Effective Shear Strength of Fiber-Reinforced Clays

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ABSTRACT: Results from unconfined compression testing of clay soils have provided evidence that the short term total shearing strength of the soils increased with the presence of randomly distributed polypropylene fiber-reinforcements. The results of a testing program are presented in which the (long term) effective shear strength of fiber-reinforced clay soils is determined utilizing both isotropic consolidated-undrained (ICU) triaxial testing with pore pressure measurement and isotropic consolidated-drained (ICD) triaxial testing. Unreinforced and reinforced specimens were prepared at constant water content and density so that effective stress failure envelopes could be defined. The results from the testing program provide insight on the influence of the fiber inclusions on the behavior of the clay specimens during shearing, namely the pore pressure generation within the reinforced and unreinforced soil specimens, and the effects of strain rate and drainage conditions on the effective shearing strength of the reinforced clay. Results from the ICU triaxial testing of fiber-reinforced and unreinforced clay specimens provides evidence that the presence of the fibers changes the behavior of the clay during shearing, which consequently alters the pore pressure generation within the specimens. Results from ICD triaxial tests are presented for the two fiber-reinforced clay soils and compared with the results from the ICU triaxial testing, which provides evidence that the effect of fibers within the clay specimens under ICU testing conditions may lead to a higher estimation of the effective shearing strength as compared to ICD testing conditions.

1 INTRODUCTION

The use of fibers in soil structures is not a new soil reinforcement technique. Ancient civilizations used straw and hay to reinforce mud blocks in order to create reinforced building blocks. Utilizing the same reinforcement mechanism, current research has focused on the effects of fibrillated polypropylene fibers as a reinforcement method in soil structures. The standard fiber-reinforced soil is defined as a soil mass that contains randomly distributed, discrete elements (fibers) that provide an improvement in the mechanical behavior of the soil composite (Li 2005). Numerous testing programs have been conducted to determine the effects of these discrete fibers on the behavior of clay soils, usually focusing only on the short term characteristics and total shearing strength of the fiber-soil mixture. Therefore, there is a lack of data pertaining to the long term effects of the fiber-reinforcement within a clay soil structure. In particular, the effects of drainage and pore pressures on the effective strength of the fiber-soil mixture, and creep along the fiber-soil interface, are of particular interest. The difficulty in determining creep strains and pore pressures in fiber-soil mixtures is that no measurements can be made at the fiber-soil interfaces. Therefore, the behavior of the bulk fiber-soil mass must be studied in order to understand the performance of the individual fiber-soil interfaces.

2 SCOPE

The goals of the testing program presented in this paper are to determine the long term strength of fiber-reinforced clays and observe the physical behavior of the soil during shearing. The results can be used to determine the effect of time and drainage conditions on the effectiveness of the fibers within a clay soil mass. Traditional isotropic consolidated-drained (ICD) and isotropic consolidated-undrained (ICU with pore pressure measurement) triaxial tests were conducted on compacted soil specimens to obtain the effective stress parameters of both unreinforced and fiber-reinforced soil specimens.

3 BACKGROUND

In general, the conclusions from strength testing of fiber-reinforced soils have been that the addition of fibers increased the shearing strength of the fiber-soil mixture. Fiber-reinforcements work in the same general sense as planar reinforcements, in that a polymer material is placed within a soil matrix and distributes stresses from potential failure planes into the surrounding soil mass by way of interface friction along the polymer-soil interface. Unlike planar reinforcements, which are only placed in one-dimension within the soil mass, fibers are randomly distributed within the soil mass and therefore are usually considered to have an isotropic effect on the soil behavior (Li 2005). Maher and Ho (1994) reported results for randomly mixed fibers with kaolinite clay tested using unconfined compression. The results provided evidence that fibers increased the compressive strength of the soil, as well as the ductility (the amount of deformation before failure) and toughness (the energy required to deform the specimen, equal to the area under the stress-strain curve) of the soil. Al Wahab and El–Kedrah (1995) tested an inorganic silty clay of medium plasticity (PI = 26) under similar testing conditions to Maher and Ho (1994). The results provided further evidence of an increase in the strength of the clay mixed to a fiber content as small as 0.2%. Puppala and Musenda (2000) conducted unconfined compressive tests using Irving (PI = 55) and San Antonio (PI = 46) clays. The results indicated increased strength and ductility of the soil with increasing fiber content. The effect of fiber length was also evaluated and it was found that as the length of the fibers was increased from 1 inch to 2 inches, the strength and axial strain at failure also increased. All results indicate an improved performance of the fiber-soil mixture, but only for short term conditions.

4 MATERIALS AND METHODS

Two clay soils were used for the testing program: Eagle Ford (EF) clay, with a plasticity index (PI) of 49, and Silty Brown (SB) clay with a PI of 54. Triaxial specimens were compacted to water contents approximately 2% dry of optimum and compacted to the maximum dry unit weight as defined by standard proctor compaction (ASTM 2000). The fibers used for this study are commercially available fibrillated polypropylene fibers known as GeoFibers (Synthetic Industries, Inc.). Reinforced specimens were hand mixed to a fiber content (weight of fibers divided by weight of soil) of 0.5% by dry weight of soil. Soil specimens were compacted to a diameter of 7.1 cm and a height of 14.2 cm. Specimens were then placed into the triaxial chamber and connected to the data acquisition system (Figure 1).

The soil specimens were back pressure saturated to "b" values of at least 0.98 for one week. After saturation, specimens were placed under a controlled effective stress and allowed to consolidate for 72 hours. Strain rates for the ICU and ICD testing were determined from consolidation curves of each specimen using the square root of time method (ASTM 2002). Each triaxial test was conducted until an axial strain of 20% was reached.

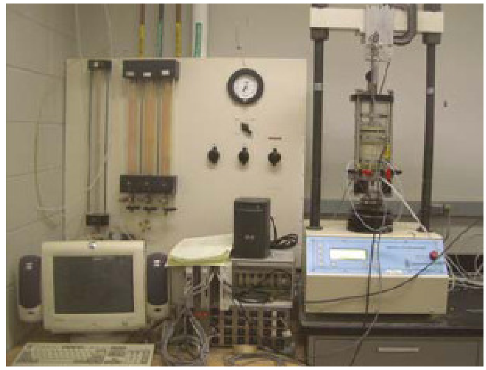
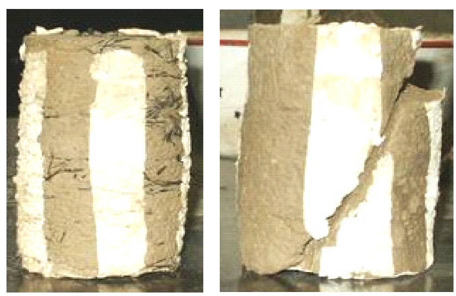


Figure 1: Photograph of the Triaxial Testing Setup.

5 RESULTS

The effects of the fiber inclusions on the soil behavior could be visually observed during the triaxial testing (sheared specimens shown in Figure 2). Axial deformation of the unreinforced specimen resulted in the development of a failure plane, while the reinforced specimens tended to bulge, indicating an increase in the ductility (the deformation required to reach failure) of the fiber-soil mixture.



(a) (b)

Figure 2: Specimen Deformation Pattern for (a) Fiber-Reinforced and (b) Unreinforced EF Clay Soil Specimens.

The change in the ductility of the soil specimens can be defined using a brittleness factor (Consoli et al. 2002, Li 2005), which quantifies the differences in the stress-strain curves of the soil (shown in Figure 3 for the EF clay). The brittleness factor is defined as the ratio of the peak principal stress ratio to the residual principal stress ratio minus unity:

$$I_B = \frac{(\sigma_1 - \sigma_3)_{peak}}{(\sigma_1 - \sigma_3)_{residual}} - 1$$

The value of I_B ranges from 1 to 0, where 0 represents perfectly ductile behavior. The brittleness factor for unreinforced clay specimens ranged from 0.61 to 0.35, while the factor ranged from 0.26 to 0.01 for reinforced soil specimens. Li (2005) also concluded that the value of the brittleness factor is influenced by the effective confining pressure within the specimen, which is attributed to the influence of the confining pressure on the effectiveness of the fibers within the soil.

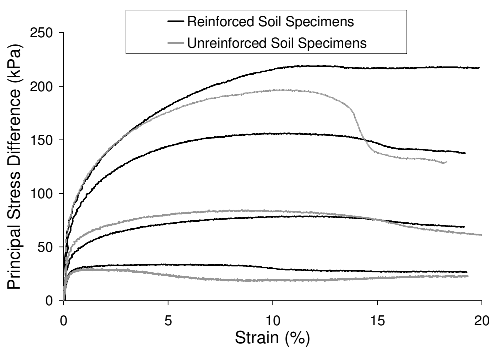


Figure 3: Stress-Strain Curves for Fiber-Reinforced and Unreinforced Eagle Ford Clay Specimens from ICU Testing.

The pore water pressures generated within the soil specimen under ICU conditions, which are related to the contractive or dilative tendencies of a soil during shearing, were consistently higher for the reinforced specimens than the unreinforced (Figure 4). This higher pore pressure generation is related to the effect of fibers on the soil specimen deformation. Li (2005) attributed this increase in pore pressure on the fibers distributing stresses within the soil mass, and therefore increasing the contractive deformations within the fiber-soil mixture (more soil undergoing shear and therefore more soil mass contracting). This also provides evidence that the deformation characteristics of a soil might influence how well fibers affect the soil behavior.

This increase in the pore pressure generation decreases the effective stress within the soil mass, yet results in a higher shearing strength. Stress paths determined using the ICU triaxial testing of the EF and SB clays are provided in Figures 5 and 6, respectively. The paths are plotted in p' – q space, where q is $(\sigma_1 - \sigma_3)$ and p' is $(\sigma'_1 + 2\cdot\sigma'_3)/3$. In general, the shape of the stress paths for both unreinforced and fiber-reinforced specimens indicates an increase in pore pressure with deformation, or a contractive volumetric deformation.

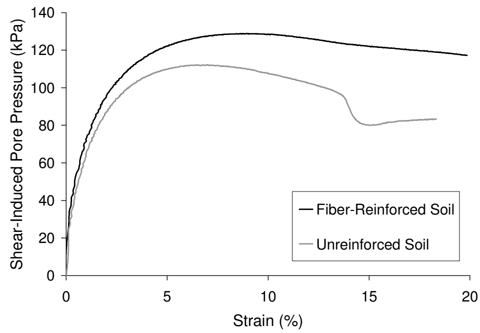


Figure 4: Pore Pressure Generation Due to Shearing Deformation for Fiber-Reinforced and Unreinforced Eagle Ford Clay.

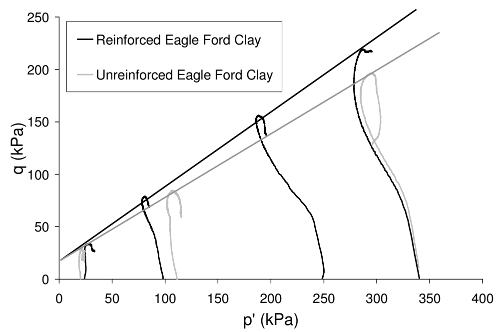


Figure 5: Stress Paths for Fiber-Reinforced and Unreinforced Eagle Ford Clay Specimens from ICU Triaxial Testing.

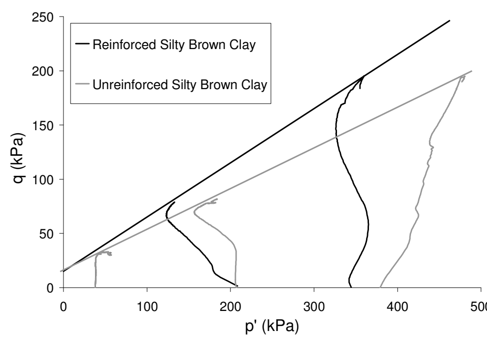


Figure 6: Stress Paths for Fiber-Reinforced and Unreinforced Silty Brown Clays Specimens from ICU Triaxial Testing.

The effective shear strength of the fiber-soil specimens, illustrated with the approximate failure envelopes, was higher than the unreinforced specimens. This increase in strength is due to a combination of an increase in the peak principal stress difference (higher peak q values), as well as the decrease in effective stress (higher pore pressures) caused by the fibers, resulting in a higher shift (to the left) in p' values. The results also provide evidence that as the effective confining pressure increases the effect of the fibers on the soil strength increases.

ICD triaxial tests were conducted to determine how time and pore pressure dissipation influence the fiber-soil mass. Stress paths for the reinforced and unreinforced EF and SB soils are provided in Figures 7 and 8, respectively.

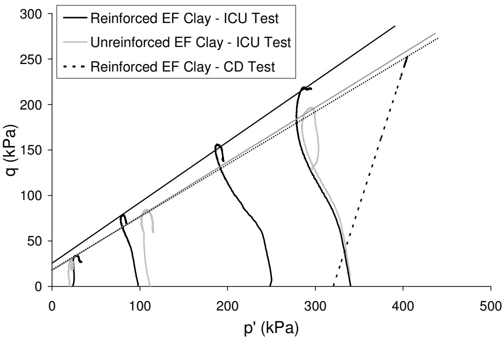


Figure 7: Stress Paths Determined from ICU and ICD Triaxial Testing of Eagle Ford Clay.

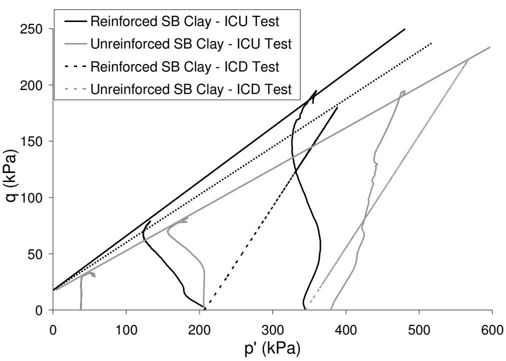


Figure 8: Stress Paths Determined from ICU and ICD Triaxial Testing of the Silty Brown Clay.

Approximate failure envelopes are presented in the figures to illustrate the reduced strength from ICD testing as compared to ICU testing. An additional ICD test conducted on unreinforced SB clay indicates that the strength of both ICU and ICD triaxial testing should be similar (no significant strain rate effects on soil strength). The decrease in strength of the fiber-reinforced soil provides evidence of an influence of either time or drainage, or both, on the behavior of the fiber-soil mass.

The differences in ICD and ICU strengths were initially attributed to creep strains along the fiber-soil interface. The effects of time on the interface strength, such as a time-dependent slip or clay particle rearrangement, would be more evident in CD test conditions due to the slower strain rate and the significant increase in testing time.

The drainage allowed during ICD testing may also reduce the effects of the fibers on the pore pressure generation within the clay specimens. The presence of fibers, which altered the deformation of the clay soil and changed the pore pressures during ICU testing, caused a larger shift in p' and caused an increase in the slope of the effective stress failure envelope. Drainage during the ICD testing reduced the effects of fibers on the effective stress by not allowing pore pressure generation, resulting in only a small increase in the fiber-soil mixture strength. The fibers within a clay soil also increase the hydraulic conductivity of the mixture, with fibers acting as a flow network (Al Wahab and El-Kedrah 1995). By allowing drainage, water will flow towards to the fibers and increase the water content along the interface, decreasing the interface strength and reducing the influence of the fibers.

6 CONCLUSIONS

Failure envelopes determined from ICU triaxial testing indicate an increase in the effective shear strength of the soil with the presence of fibers, which is in agreement with short term testing results. Results from ICD triaxial tests indicate that the strength of the fiber-soil mass were lower for long term-fully drained conditions, providing evidence that the effective strength of the fiber-soil mixture may significantly decrease with time and drainage. Although this decrease in strength was initially attributed to creep along the fiber-soil interface, results from this testing program indicate that the effects of fibers on the pore pressure during ICU testing may give a higher estimation of effective strength.

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