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USE OF FIBER-REINFORCED SOIL FOR BLAST PROTECTION

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ABSTRACT

Soil berms have been used to resist the blast effect of conventional weapons on structures such as bunkers, aircraft shelters, and weapon facilities. The resistance to blasting depends on the ductility of the soil material; that is, on its ability to retain the maximum shear strength even at very high strain levels. Among other solutions, soil berms have been particularly useful to reduce the shock, pressure, and impact of explosions/blasts on the structure. The use of geosynthetic reinforcements not only allows construction of the berms under geometry constraints, but it also has the potential to improve the ductility of the blast protection system. This paper focuses on the use of fiber-reinforcement to increase the ductility of soil berms used for blast protection.

An experimental testing program involving triaxial tests of unreinforced and fiber-reinforced soils was conducted to evaluate the ductility and overall improvement on the mechanical response due to the presence of polymeric fibers. The study was conducted for both coarse-grained and fine-grained soils. Soils under comparatively high relative compaction exhibited a brittle response that led to significant post-peak shear strength losses. .Instead, the addition of fibers to both the granular and cohesive soils not only increases the shear strength but, equally important, reduced the post-peak shear strength loss of the soil. Overall, the use of fibers was found to be a promising alternative to enhance the performance of soil berms for blast protection.

INTRODUCTION

The various branches of the armed services often require structures designed to resist the blast effects from conventional weapons. Such structures include bunkers, aircraft shelters, and weapon facilities. Blast effects include high-pressure impulse loading, project/fragment impact and penetration, and cratering. Conventionally, blast protection has been provided by heavily reinforced concrete structures, buried structures, soil protection berms, or a combination of these approaches. However, these blast protection methods may be expensive as well as sensitive to multiple strikes (Bachus et al. 1993).

Soil berms have been particularly useful to reduce the shock, pressure, and impact of explosions on the structure. However, the use of unreinforced soil covers or berms is often restricted by the amount of land available for construction and by the logistics of moving large volumes of soil. This limitation can be addressed by the use of geosynthetic reinforcements, which allow for construction of steep inclinations. Specifically, the use of geosynthetic soil reinforcement techniques in protection berms or bunkers can provide the following benefits:

[1] Reduce the land area and quantity of soil required for construction compared to unreinforced berms.
[2] Simplify the repair of bomb damage compared to reinforced concrete structures.
[3] Reduce construction time, compared to reinforced concrete structures, which may prove crucial in military operations.
[4] Provide ductility to the blast protection structures, which improves the energy absorbing potential of the structure and reduces the susceptibility to multiple strikes.

While the first three of the listed benefits represent economic advantages that can be accounted for in cost evaluations, the focus of this paper is on quantification of the ductility of reinforced soil structures (item [4] above), as this is an aspect that requires technical evaluation. More specifically, this paper focuses on the use of fiber-reinforced soil, as this approach has the potential to significantly increase the ductility of soil berms. In addition, fiber-reinforced soil is particularly suitable to ‘retrofit’ existing structures that require improved blast protection capabilities, as well as to ‘patch’ or repair damaged structures (Bachus et al. 1993). The ductility of fiber-reinforced soil will be evaluated by quantifying the ability of fibers to prevent the shear strength loss of soil that occurs after the peak shear strength has been achieved.

This paper provides a review of the design consideration in blast protection berms, the use of geosynthetic reinforcement for blast protection, and past research on the use of polymeric fibers for related applications. Subsequently, the results are presented of an experimental testing program aimed at quantifying the increased ductility of fiber reinforced soil, in relation to that of unreinforced soil. Conclusions and future advances involving fiber reinforcement for blast protection are finally provided.

CURRENT STATUS ON THE USE OF GEOSYNTHETIC REINFORCEMENTS FOR BLAST PROTECTION

General

The design of blast protective structures aims at avoiding personal losses but also at protecting equipment, and explosives from the blasts of conventional weapons. Conventional design of blast protective structures, such as military bunkers, involves heavily reinforced concrete walls with a minimum thickness of 12” (Drake et al. 1989). These structures are often constructed with a surrounding protective soil slope or berm (Bachus et al. 1993). The concrete structure is designed to resist significant compressive stresses and to withstand flying debris. Protective soil berms surrounding the structure buffer the shock and pressure that the structure receives and increases the number of repeated explosions that the structure can tolerate. Soil berms have been traditionally constructed using flat slopes (ranging from 1.5H: 1V to 2.5H: 1V) in order to provide stability under both static and dynamic loading conditions. Accordingly, the construction of berms with gentle soil slopes increases space requirements for these structures, which may lead to impractical solutions.

<u>Overview on blast protection berms</u>

Soil berms offer a practical alternative when soils are available in the vicinity of the structure to be protected. Specifically, soil can provide good insulation against blast pressures, and can also be easily repaired in case of damage (Bachus et al. 1993). A typical bunker layout is shown in Figure 1. The soil berm provides two functions in the bunker performance: (1) protect the integrity of the reinforced concrete structure from both pressures caused by blasting and flying debris, and (2) dampen the energy of the blast to protect the occupants and equipment inside the facility.

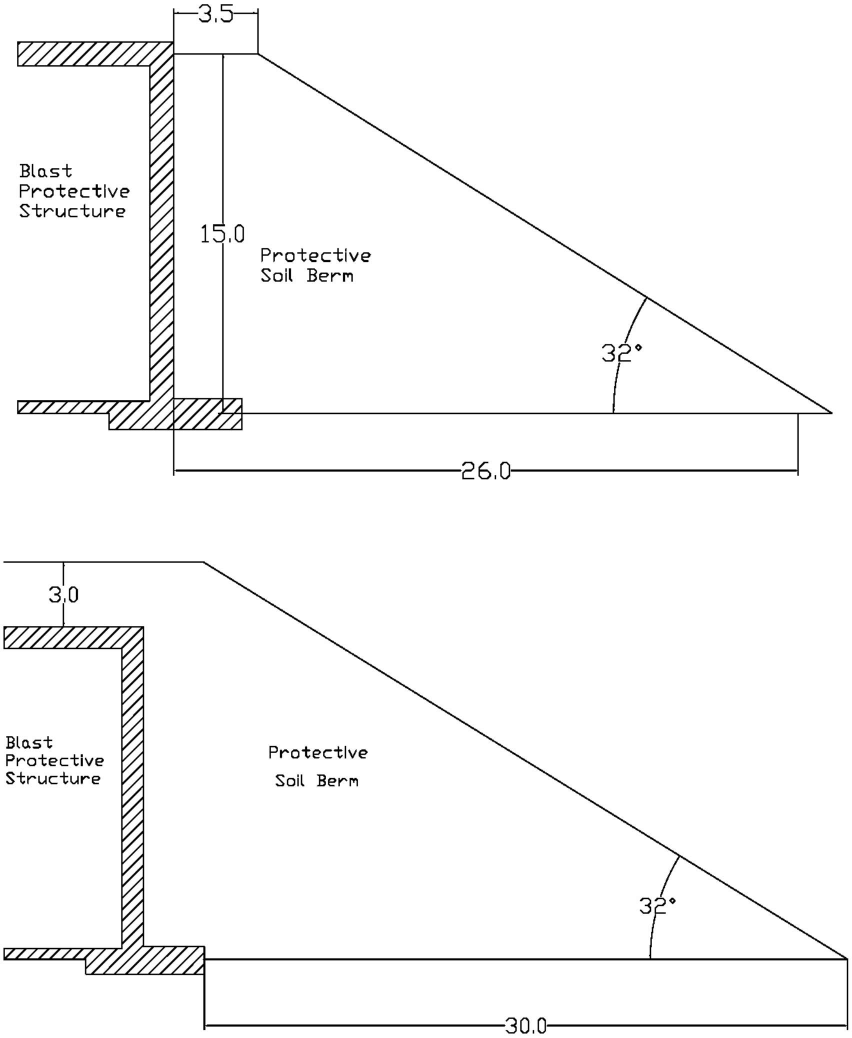


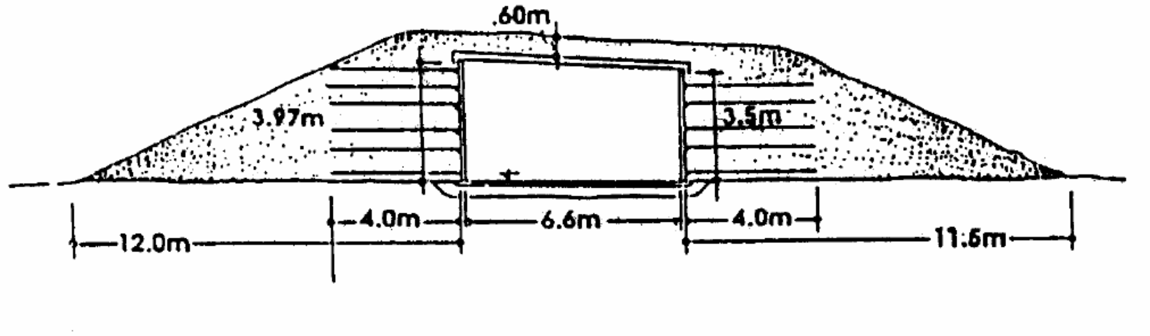
Figure 1: Typical design alternatives of a blast protective bunker (Drake et al., 1989).

Cotharp et al. (1985) studied the effect of blast loading on soil covered bunkers and found that the soil cover reduced the blast pressures against the bunker wall, decreased the flexural deformation of the wall, and decreased the damage to the wall caused by the penetration of shrapnel. Hyde (1989) conducted similar studies for bunkers covered by a sand berm, with the results confirming the conclusions made by Cotharp et al. (1985). The effectiveness of soil berms against blast loading stems from the ability of soil to dissipate (absorb) more energy than reinforced concrete (Kokusho and Ishizawa 2004).

Schimming and Saxe (1964) conducted cyclic direct shear on Ottawa Sand and found that the sand showed similar strength under static and dynamic loading. However, Farr (1990) used submillisecond loading on multiple cohesionless soils and found that increasing strain rate during testing led to a significant increase on the sand stiffness. Altun at al. (2005) provided evidence that using cohesionless soils with low fines content and a high particle angularity increased the soils resistance to deformations and strength loss during cyclic loading.

Overview on the use of reinforcement for blast protection berms

The use of protective berm constructed using soil reinforcement was evaluated by Reid (1991). A bunker with internal dimensions of 47 feet by 22 feet in plan and 11 feet high was constructed using metallic reinforcements and concrete facing panels (Figure 2). The reinforced soil mass extended at uniform height for a length of 13 ft (4 m). The reinforced soil structure was designed using conventional design accounting only for static loads. No noticeable effect on the structure was observed after simultaneously detonating forty 454 kg (1,000 lb) bombs (with an equivalent explosive weight of 189 kg) at a distance of 87 feet from a side wall of the structure. Detonation of 500 lb bombs just outside the structure produced small displacement of individual facing panels, while detonation of 500 lb bombs as close as 10 ft from the facing produced some localized failures, which were considered of easy repair.



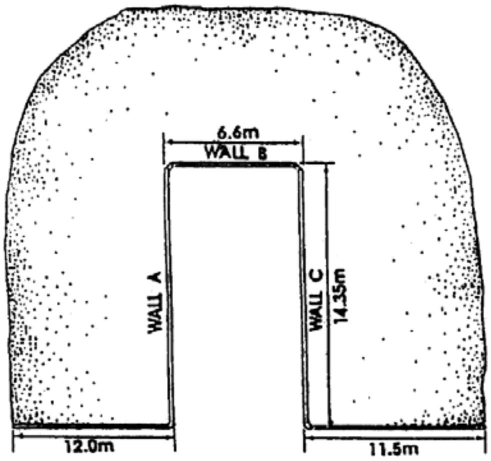


Figure 2. Reinforced soil bunker used in field testing program (Reid, 1991).

Good evidence of the relevance on the blast performance of the ductility of the protective berm structure is provided by Ng et al. (2000). This study provides a comparison on the blast performance between a concrete-faced wall reinforced using metallic strips and a more ductile wall reinforced using geotextiles (wrapped around facing). While both structures are more flexible than conventional concrete reinforced structures, the results of the full-scale testing program provided clear evidence that geosynthetic reinforcement with flexible wrapped around facing provides superior performance than metallic reinforced structures against blast protection.

Fiber reinforcement is a promising solution to stabilize soil blast protection soil berms (Bachus et al. 1992). Commercially available products include polypropylene fibers distributed with lengths ranging from one to two inches. Two internal failure mechanisms, pullout and breakage, can be identified for fiber-reinforced soil (Maher and Gray 1988, Zornberg 2002). Under relatively low confining pressures, the fibers will develop a maximum tension under which they will be pulled out from the soil matrix being sheared. In this case, the 'equivalent' shear strength of fiber-reinforced soil composite depends on the interface shear strength between fiber and soil. Under relatively high confining pressure, the fibers will develop a maximum tension under which they will break. In this case, the equivalent shear strength of fiber-reinforced soil depends on the tensile strength of fibers. A discrete framework for the design of fiber-reinforced structure was recently proposed to use these failure mechanisms for prediction of the equivalent shear strength of the fiber reinforced soil mass (Zornberg, 2002). For practical applications it should be noted that, unlike a soil mass reinforced using uniaxial inclusions, the failure mechanism governing the behavior of a soil mass reinforced using polymeric fibers is pullout. This is an important aspect, as failure by pullout rather than breakage is expected to lead to a comparatively ductile behavior in a fiber-reinforced soil composite.

Testing programs have been conducted on the effects of fiber-reinforcement (or micro reinforcement) under dynamic/cyclic loading conditions, especially when mimicking blast loading. Maher and Woods (1990) used resonant column and torsional shear devices to measure the shearing modulus and damping ratio of fiber-reinforced Muskegon Dune Sand. Results of the testing provided evidence that increasing straining amplitude leads to increased stiffness of the soil-fiber mixture. However, increasing amplitude led to a reduction in the damping of the fiber-reinforced soil reduced to the damping ratio of the soil (i.e. fibers did not contribute to damping). Results from the testing also provided evidence that an increasing aspect ratio of the fibers (fiber length/fiber diameter) resulted in a more effective fiber-soil mixture (higher increase in shearing modulus), with the optimum fiber content being approximately 0.4%.

Al-Refeai and Al-Suhaibani (1998) used triaxial, California bearing ratio (CBR) (ASTM D 1883) and resonant column tests to determine the static and dynamic strength of fiber-reinforced sands. During soil preparation, it was found that mixing the sand to a water content of 5% increased the effectiveness of the fiber-soil mixing (provided a more uniform fiber-soil mixture). Triaxial test results confirmed that the static strength of the fiber-reinforced sand was significantly higher than that of unreinforced specimens. Results from the CBR and resonant column testing provided evidence that the fiber-reinforced sand had a higher stiffness than the unreinforced soil, especially at higher straining amplitudes. It was hypothesized that this increase in the stiffness was caused by the increasing stresses along the fiber-soil interface caused by the increased deformation of the sand mass at higher strains. Al-Refeai and Al-Suhaibani also reported that an increasing fiber aspect ratio led to an increased stiffness of the reinforced soil mass. They also reported an optimum fiber content of approximately 0.4%.

EXPERIMENTAL TESTING PROGRAM

In order to quantify the potential improvement in ductility due to the use of fibers, a triaxial compression testing program was implemented as part of this study to evaluate the post-peak behavior of fiber-reinforced soil. Both granular and fine-grained soils were used in the testing program. The properties of the granular soil (Soil 1) and of the fine-grained soil (Soil 2) are summarized in Table 1.

Soil 1 is a clean, uniformly graded sand, commercialized as Monterey No.30 sand (Zornberg et al. 1998). It classifies as SP according to the unified soil classification system (USCS). The friction angles corresponding to relative density (Dr) of 48% and 65% are 31.6° and 35.2° respectively. Soil 2 is a dark brown fat clay with 96% of fines, classifying as CH. The effective shear strength envelope of Soil 2 was characterized by a cohesion of 16.0 kPa and a friction angle of 17.4°.

Table 1 Summary of soil properties

Soil type	**Soil 1**	**Soil 2**
USCS classification	SP	CH
% Fines	0	96
Dry unit weight, kN/m^3	15.54 (Dr= 48%) 15.91 (Dr=65%)	12.95
Friction angle, degrees	31.6 (Dr=48%) 35.2 (Dr=65%)	17.4
Cohesion, kPa	0	16.0

The tests were conducted using commercially available fibrillated polypropylene fibers. The properties of the fibers used in this study are summarized in Table 2.

Table 2 Properties of Fibers Used in the Tests

	Soil 1 tests	Soil 2 Tests
Linear density (deniers)	3620	360 & 1000
Fiber content (%)	0.1, 0.2, 0.3 & 0.4	0.2 & 0.4
Length of fibers (mm)	51	25 & 51

Note: 1 denier = 1/9000 g/m

The fiber-reinforced soil specimens were prepared using up to 0.4% fibers, measured in terms of dry weight of soil. Fibers were randomly mixed with soils by hand and compacted to desired soil unit weight. The triaxial testing program involved consolidated drained (CD) tests for Soil 1 and consolidated undrained (CU) tests with measurement of pore water pressures for Soil 2. Large specimens were used for the testing of Soil 1, with a diameter of 152 mm (6 inches) and a height of 304 mm (12 inches). For testing of Soil 2, the specimens had a diameter of 71 mm (2.8 in.) and a height of 142 mm (5.6 in.). The CU tests were performed in general accordance with ASTM D4767. Specimens were back pressure saturated and pore water pressure was measured.

The load frame used was a Humbolt HM – 3000, with strain rate capabilities ranging from 0.0001 to 9.9999 inches per minute and load capacity of 10,000 lbs. The data acquisition system consisted of a desktop computer with the LabVIEW 7.0 program and equipment. Using the LabVIEW program, data from the pore pressure transducer (Durham Geo Model No: E – 124), LVDT (Linear Variable Differential Transformer, Shaevitz Model No: 1000 HR- DC) and load cell (Omega Model No: LC401 – 10K) were logged at regular intervals. The triaxial cell was connected to a pressure panel with burettes to measure volume changes of the soil. Back pressure lines were connected to the panel in order to run the drained tests. The testing setup is shown in Figure 3 for the clay triaxial specimen.

The triaxial testing program for Soil 1 include 30 tests, conducted using two soil prepared at two relative densities (48% and 65%), a wide range of five fiber contents (0%, 0.1%, 0.2%, 0.3% and 0.4%), and three confining pressures (60 kPa, 115 kPa and 210 kPa). A total of 57 tests were conducted for Soil 2, including 9 tests on unreinforced specimens, and 48 tests on fiber-reinforced specimens. Two fiber contents (0.2% and 0.4%), two fiber lengths (25 and 51 mm) and two fiber linear densities (360 and 1000 deniers) were used for the testing of fiber-reinforced specimens. The tests for Soil 2 were conducted at confining pressures 70, 140 and 280 kPa (10, 20 and 40 psi). Results from these tests that are relevant for the evaluation of the post-peak behavior of fiber-reinforced soil are discussed in the following section.

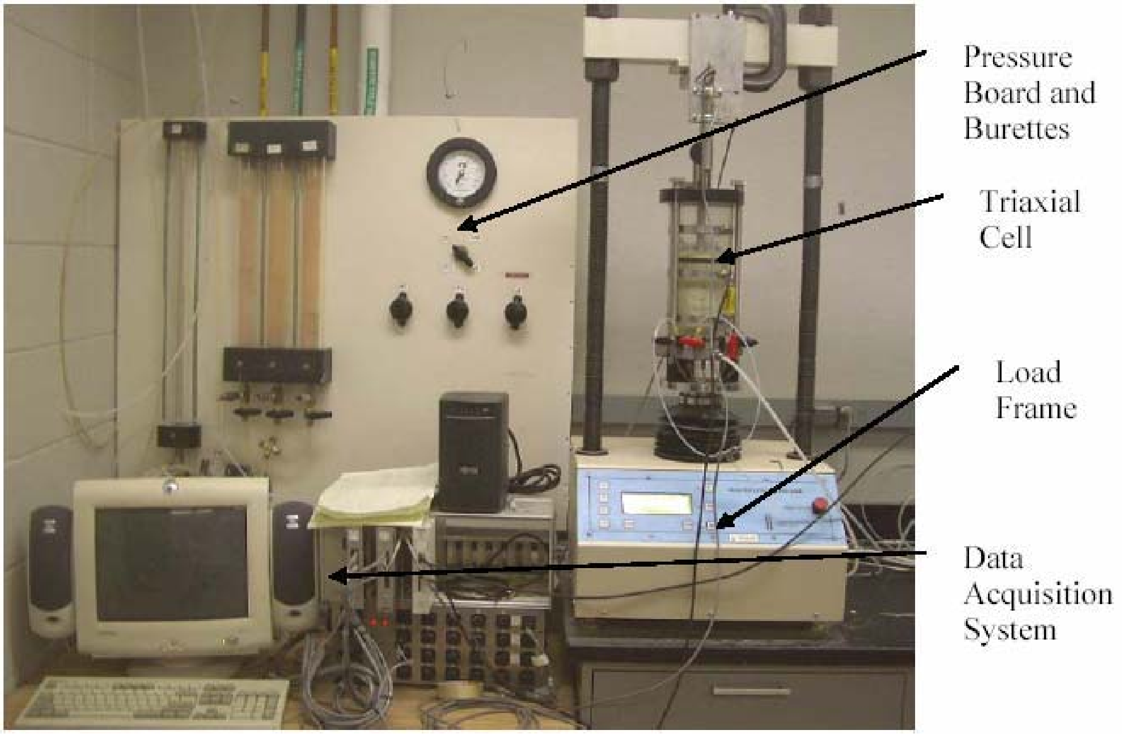


Figure 3. Triaxial test setup.

ANALYSIS OF TEST RESULTS

The stress-strain curves of unreinforced Soil 1, compacted at two different relative densities (48% and 65%), are shown in Figure 4. The specimens prepared with a relative density of 48% exhibit a slight post-peak shear strength loss. However, the post-peak strength loss in specimens prepared with a relative density of 65% is well-defined. The stresses at large strain levels seem to converge to the same residual value, although specimens may not have been reached critical state for the maximum stroke allowable in this experimental setup. The results in the figure illustrate the effect of increased compaction (i.e. increased relative density) within the soil mass. That is, increased compactive effort will lead to higher peak shear strength of the soil mass, although this increased strength will be lost at comparatively high strains. It should be noted that the soil behavior at large strains (quantified as the soil ductility) is a relevant aspect in the design of blast protection soil berms.

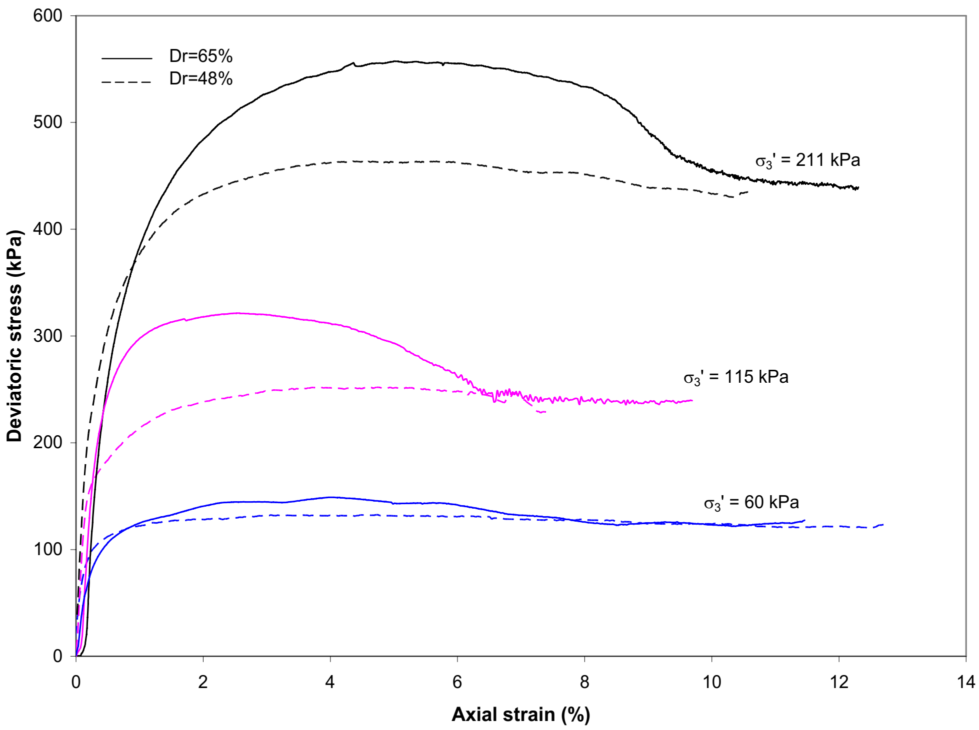


Figure 4. Stress-strain response of unreinforced doil (Soil 1).

A comparison of the stress-strain behavior of specimens prepared using varying fiber contents (χ_w) for specimens compacted to 65% relative density is shown in Figure 5. The test results clearly indicate that the presence of fibers leads not only to a higher peak-shear strength but also to a ductile behavior of the reinforced-soil specimens. That is, the specimens do not show any post-peak shear strength loss. The ductile ductile behavior is more significant for specimens placed at higher fiber contents. Specimens prepared using a fiber content as low as $\chi_w = 0.1\%$ appear to have almost eliminated post-peak strength loss. The specimens compacted using $\chi_w = 0.4\%$ clearly show no post-peak shear strength loss up to the maximum strain tested in this study. For specimens placed at varying fiber content, the strain at peak strength increases with increasing fiber content. For unreinforced soil, the strain at peak strength is approximately 5%, while for specimens placed using $\chi_w=0.4\%$ the peak strength is reached at strain level of approximately 9%.

The stress-strain responses at low strain levels are similar for the various specimens tested with varying fiber contents. This can be observed by the fact that all stress-strain curves are approximately the same up to a strain value of approximately 1.5% (Figure 5). This observation suggests that soil matrix resists most of the applied load at relatively low strain levels (strains less than approximately 1.5%). As the strain level increases, displacements along the soil-fiber interface increase, and tension will be gradually developed within the fibers, which will then contribute to resist the applied shear forces. The mobilized fiber tension at high strain levels compensates for the post-peak shear strength loss of the soil matrix. This is consistent with the more ductile behavior observed on fiber-reinforced soil.

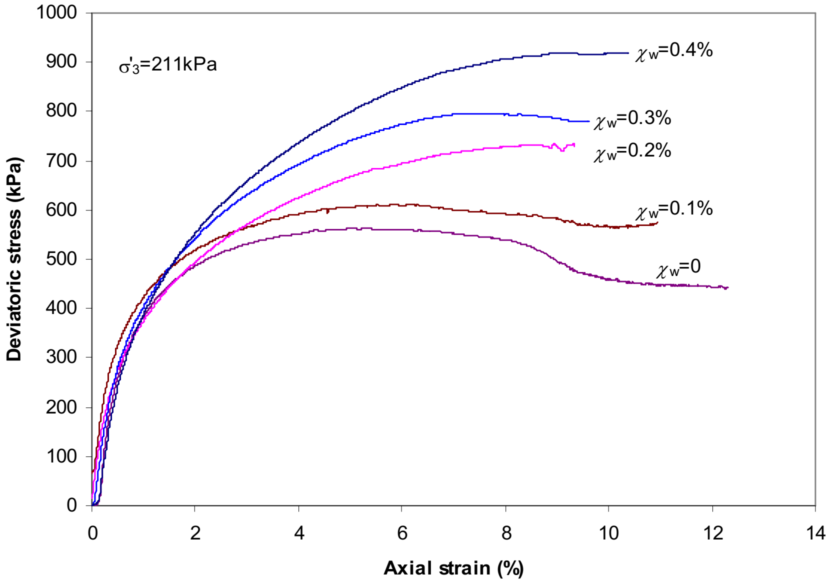


Figure 5. Stress-strain behavior of specimens prepared with different fiber contents (Soil 1, Dr=65%, σ_3=211 kPa).

Results from the testing program also provide evidence that fiber-reinforcement tends to restrain the volume dilation of the soil matrix, which may also contribute to eliminate the post-peak shear strength loss. A comparison of the volumetric strain between the reinforced and unreinforced specimens is shown in Figure 6. The volumetric dilation of fiber-reinforced soil is less than that of unreinforced soil under same axial strain level.

The ductility of the soil can be quantified by comparing the peak and residual strength using a brittleness index (Consoli, 2002), which can be defined as:

$$I_B = \frac{\Delta\sigma_{1,p}}{\Delta\sigma_{1,ult}} - 1 \quad (1)$$

where: $\Delta\sigma_{1,p}$ = peak deviator stress; and $\Delta\sigma_{1,r}$ = residual deviator stress. The brittleness increases as I_B increases (i.e. the ductility increases as I_B decreases). I_B = 0 represents a perfectly ductile behavior.

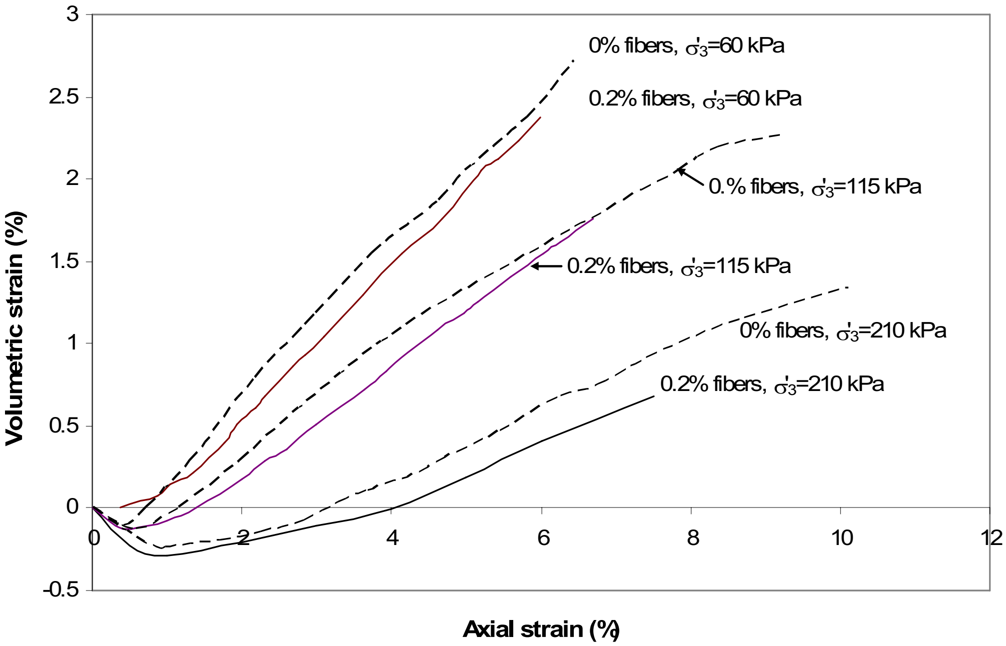


Figure 6 Volumetric strain - axial strain curves for reinforced and unreinforced soil (Soil 1, Dr=65%).

The brittleness index as a function of fiber content for test results obtained for Soil 1 (compacted to Dr=65%) is shown in Figure 7. For each of the 3 confining pressures used in this study, the brittleness of the soil mass decreased with increasing fiber content. A small addition of fibers to the soil matrix significantly reduced the post-peak shear strength loss. As the fiber content increases, the fiber-induced tension is significant enough to compensate for the post-peak shear strength loss of the soil matrix and a ductile behavior is obtained. Therefore, the brittleness index will approach 0 with the addition of fiber-reinforcement.

The behavior of fine-grained soils during shearing is influenced by the overconsolidation ratio, stress history, soil structure, and drainage conditions. For fiber-reinforced clays, fibers are expected not only to resist shearing forces but also to restrain the volume dilation of soil. Such behavior will influence the generation of excess pore water pressure under undrained conditions. Therefore, the mechanism of fiber-reinforcement for clays is more complicated than that for granular soil.

The deviator stress vs. axial strain and excess pore water pressure vs. axial strain curve for the fine-grained (Soil 2) specimens, with and without fiber-reinforcement, are shown in Figures 8 and 9, respectively. As shown in Figure 8, the unreinforced specimens tested under undrained condition showed significant post peak shearing strength losses. In contrast, the fiber-reinforced specimens were capable of retaining most of the shearing strength at high strain levels. This provides evidence that fiber-reinforcement also improves the ductility of cohesive soil under undrained conditions.

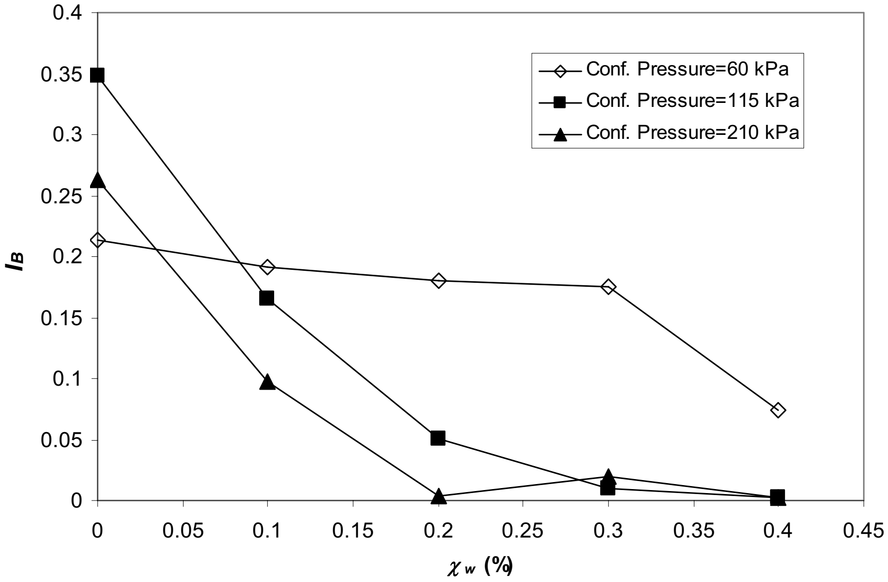


Figure 7. Effect of fiber content on Brittleness Index.

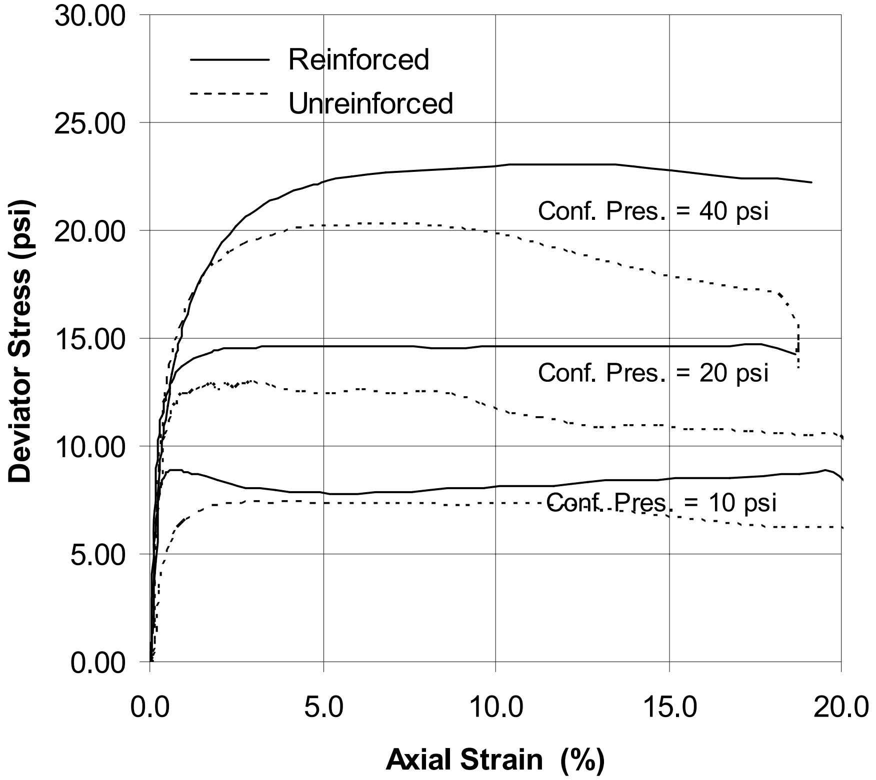


Figure 8. Deviator Stress vs. Axial Strain Curve (Soil 2, χ_w=0 and 0.4%, 360 Denier Fibers).

As shown in Figure 9, excess pore water pressure of the unreinforced specimens decreased slightly after the peak, indicating a tendency of the soil to dilate during shearing. Compared to unreinforced specimens, the fiber-reinforced specimens show either a consistent increase or slighter decrease in excess pore water pressure. This indicates that fiber-reinforcement tends to restrain the volume dilation in an undrained test condition.

A view of unreinforced and reinforced specimens of fine grained-soils at completion of shearing is shown in Figure 10. The unreinforced soil shows a well-defined shear band, where large localized shearing strains have occurred during shearing. Instead, the reinforced specimen exhibits bulging, indicating the strain have been more uniformly distributed throughout the soil specimen during shearing. This illustrates that the presence of polymeric fibers was effective in preventing strain localization, which is consistent with the observed elimination of post-peak shear strain loss and the improved ductility of the soil.

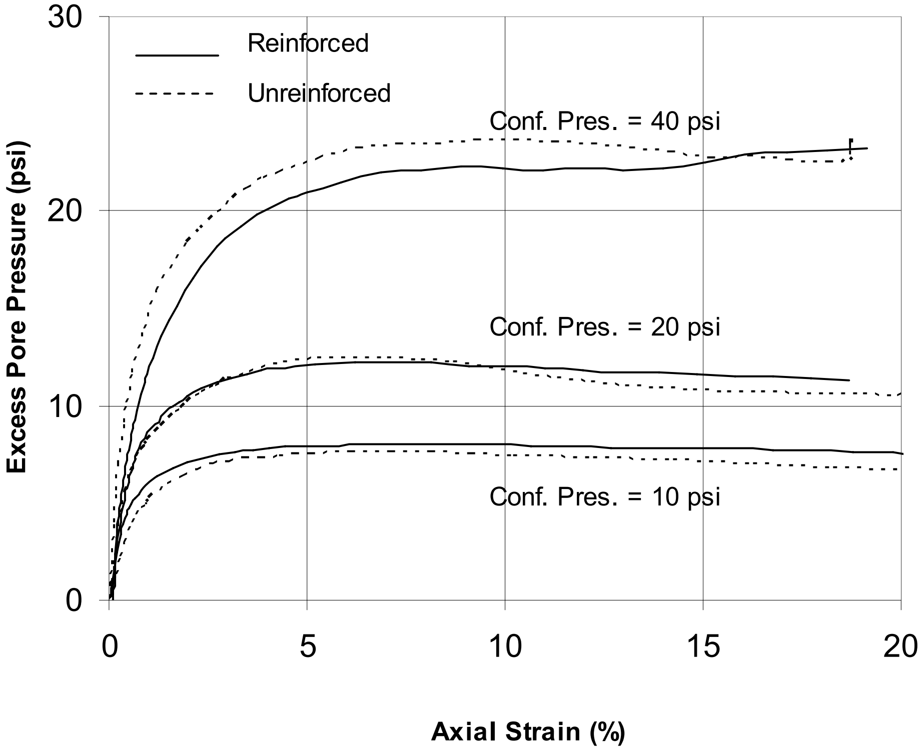


Figure 9. Deviator Stress vs. Axial Strain Curve (Soil 2, χ_w=0 and 0.4%, 360 Denier Fibers).

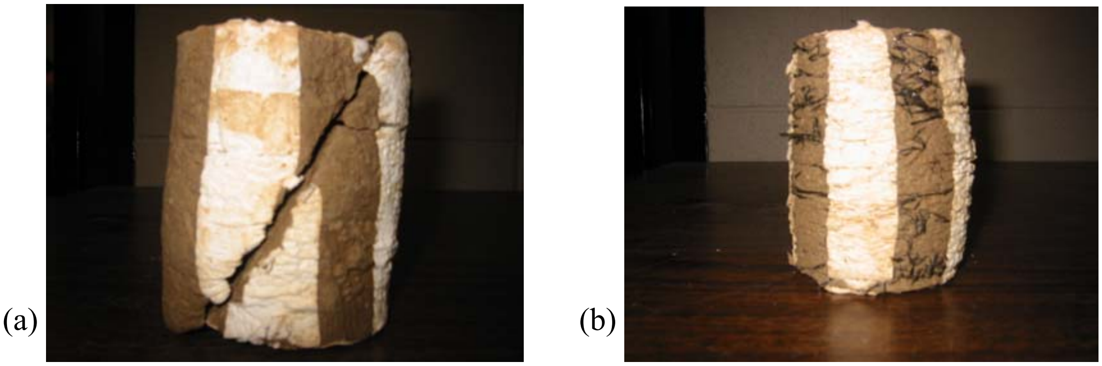


Figure 10. Specimens after the completion of triaxial testing: (a) unreinforced specimen; (b) fiber-reinforced specimens.

CONCLUSIONS

Ductility is an important property for the design of blast protection berms. However, soils under comparatively high relative compaction typically exhibit a brittle response that leads to significant post-peak shear strength losses. Accordingly, an experimental testing program was conducted to evaluate the ability of fiber-reinforcement to minimize or eliminate post-peak shear strength losses of compacted soil. The results of the experimental testing program indicate that the addition of fibers to both granular and fine-grained soils significantly improved the mechanical properties required of soils to be used in blast protection berms. Specifically, addition of a nominal amount of polymeric fibers (e.g. 0.1 to 0.4%) not only increases the shear strength but, equally important, transforms a soil with brittle response into a ductile soil.

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