EFFECT OF FIBER CONTENT ON THE MECHANICAL BEHAVIOR OF FIBER-REINFORCED CLAY

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ABSTRACT

Existing models of soil behavior have been developed based on the understanding of interaction between particles, much of it is conceptually based on sand and modified to describe the behaviors of clayey soils. There are other classes of fibrous soils and soils amended with fibers for which the current understanding of soil behavior does not represent well. The research presented within this paper is an investigation into the engineering properties of fiber reinforced clay soil and to understand the impact of adding fibers. This paper includes the results of undrained triaxial compression tests performed on soil-fiber composite to evaluate the pore pressure response, strength and stiffness properties. Parametric studies are performed for three different fiber contents (0%, 1% and 2%). In near future, the results of this testing will be evaluated within the context of material models developed to explain the anisotropic properties of fibrous peat (stiffness and strength) as a result of the fibrous composition. This work is fundamental in nature, but the results are anticipated to be applicable to the undrained anisotropic behavior and strength of fibrous organic soils and soils reinforced with elements that act in tension.

RÉSUMÉ

Les modèles existants de comportement du sol ont été développés sur la base de la compréhension de l'interaction entre les particules, une grande partie de celui-ci est conceptuellement basé sur le sable et modifié pour décrire les comportements des sols argileux. Il existe d'autres classes de sols fibreux et de sols modifiés avec des fibres pour lesquelles la compréhension actuelle du comportement du sol ne représente pas bien. La recherche présentée dans ce document est une enquête sur les propriétés d'ingénierie de la fibre de terre d'argile renforcée et de comprendre l'impact de l'ajout de fibres. Cet article comprend les résultats des essais de compression triaxiale non drainés effectués sur le composite sol-fibre pour évaluer la réponse de la pression interstitielle, la résistance et les propriétés de rigidité. Des études paramétriques sont effectuées pour trois teneurs en fibres différentes (0%, 1% et 2%). Dans un avenir proche, les résultats de ces essais seront évalués dans le contexte des modèles de matériaux développés pour expliquer les propriétés anisotropes de la tourbe fibreuse (raideur et résistance) à la suite de la composition fibreuse. Ce travail est fondamental dans la nature, mais les résultats devraient s'appliquer au comportement anisotrope non drainé et à la force des sols organiques fibreux et des sols renforcés par des éléments qui agissent en tension.

1. INTRODUCTION

Modification by inclusion is one of the potential methods for improving the properties of existing soil. Traditional methods of soil reinforcement involved the use of continuous planar reinforcements (metallic strips, geotextiles etc.) that requires large anchorage length and demands anchoring to a competent material on both sides (Zornberg, 2002). Even though the tensile strength of the soil mass is improved, these continuous reinforcements introduce a plane of weakness as the shearing resistance along the soil reinforcement interface is less than the soil alone (Li, 2013). There is also a greater chance of pullout when planar reinforcements are placed in the soil. The best alternative solution is to add short, discrete fiber reinforcement to a soil mass, mix in the same way as lime or cement, and followed by subsequent compaction. Randomly fiber-reinforced soil mass shows an isotropic increase in the shear strength of soil mass and no planes of weakness are introduced (Li, 2013). The objective of this study is to reinforce kaolinite clay soil with randomly oriented polypropylene fibers, and to quantify the strength and stiffness properties of this soil through extensive laboratory techniques.

Most of the existing studies are performed on fiber-reinforced sands and a very few have been performed on fiber-reinforced clay soil. This is mainly due to the difficulty in sample preparation and the difficulty in quantifying the pore pressure response and interface shear strength between soil and fibers. Adding to that, the models used to describe the mechanical behavior of soil, more specifically the critical state family of models (e.g. Schofield & Wroth 1968, Roscoe & Burland 1968), assume isotropic elasticity. However, according to Quigley, 1980, most post glacial clays are deposited vertically. They are subjected to equal horizontal stress, but the properties do vary from top to bottom and are referred to as transversely isotropic or cross-anisotropic. To date, no studies have been attempted to evaluate the cross-anisotropic behavior of fiber-reinforced clay soils. In near future. this research will also help to close the knowledge gap surrounding the study of cross-anisotropic behavior of fiber-reinforced clay soils.

2. BACKGROUND

Maher and Ho (1994) investigated the mechanical properties of kaolinite fiber-reinforced clay soil and determined that the inclusion of fibers increased the peak compressive strength and ductility of the composite. However, the tests performed mainly included the Unconfined Compressive Strength (UCS) tests and the Brazilian splitting tensile tests. Zornberg (2002) proposed a discrete framework for the evaluation of fiber-reinforced soil slopes by considering the contribution of soil and fibers separately. Critical normal stress at which the mode of failure changes from fiber pullout to fiber breakage was defined using this framework. Zornberg et.al. (2004) performed large scale triaxial tests to characterize the mechanical behavior of tire shred- sand composites. They concluded that the shear strength of tire shred-sand mixture increased with increasing tire shred aspect ratio and this effect is more significant at low confining pressures.

Tang et.al. (2012) proved that the addition of polypropylene fibers to the soil matrix improved the bonding strength and restricted the relative movement of fibers in the matrix. As a result, the fibers were able to bear some tensile stress and the crack initiation during drying could be decreased. Li (2013) performed triaxial compression and triaxial extension tests to evaluate the effect of soil type, soil density and fiber orientation on the shear strength of the composite. The results were later validated with the discrete framework proposed by Zornberg (2002). Costas et.al (2013) conducted a series of direct shear tests on fine soil samples with different percentages of fiber and determined that the shear strength of the soil increased up with the optimum dosage of fibers, beyond which it decreases or remains constant. Mirzababei et.al (2018) performed a series of Consolidated Undrained triaxial tests on carpet fiber-reinforced clay soil and developed a simple regression model to predict the effective stress ratio and deviatoric stress of fiber-reinforced clay.

3. TEST MATERIALS

3.1. Kaolinite Clay

The clay soil adopted in this study is 'EPK Kaolin' manufactured by Edgar Minerals Inc. The soil is classified as MH according to the Unified Soil Classification System (USCS). The soil properties are presented in Table 1.

Table 1: Characteristics of the clay soil tested

Liquid Limit (%)	58
Plastic Limit (%)	41.57
Plasticity Index (%)	16.43
Optimum Moisture Content (%)	28
Maximum Dry Density (kN/m^3)	15.2

3.2. Fibers

Reinforcements used are the precision cut polypropylene fibers supplied by MiniFIBERS. Inc. The properties of the fibers are given in Table 2. Polypropylene fibers are adopted for this study by considering its low cost, easy availability and chemical inertness. These fibers have a high melting point and so is convenient to place in the oven for water content determination.

Table 2: Properties of the polypropylene fibers

Length (mm)	18
Thickness (mm)	0.035
Specific gravity (g/cc)	0.91
Modulus of elasticity (GPa)	8.5-12.5

3.3. Sample preparation

Proctor compaction tests were performed on both unreinforced and fiber-reinforced soil before preparing the samples for triaxial testing. There was no significant change in the Optimum Moisture Content (OMC) of kaolinite clay by introducing fibers to the soil. However, the maximum dry density increased proportionally with the fiber content. To consider this factor into account, both unreinforced and fiber-reinforced samples were prepared at the OMC (29%). The weight of mix placed in the compaction mold was calculated to target the maximum dry density determined from the proctor tests.

To prepare the unreinforced specimens, the required quantity of dry kaolinite clay was mixed with deaired, distilled water at OMC in a mechanical mixer. The prepared unreinforced sample lot was transferred to a plastic bag and stored in the moisture room for at least 48 hours prior to the sample preparation. The soil-water mix was then placed in a split mold of 50mm diameter and 100mm height as 5 equal layers with each layer followed by subsequent compaction. Care was taken to ensure that the compaction energy is consistent for each samples prepared. An arbor press was used to compact all samples and the number of blows were restricted to 15 per layer.

One of the most challenging aspect of this study was the preparation of fiber-reinforced samples for triaxial testing. To prepare these samples, several methods were carried out, and the best one was adopted. In the first method, the entire clay soil was mixed with water (at OMC) using a mechanical mixer and the polypropylene fibers were added to this soil-water mix. However, there was no bonding between the fibers and soil and the method was discarded. In the second method, the kaolinite clay soil in the dry state was mixed with the dry polypropylene fibers and then the water was added to the soil-fiber mix using the mixer. Since polypropylene fibers are highly hydrophobic in nature, they absorb the entire water added to the mix quickly, leaving the soil to be in a dry state. In the third method, half of the dry kaolinite clay was mixed with half of the water using a mixer. The remaining half of the soil, half of the water and all fibers were then added to the clay–water mixture prepared in the previous step. This mixture of clay-water-fiber was then mixed gently (Roustaei et.al, 2015). Visual examination ensured that a highly uniform mixture of soil-fiber composite was obtained by adopting this method. The fiber-reinforced soil lot (Figure 1(a)) was placed in a 2-part split compaction mold (50mm X 100mm) as five equal layers with each layer followed by subsequent compaction using the same arbor press used for preparing unreinforced samples. The number of blows were restricted to 15 per layer to ensure consistency in sample preparation. Figure 1(b) indicates a soil sample reinforced with 1% by weight of fibers and prepared by the above-mentioned method.

Figure 1: Fiber-reinforced soil adopted for testing a) Soil lot; b) Fiber-reinforced soil sample

3.4. Testing Method

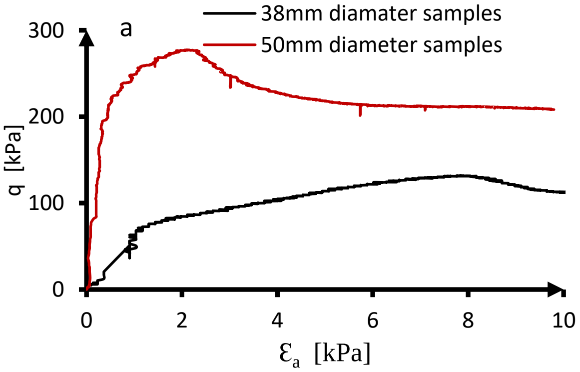
The specimen strength was measured by performing traditional Isotropic Consolidated Undrained (ICU) triaxial tests, in accordance with ASTM D4767. Humboldt HM-5020 load frame with a capacity of 15 kN was used for the testing. The axial load was measured by a load cell of capacity 1 ton and the displacement was measured by a Linear Potentiometer (LP) of maximum travel length 50mm. A pressure panel was used to control the cell and back pressure applied to the sample. The pore water pressure developed within the specimen was measured by connecting a transducer at the base of the cell. The volume change in the sample during the consolidation phase was measured by attaching an automatic volume change device to the back pressure line of the triaxial chamber. Prior to testing, the samples were saturated by applying a back pressure of 390 kPa and a cell pressure, which was slightly greater than the back pressure until a B value greater than 0.97 was achieved. The specimen was then consolidated by keeping the difference between cell pressure and back pressure equal to the desired effective stress. Following consolidation, shearing was initiated on the samples and the rate of shearing was decided based on the consolidation curves. The testing was continued until a 20% axial strain was obtained.

4. RESULTS

4.1. Unreinforced soil sample

4.1.1. Effect of specimen diameter

A study was initially performed to observe the effect of specimen size on the maximum strength values attained. Consolidated Undrained (CU) triaxial tests were performed on samples of diameter 38mm and 50mm for two values of effective stresses, mainly 50 kPa and 100 kPa. Figure 2(a) and Figure 2(b) indicate that a 50mm diameter sample gives a better indication of the strength developed within the specimen. This increase in strength observed in a 50mm diameter sample could also be due to the increase in the unit weight of samples.



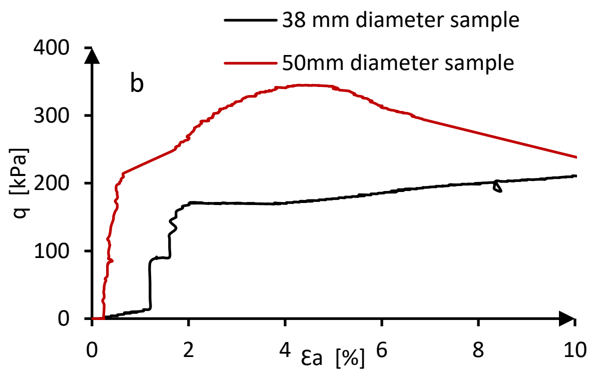


Figure 2. CU test results for unreinforced samples a) effective stress 50 kPa; b) effective stress 100 kPa

Adding to that, it was difficult to incorporate 18mm long polypropylene fibers in samples of diameter 38mm due to boundary restrictions. Hence the remaining part of this study was performed on samples of diameter 50mm.

4.1.2. Effect of confining stress

Samples of unreinforced kaolinite clay were tested for three values of effective stresses mainly 50 kPa, 100 kPa and 200 kPa. The plots of deviatoric stress (q) and induced pore water pressure (u_w) versus axial strain (ε_a) are demonstrated in Figure 3(a) and Figure 3(b).

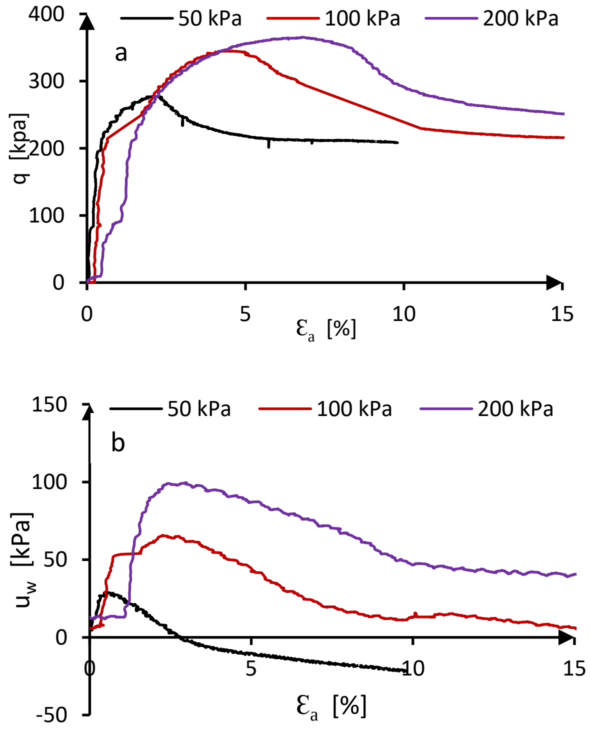


Figure 3. CU test results for unreinforced soil samples: a) deviatoric stress; b) Induced pore water pressure

Figure 3 (a) indicates a linear elastic behavior for the unreinforced samples, followed by a strain softening response. However, the peak strength attained by the samples increased with an increase in the effective confining stress. The maximum value of strength was attained at a strain of 2% (275.3 kPa), 4% (351.65 kPa), and 7% (364.13 kPa) for the samples subjected to an effective stress of 50 kPa, 100 kPa and 200 kPa respectively. Figure 3 (b) shows that the maximum value of pore pressure was attained at an axial strain of 0.05%, 2%, and 3% for the samples subjected to an effective stress of 50 kPa, 100 kPa and 150 kPa respectively which was then followed by a steep reduction. Negative pore pressure values were observed for samples consolidated at an effective stress of 50 kPa. This behavior of a highly over consolidated soil could be due to the higher compactive effort applied to the soil during the specimen preparation.

4.2. Fiber-reinforced soil samples

As a next step in this study, reinforced soil samples were prepared with four different percentages by weight of fiber content, which includes 0%, 0.5%, 1% and 2% (adopting the method described in Section 3.3). The prepared specimens were tested for three values of effective stresses, mainly 50 kPa, 100 kPa and 200 kPa to accumulate low to slightly high stress ranges observed in the field. No significant improvement was observed in samples reinforced with 0.5% fiber and the test results obtained are not used for the analysis.

The effect of fiber inclusion was visually observed in the samples after failure. The samples of unreinforced clay soil failed at lower values of axial strain by developing well defined failure plane (Figure 4 (a)). However, in the case of fiber-reinforced specimens, no visible failure plane was observed, and the samples indicated a tendency of bulging (Figure 4 (b)). The testing was stopped once an axial strain of 20% was attained, even though no failure was observed in the samples. This change in behavior of the specimen is an indication of the improvement in the ductility of the specimens by the inclusion of fibers. This improvement in the ductility and residual strength is beneficial for loading cases in which large displacements are anticipated (Li, 2005).

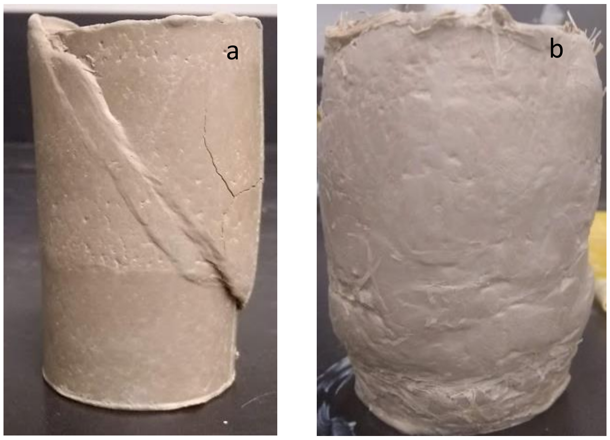


Figure 4: Deformation pattern in samples after failure a) Unreinforced sample; b) Reinforced sample

Previous studies showed that the change in the ductility of the specimen can be defined using a brittleness factor as indicated in Equation 1 (Consoli et.al. 2002, Freilich et. al. 2010). The brittleness factor (I_B) is defined as the ratio of the peak deviatoric stress attained to the residual deviatoric stress minus unity. The range of I_B varies from 0 to 1 where 0 indicates a highly ductile behavior and 1 indicated a highly brittle behavior (Freilich et. al. 2010).

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

where σ_1 is the major principal stress and σ_3 is the minor principal stress developed within the soil. Adding fibers to the soil, reduced the brittleness factor to zero when tested at all three values of confining stresses. This clearly indicates the transition from brittle behavior to ductile behavior by the introduction of fibers.

4.2.1. Effective Confining Stress: 50 kPa

Figure 5(a) and Figure 5(b) indicates the quantification of strength and pore water pressure developed within the specimen when tested at an effective confining stress of 50 kPa. These results provide an indication of the effect of fiber reinforcement in soils that are located at a lower depth below the ground surface (Roustaei, 2015).

Even though there was no considerable improvement in the peak strength of the composite by adding 1% (by weight) of fibers, a change was observed in the failure mechanism. A sudden brittle behavior was replaced by a slow ductile mode of failure. However, an increase of 43% was observed in the peak deviatoric stress by reinforcing the soil with 2% fibers (Figure 5 (a)). The I_B value reduced from 0.3 to 0 when fibers were introduced into the matrix. A bulging mode of failure was observed in both cases (1% fiber-reinforced and 2% fiber-reinforced) which again indicates an improvement in the ductility of the composite.

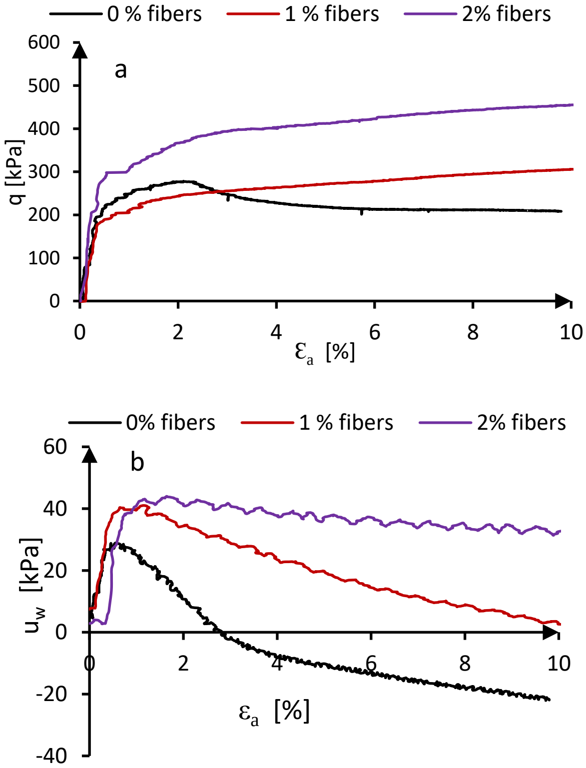


Figure 5: CU triaxial tests on reinforced soil samples tested at an effective confining stress 50 kPa a) deviatoric stress (q); b) Induced pore water pressure (u_w)

Figure 5(b) indicates that the induced pore water pressure developed within the specimen increases when reinforced with 1% and 2% by weight of fibers. A reduction in the contractive volumetric deformation was observed with an increase in the fiber content. However, no statements can be drawn about this behavior at this point and there is a necessity to continue testing with higher values of fiber contents (3% and 4%) to arrive at a general conclusion.

4.2.2. Effective confining stress: 100 kPa

For samples tested at an effective stress 100 kPa, it is evident that the fiber-reinforced soil specimens show a higher shear strength and less post peak shear strength loss (Figure 6(a) and Figure 6(b)). The initial portion of the stress strain curves is similar for both unreinforced and reinforced soil. Li, 2005 also observed the similar behavior and concluded that, the soil appears to take most of the applied load at small strain levels, while the load resisted by the fibers is more substantial at higher strain levels. Previous studies also proved that if, short fibers (fibers with length less than 76.2mm) are added to the soil, the stresses are transferred to the soil first and then to the fibers. However, for continuous fibers (fibers with length greater than 76.2mm), the stresses are transferred to the soil and fibers at the same time (Hejazi et.al, 2012). The larger strain corresponding to the peak deviator stress as observed in fiber-reinforced samples suggest that fibers increase the ductility of the soil-fiber composite. The maximum deviatoric stress was attained at an axial strain of 5% for unreinforced soil and thereafter it is followed by a strain softening behavior. However, for samples reinforced with 1% and 2% fibers, the maximum deviatoric stress was attained at a smaller axial strain of 1%, which was then followed by a linear strain hardening behavior. The I_B value reduces from 0.4 to 0 when reinforced with 1% and 2% of fibers.

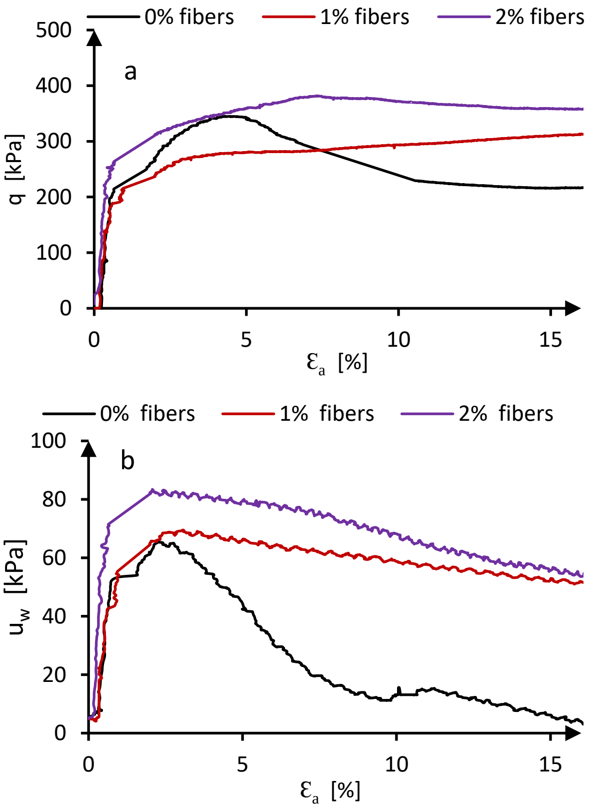


Figure 6 : CU triaxial tests on reinforced soil samples tested at an effective confining stress 100 kPa a) deviatoric stress (q); b) Induced pore water pressure (u_w)

Figure 6(b) indicates that the maximum value of pore pressure was attained around an axial strain of 2.5% for all three samples followed by a reduction with continuous loading. The unreinforced soil samples exhibited a highly dilative behavior with the induced pore water pressure almost reduced to zero at 18% axial strain. However, there was only a slight reduction for the samples reinforced with 1% and 2% fibers. According to Li (2005), this increase in the pore pressure developed within the composite is due to the effect of fibers distributing the stresses in the soil mass and therefore increasing the contractive deformation within the soil-fiber composite.

4.2.3. Effective Confining Stress: 200 kPa

Figure 7 (a) and Figure 7 (b) represents the deviatoric stress (q) and pore water pressure (u_w) versus axial strain (ε_a) for samples tested at an effective stress of 200 kPa and reinforced with 0%, 1%, and 2% by weight of fibers. These results provide an indication of the effect of fiber reinforcement in soils that are located at higher depth below the ground surface.

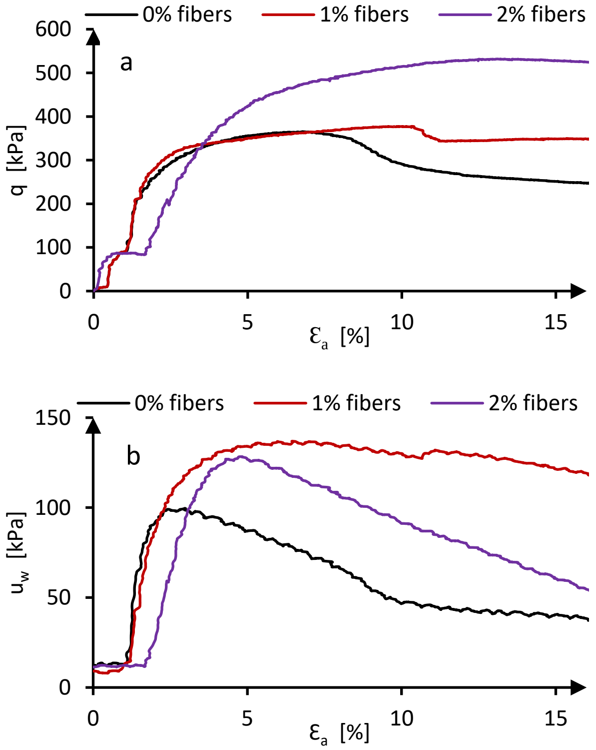


Figure 7: CU triaxial tests on samples tested at an effective stress of 200 kPa a) deviatoric stress (q); b) Induced pore water pressure (u_w)

The effect of fibers becomes more evident when tested at a higher value of confining stress. There wasn't any significant improvement in the strength of the composite when reinforced with 1% (by weight) fibers and tested at an effective stress of 50 kPa and 100 kPa. However, when the effective stress was increased to 200 kPa, the peak deviatoric stress increases by 4.5% and the induced pore water pressure increases by 40%. Adding 2%, fibers to the soil increased the peak deviatoric stress by 47% and reduced the brittleness factor (I_B) to 0. Freilich (2010) also proved that the effect of fibers on the soil strength increases with an increase in effective confining stress.

The variation of induced pore water pressure with fiber content (Figure 7(b)) was similar to that observed at an effective stress of 50 kPa. The maximum value of pore pressure developed within the specimen increased by adding 1% fibers, however a reduction was observed in the pore water pressure developed with further increase in fiber content. Hence, more tests need to be performed to arrive at a general conclusion of the pore pressure response of fiber-reinforced soils with increase in fiber contents.

4.2.4. Effect of confining stress on the strength mobilisation of reinforced samples

Figure 8(a) and 8(b) shows the variation of peak deviatoric stress and induced pore water pressure in samples reinforced with 1% and 2% fibers and tested at three different values of confining stresses.

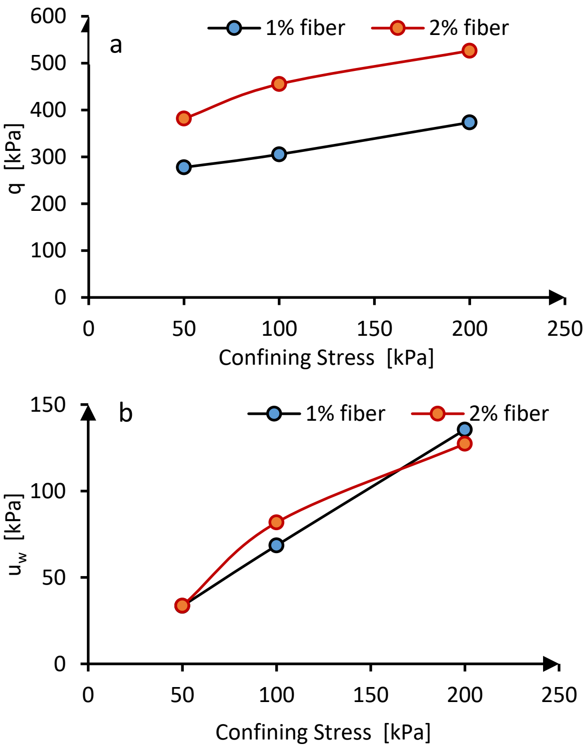


Figure 8: CU triaxial tests on samples reinforced with 1% and 2% fibers a) deviatoric stress (q); b) Induced pore water pressure (u_w)

It is obvious from Figure 8(a) that, the peak deviatoric stress attained increases with an increase in confining stress for both 1% and 2% fiber-reinforced soil. This behavior is similar to that observed in unreinforced soil (Figure 3(a)). Previous researchers also observed the same trend and concluded that, the mobilising effect of fibers becomes more evident at higher values of confining pressures (Li, 2005 and Freilich, 2010). Figure 8(b) indicates that maximum value of pore water pressure in soil reinforced with 1% fibers increases with an increase in confining stress. However, for soils reinforced with 2% fibers, the pore water pressure increases initially but then decreases with further increase in confining stress. In the future, further studies will be performed by varying the fiber contents and confining pressure to generalize the effect of increasing fiber content on the induced pore water pressure.

4.2.5. Effect of fiber content on the toughness of soil-fiber composite

The toughness of a material can be estimated as the area under the stress-strain curve (Maher and Ho, 1994). Figure 9 shows the improvement in the toughness of the composite with an increase in the fiber content for three values of confining pressures.

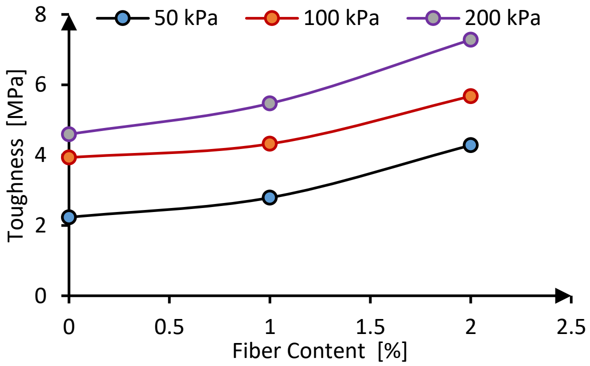


Figure 9: Effect of fiber content on the toughness of soil-fiber composite

An estimation of the toughness of the soil is an indication of the soil's resistance to hydraulic fracturing (Nishimura et.al, 2004). Figure 9 shows that increasing the fiber content increases the toughness of soil-fiber composite for all values of effective stresses. This shows the applicability of fiber-reinforced soils in earth structures that are subjected to cracking due to alternate wetting and drying cycles. The improvement in toughness in par with the ductility could increase the resistance of this composite to freeze-thaw cycles and is applicable when used as clay liners for landfills.

5. PRELIMINARY CONCLUSIONS

In this study, the behavior of polypropylene fiber-reinforced clay soil was evaluated for three different values of confining stresses. Based on the experimental results the following main conclusions can be drawn:

- Adding short, discrete polypropylene fibers to the clay soil increases the peak deviatoric stress, ductility and toughness of the composite.
- A linear elastic - strain softening response was replaced by a linear elastic - strain hardening response when fibers are introduced into the soil.
- The initial portion of the curves are similar for both unreinforced and fiber-reinforced soil samples. This indicates that the load resisted by the fibers is substantial at higher strain levels.
- Unreinforced soil samples failed by forming a well-defined failure plane, however fiber-reinforced samples showed a tendency to bulge and the test was stopped when an axial strain of 20% was approached.
- This change in the failure mode of soil when reinforced with fibers indicate an improvement in the ductility. An

increase in ductility is always accompanied by an increase in the cracking resistance and could be applied when this composite is used as landfill liners or final covers.

- The toughness of the soil-fiber composite also increases with an increase in the fiber content and confining pressures. This behavior would be highly beneficial when the fiber-reinforced samples are used in earth structures that are prone to cracking.
- No conclusions can be made on the development of pore water pressure within the specimen by the inclusion of fibers. Hence more tests need to be carried out at higher fiber contents (3% and 4%) and confining pressures to arrive at a general conclusion.

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