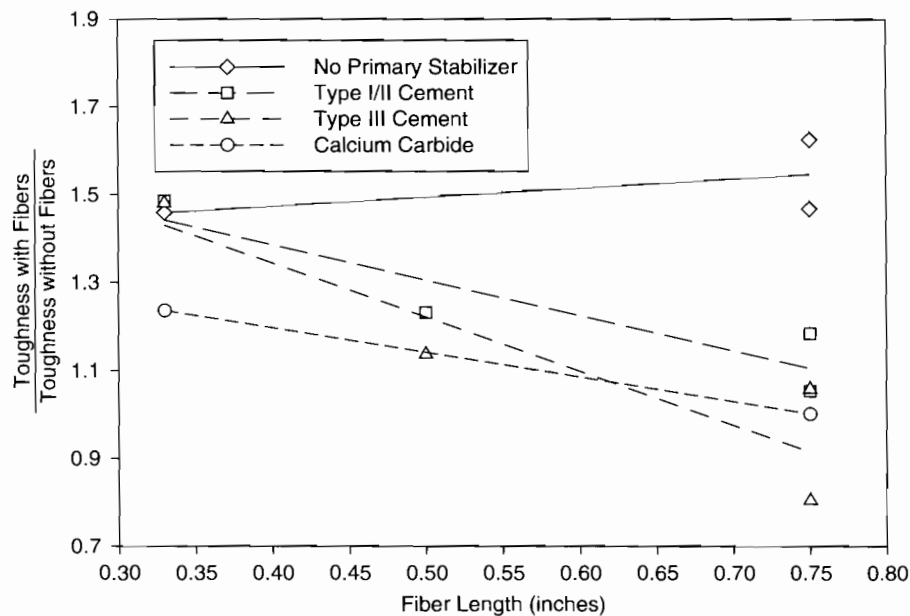


FIGURE 4 Three-day normalized toughness calculated at 2% strain versus fiber length for Staunton clay treated with 5% primary stabilizer and 1% fibers by dry weight of soil.

this case, the toughness is calculated at 2% strain. Figure 4 shows the effect of fiber length on the 3-day normalized toughness, where the normalization is by the 3-day toughness for each primary stabilizer without fibers. The Staunton clay treated with 5% primary stabilizer, and 1% of the shorter fibers produced the highest toughness values.

Figure 5 shows the 3-day stress-strain curves for Staunton clay treated with 5% Type III cement and 1% fibers by dry weight of clay. The stress-strain curves illustrate the changes in toughness

and strength for each fiber type. Only the PVA1 fibers increased toughness without decreasing strength.

VBC: Fibers as Secondary Stabilizers

In an attempt to isolate the contribution of chemical bonding between the PVA1 fibers and soil, the nylon and MP fibers were cut in

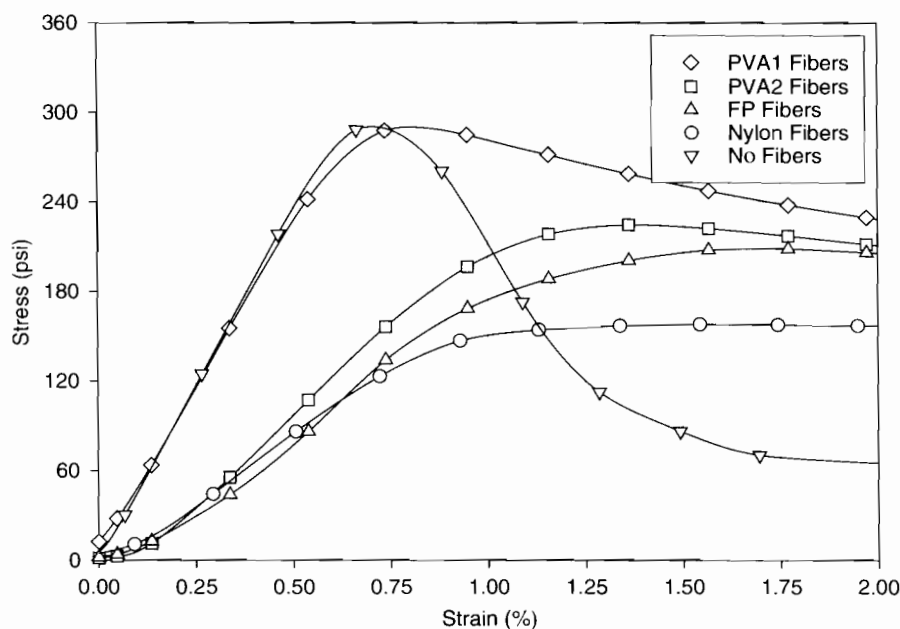


FIGURE 5 Three-day stress-strain curves for Staunton clay treated with 5% Type III cement and 1% fibers by dry weight of soil (1 psi = 6.89 kPa).

TABLE 5 Three-Day UCS for VBC Treated with 5% Primary Stabilizer and 1% Fibers by Dry Weight of Soil

Fiber Type	UCS				
	No Primary Stabilizer (psi)	Type III Cement (psi)	Pelletized Quicklime (psi)	Pulverized Quicklime (psi)	Calcium Carbide (psi)
No fibers	7	112	93	79	89
PVA1 fibers	— ^a	108	103	105	99
Halved MP fibers	—	110	98	—	99
Halved nylon fibers	—	109	—	—	—

^aTests not conducted.

half, resulting in a length of 0.375 in. (9.5 mm) to approximate the length of the PVA1 fibers, which have a length of 0.33 in. (8.4 mm). Therefore, the chemical interactions should largely be responsible for differences between the fiber-reinforced soil specimens, because the nylon, MP, and PVA1 fibers have similar diameters of 0.0013 in. (0.033 mm), 0.002 in. (0.051 mm), and 0.0016 in. (0.041 mm), respectively.

Table 5 shows the 3-day UCS for VBC treated with 5% primary stabilizer without fibers and with 1% fibers by dry weight of soil. The addition of 1% halved MP fibers or PVA1 fibers to VBC treated with either 5% pelletized quicklime, pulverized quicklime, or calcium carbide all produced slightly higher strengths than exhibited by the chemically stabilized VBC without fibers. By contrast, the VBC treated with 5% Type III cement experienced little change in strength because of the addition of fibers. Without treatment, the VBC had a 3-day UCS of 7 psi (48 kPa) and did not appear to gain strength over time.

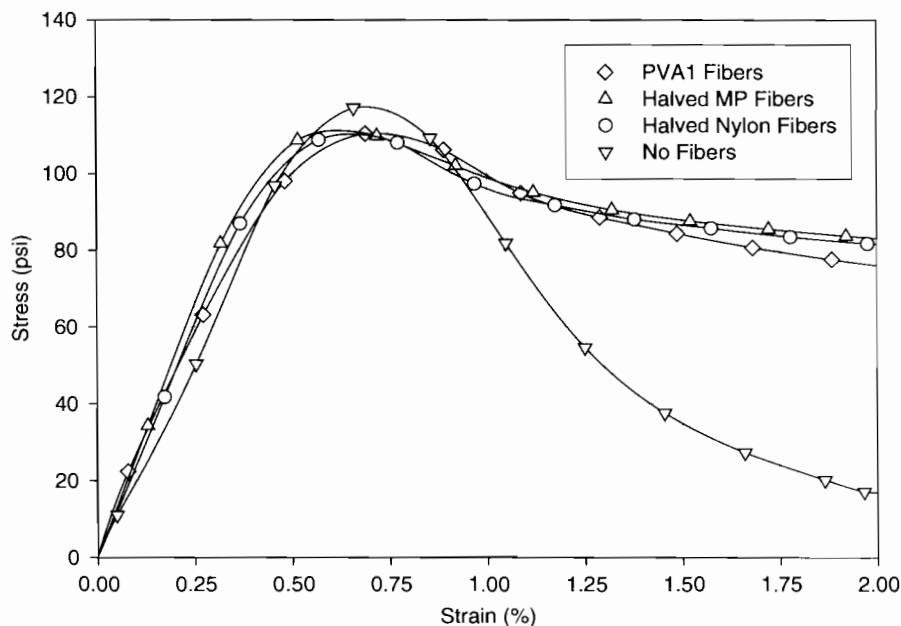
Figure 6 shows the 3-day stress–strain curve for VBC treated with 5% Type III cement and 1% fibers by dry weight of soil. The shapes

of the stress–strain curves for the VBC treated with cement and fibers were much more similar than the corresponding plots for Staunton clay (Figure 5). These results indicate that the fiber dimensions may have more influence on the stress–strain response than the chemical composition of the fibers.

DISCUSSION OF RESULTS

Fibers as Primary Stabilizers

When used as primary stabilizers, all of the fiber types and dosages increased the strength and toughness of the Staunton clay. Overall, treatment with the longer FP fibers at the highest mixable dosage rate of 1% increased the strength and toughness of the Staunton clay the most. Longer fibers may have been more effective in this case because the untreated soil was quite ductile and failed at high strains, which may have allowed a greater portion of the tensile strength of the longer fibers to be mobilized.

**FIGURE 6** Three-day stress–strain curves for VBC treated with 5% Type III cement and 1% fibers by dry weight of soil.

The strength increase from the addition of fibers as a primary stabilizer may be more significant than the increase in toughness, because the untreated Staunton clay with a water content of 33.5% is already quite ductile. However, even the highest strengths for the wet Staunton clay treated with fibers were still low. Therefore, using fibers as a primary stabilizer for clays with high water contents may not provide enough improvement to be of any significant value in most field applications.

Fibers as Secondary Stabilizers

For a secondary stabilizer to be considered effective, it must improve performance more than the primary stabilizers at a lower dosage rate, with this improvement being great enough to outweigh the added cost and complexity.

As secondary stabilizers, most of the fiber types increased the toughness of the chemically treated Staunton clay and VBC, but often decreased the UCS. Shorter fibers tended to increase toughness the most and decrease UCS the least for Staunton clay treated with 5% primary stabilizer and 1% fibers. Shorter fibers may have been more effective because there are a larger number of shorter fibers than longer fibers at the same dosage rate, so more fibers may be properly oriented and positioned to resist loading. However, longer fibers were better for the Staunton clay treated with 5% calcium carbide and 1% nylon fibers. Similar to the untreated Staunton clay, this mixture reached its peak strength at high strains where the fibers may become more effective as they become more straightened and tensioned. If the toughness effects of fiber reinforcement are mainly influenced by fiber length and soil stiffness, shorter fibers may be more effective for untreated clays with much lower water contents than the clays tested in this study, because such clays would have more stiff and brittle responses.

The decrease in UCS with the addition of 1% fibers to the Staunton clay treated with 5% primary stabilizer may have been caused by planes or pockets of weakness introduced by the fibers, and the load may not have been transferred well between the fibers and a soil with such a high water content, because the water may have acted as a lubricant (19). The PVA2 fibers may have introduced larger pockets of weakness as a result of the larger fiber diameter, which is more than two times the diameter of any of the other fibers. In addition, the oiling agent covering the fibers may have acted as an additional lubricant between the fibers and the soil. The FP fibers may have introduced small failure planes, because they may not have been mixed well into the soil and did not fully break apart into "stems and webs" (7). The nylon fibers also may have introduced pockets of weakness, because these fibers also did not mix well into the soil and often "bunched up," creating pockets of nylon fibers throughout the soil.

The fiber composition did not have a large influence on effectiveness, as shown by the similar stress-strain curves for VBC treated with 5% Type III cement and 1% fibers of different materials but all of approximately the same dimensions. In addition, the fibers were observed to pull out of the soil matrix, and no distress of the fibers was visible, so the fiber material strength most likely did not influence the treated soil's strength.

The PVA fibers did not exhibit any evidence of improvement because of hydrogen bonding with untreated or treated clay. In treating the Staunton clay and VBC, the PVA fibers showed no signs of distress after failure; in treating the VBC, the fibers performed sim-

ilarly to the MP and nylon fibers, which had approximately the same dimensions. Although Kanda and Li (9) stated that the effectiveness of PVA fibers was independent of water-to-cement ratio (wc/c) for concrete mixtures, the effectiveness of the PVA fibers may have been influenced by the drastically higher wc/c of the Staunton clay and the VBC, which was approximately 8 to 22 times higher than the wc/c of a typical concrete mixture.

CONCLUSIONS

The combination of chemical stabilizer and short fibers was most effective in treating the two clays, because the chemical stabilizer greatly increased the UCS and the short fibers significantly increased the toughness. Because soil treated with only a chemical stabilizer is often brittle, the addition of the short fibers may be important. Other key findings are listed as follows:

1. When used as primary stabilizers, increasing the dosage rate of fibers continued to increase the strength and toughness of the soil, but the maximum dosage rate was limited to 1% of the dry weight of soil because mixing became difficult above this dosage.
2. When used as primary stabilizers, longer fibers may have increased the strength more than shorter fibers because the soil was ductile and bulged at high strains before failure, which should have allowed a greater mobilization of the strength of long fibers before pullout.
3. Although adding fibers as a primary stabilizer to a soft clay may have resulted in strength increases, the magnitude of the increase may not be enough for airfield applications.
4. The most important effect of adding fibers to a clay treated with a primary chemical stabilizer may have been an increase in toughness, because soil treated with only a primary stabilizer was often brittle, and the fibers had little effect on peak strength.
5. As secondary stabilizers, shorter fibers appeared to increase toughness the most, because the treated soil was brittle and failed at small strains, where a greater number of short fibers may have been oriented to resist loading than fewer long fibers at the same dosage rate.
6. As secondary stabilizers, the size and shape of the fibers may have been very important, because fibers that were too large or did not disperse well during mixing may have decreased the UCS of a treated clay by introducing failure planes or pockets of weakness.
7. The fiber material may not have had much influence on the UCS as secondary stabilizers, as demonstrated by the similar stress-strain curves of soil treated with different fiber types of similar dimensions.
8. Hydrogen bonding between the PVA fibers and untreated or treated clay may not have occurred as a result of the very high wc/c of the Staunton clay and VBC.

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