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ORIGINAL PAPER

Influence of Synthetic and Natural Fibers on Dewatering Rate and Shear Strength of Slurries in Geotextile Tube Applications

J. M. Spritzer[1] · M. M. Khachan[1] · S. K. Bhatia[1]

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Abstract This study investigates the effect of fibers on the dewatering time, filter cake properties, and shear strength of filter cakes with fine-grained silty clay. Synthetic nylon fibers with lengths of 6, 12, and 18 mm and one natural jute fiber with an average length of 8 mm were added to slurries with 33 % fines in concentrations of 0.5 % by soil mass. Optimum dose tests for particle flocculation showed that slurries reached a turbidity of 20 NTU with up to 19 % less flocculatant material compared to slurries with no fibers. Pressure filtration tests showed that the dewatering time decreased significantly with both synthetic and jute fibers, but were not dependent on fiber length. However, fall cone tests and unconsolidated undrained tests showed that the increase in shear strength was dependent on fiber length. Increases in shear strength were over 100 % with 12 mm nylon fibers, while filter cakes with 6 and 18 mm nylon fibers increased the shear strength by 43 %. Jute fibers did not show as high of a strength gain as the nylon fibers, but did increase dewatering times by an average of 14–22 % compared to filter cakes with nylon fibers.

Keywords Geotextile dewatering · Fiber reinforced slurries · Unconsolidated undrained shear strength · Pressure filtration test · Fall cone test

Introduction

Dredging of sediments and the dewatering of the dredged sediment/slurry through geotextile tubes have become increasingly common in the United States. However, a variation in slurry particle sizes, particularly fine-grained particles, creates issues with soil loss and dewatering rates within geotextile tubes. Small particles often pass through the geotextile tubes, as well as cause long dewatering times due to their low permeability. Therefore, cationic synthetic polymers have been used extensively as "conditioners" for slurry (soil–water mixture) flocculation in the geotextile tube dewatering industry. Multiple studies have been conducted which show the benefits of using cationic polyacrylamide (CPAMs) flocculants in geotextile tube dewatering [1–3]. The CPAMs, which have relatively long molecular chains due to their high molecular weight, cause soil particles to attach to their surface through charge neutralization and bridging mechanisms. These studies showed that the particle–polymer attraction effectively increases the soil floc size, thereby causing faster dewatering and a decrease in soil loss through geotextile tubes.

Geotextile tubes can rupture if overstressed and become unstable if stacked. This happens when the slurry inside the tube has low percent solids and low shear strength. By increasing the shear strength of the filter cake to allow the filter cake to dissipate some of the overlying loads, this would reduce stresses in the geotextile tubes. Synthetic fibers have been used extensively to increase the shear strength of different soil types in many studies [4–10].

✉ J. M. Spritzer
jmspritz@syr.edu

M. M. Khachan
mmkhacha@syr.edu

S. K. Bhatia
skbhatia@syr.edu

[1] Department of Civil and Environmental Engineering, Syracuse University, 151 Link Hall, Syracuse, NY 13244, USA

Furthermore, recent studies have been conducted using natural fibers to increase shear strength of soils [4, 9, 11–12]. Natural fibers are believed to act in the same way as synthetic fibers, while providing an environmentally-friendly alternative.

Many of these studies investigated how the amount of fiber additions effect shear strength and other engineering properties of soil [4, 6, 8, 10]. Some studies showed the comparative benefits of using different fiber lengths [4, 6, 9] and different water contents of soil samples [9]. Few studies have been conducted in which the fibers were added to the sample in the slurry form. Moreover, many of these studies used triaxial tests, consolidated drained (CD) or undrained (CU), and/or direct shear tests to determine the benefits of using randomly distributed fibers on the shear strength of soils [4–6, 8–12]. Generally, it has been observed that there is significant increase in shear strength, as well as a reduction in post-peak strength losses with fiber additions. The literature also suggests that the length, as well as the diameter of the fiber have an effect on the strength gain in the soil samples.

Freitag [5], in an early investigation, used 1 % of 20 mm long polypropylene (PP) fibers with a diameter of 0.1 mm in lean sandy clay (CL). Samples without fibers were prepared to determine the maximum dry density (MDD) and optimum moisture content (OMC). The OMC was found to be 21.8 % for this soil. Samples were tested under water contents between 17 and 23.5 % with and without PP fibers to find the increase in the unconfined compressive strength (UCS) with fiber additions. Freitag showed that samples slightly wet of the OMC (22.4 %) had the greatest gains in strength with up to a 25 % increase compared to unreinforced samples. Samples slightly dry of the OMC (20 %) had the highest overall strength, but did not exhibit as high of increases in strength.

Ranjan et al. [9] used different length to diameter fibers (aspect ratio) to quantify strength gains at different fiber concentrations. They used synthetic and natural fibers with lengths in a range of 15–38 and 10–25 mm, respectively, and diameters of 0.3 and 0.2 mm, respectively. This equates to aspect ratios of 50, 75, 100, and 125 for both synthetic and natural fibers. The results showed that the higher the aspect ratio, the greater the gain in strength, regardless of the concentration of fibers.

Kumar et al. [6] used polyester (PE) fibers at lengths of 3, 6, and 12 mm and concentrations of 0.5, 1.0, 1.5, and 2.0 % by weight of a clay (CH) soil. Mixtures of soil and fibers were compacted to their MDD and OMC before being tested using the UCS test with a strain rate of 0.5 %/min. An increase in the unconfined compressive strength of roughly 90 % with 0.5 % 12 mm fibers was observed compared to unreinforced samples. Similarly, a 75 % strength gain was observed with the addition of 0.5 % 6 mm fibers.

Tang et al. [10] used 12 mm synthetic PP fibers to increase the shear strength and ductility of a clayey soil (CL). The fibers were added to soil samples in the dry form and mixed by hand at low percentages of 0.05, 0.15, and 0.25 % by weight of soil. Water was then added and the samples were compacted to their respective MDD and OMC. UCS tests were conducted on the samples with a 3 %/min strain rate at the different fiber contents. The results showed a strength increase of 25–40 % for samples with the low fiber concentrations compared to the no fibers samples.

Ahmad et al. [4] used natural oil palm empty fruit bunch (OPEFB) fibers of 15, 30, and 45 mm lengths and concentrations of 0.25 and 0.5 % by weight of a silty sand (SM) soil. The fibers were added in the dry form and were mixed by hand. The samples were then compacted to their MDD and OMC. The OPEFB fibers were coated with acrylic butadiene styrene thermoplastic and were compared to the uncoated fibers. Several CD and CU tests were performed at a strain rate of 0.1 %/min with different combinations of fiber lengths and concentrations. The results indicated that coated OPEFB fibers performed much better than the uncoated fibers for all lengths and concentrations in terms of strength due to the fact that they had an increased diameter and surface area. Furthermore, Ahmad et al. reported the optimum length for their study was the 30 mm (coated and uncoated) at a concentration of 0.5 % in both the CD and CU tests. The 45 mm OPEFB fibers would observe a decrease in peak deviator stress compared to the 30 mm fibers.

All of these studies have demonstrated the benefit of adding fibers in soil for strength gain. This study aims to expand on soil strengthening with synthetic and natural fibers for geotextile tube dewatering applications. A majority of the studies have been conducted with fibers when added to soil in the dry form, while this study shows the advantages of adding fibers in silty slurries. Moreover, the main concern of this study is to investigate the role of fiber length on the dewatering time and shear strength of flocculated slurries.

One fiber concentration, 0.5 % by weight of soil, has been chosen based on review of literature which suggests an optimum concentration of fibers between 0.5 and 0.75 %. Three different lengths of synthetic fibers, 6, 12, and 18 mm, made of nylon were selected based on their commercial availability to be used for this study. These fibers have relatively small diameters (3.0–10.0 µm) and a medium specific gravity (1.15) compared to other synthetic fiber materials. One natural fiber, a jute fiber, with an average length of 8 mm was also selected which has a larger diameter (5.0–25.0 µm) and specific gravity (1.40) compared to the nylon fibers.

The samples were prepared in the slurry form in order to most closely model the addition process of fibers to dredged sediments in dewatering applications. Optimum dose jar tests were performed on slurries with and without fibers to determine the optimum CPAM dose for the slurry. Pressure filtration tests (PFTs) were performed to observe the change in dewatering time with increasing fiber lengths. UU tests were used to determine the undisturbed shear strength of filter cakes which would most closely replicate filter cakes that would form in geotextile tubes after dewatering. Fall cone tests (FCTs) were also used to obtain the shear strength, which could be used as a means of in situ testing.

Materials

Soils

Tully soil was collected from Clarks Gravel Pit in Tully, NY. The soil was sieved through a No. 200 mesh in wet form by hand. The fines were collected and were oven dried for 24 h. A Hydrometer analysis, performed in accordance with ASTM D1140 [13], showed the Tully fines had 88 % silt and 12 % clay particles, and a specific gravity of 2.65. Particle sizes D_{10}, D_{30}, and D_{60} were measured as 0.003, 0.009, and 0.062 mm, respectively from a sieve analysis in accordance with ASTM D422 [14]. The coefficient of uniformity (Cu) and coefficient of curvature (Cc) were calculated as 22 and 2.2. The liquid limit, plastic limit and plasticity index were measured in accordance with ASTM D4318 [15]. These values were found to be 23.6, 18.0, and 5.6 %, respectively. Based on this initial soil analysis, the Tully fines are classified as silty clay (CL-ML) in accordance with ASTM D2487 [16] standards. Furthermore, the shear strength at the liquid limit showed the Tully fines have a shear strength of roughly 1 kPa from a lab vane test.

Fibers

Nylon fibers were obtained from NYCON Corporation in Fair Hills, PA. The NYCON-RC series of fibers were selected for testing due to their relatively thin diameters, variety of cut lengths, availability, and non-absorbent properties. The RC series of fibers are made of nylon in the form of a monofilament bundle. Natural fibers were acquired from Bast Fibers, LLC, located in Cresskill, NJ. Cut jute fibers were selected for testing due to their availability and comparable performance to synthetic fibers.

The nylon fibers do not absorb water and were air blown with low pressure in a plastic container to separate the fibers for better dispersion before being added to a slurry. Jute fibers were not air blown but rather were soaked in water for 24 h before being mixed in the slurry. The jute fibers were soaked in water instead of air blown because it is anticipated that the jute fibers would retain water during testing. Therefore, in order to minimize water retention, the fibers were initially soaked, which also effectively dispersed the fibers before adding to the slurry. 0.5 % by soil mass of both types of fibers was added to each sample in slurry form. The properties of the nylon and jute fibers are given in Table 1. Scanning electron microscope (SEM) images of the fibers are shown in Fig. 1 to show the comparative fiber diameters and surface textures. It should be noted that the jute fibers SEM image show several fibers clumped together. If the jute fibers were air blown prior to SEM imaging, the jute fibers would've had less clumps, similar to the nylon fibers.

Polymer

A CPAM flocculant was obtained from BASF Corporation. The polymers have a high charge density (3.05 meq/g) and molecular weight (15–20 $\times$ 10^6 g/mol) compared to other CPAMs commercially available [17]. The polymers come in a solid crystal form and were diluted to effectively flocculate soil particles in slurry form. Solutions of 2500 ppm (0.25 %) polymer-deionized (DI) water were created for all tests. The solid polymer was added to the DI water and allowed to dissolve for at least 24 h. No polymer solution was used after 7 days to ensure that the polymer concentration did not lose its effectiveness.

Geotextile

A high strength polypropylene (PP) woven monofilament geotextile commonly used in dewatering processes was selected for this study and was provided by TenCate. This geotextile has an apparent opening size (AOS) and permittivity compatible with the Tully fines soil when flocculated. Tully fines which are not flocculated were observed to pass directly through the geotextile as

Table 1 NYCON-RC and jute fibers properties

Property	NYCON-RC	Jute
Diameter (μm)	3.0–10.0	5.0–25.0
Length (mm)	6.0, 12.0, 18.0	7.0–9.0
Specific gravity	1.15	1.47
Tensile strength (MPa)	300	331–414[a]
Flexural strength (MPa)	2800	153–164[b]

[a] Obtained from Biswas et al. [11]

[b] Obtained from Sinha and Panigrahi [12]

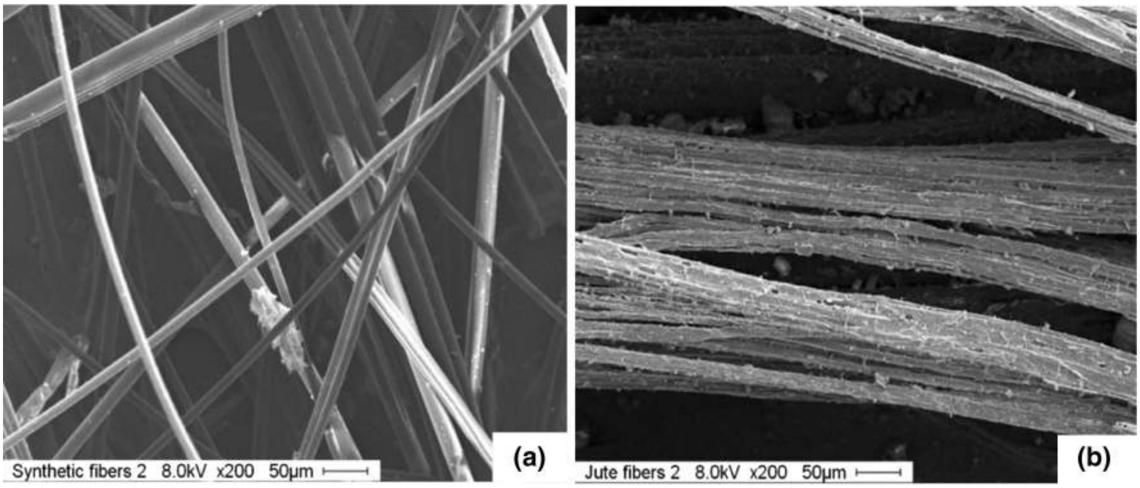


Fig. 1 SEM images of nylon (**a**) and jute (**b**)

expected. The physical and hydraulic geotextile properties are presented in Table 2.

Test Methods

Jar Test

Jar tests were performed to determine the optimum polymer dose for each condition using a similar jar test method provided by ASTM D2035 [18] and methods described in literature [3, 6–7]. Slurries of 33 % Tully fines by total mass were prepared by first placing 441 mL deionized (DI) water into a 1 L glass beaker. In order to accommodate for water that is added in the form of the polymer dose, the total amount of water initially added was measured as the total water volume (486 mL) less the amount of water from the polymer dose which is added during the jar test, estimated as roughly 200 ppm (45 mL). 242 g of soil was added to obtain a 33 % by total mass of slurry. In the case that fibers were used, 0.5 % of fibers by mass of soil (1.21 g) were added into the water. Nylon and jute fibers were dispersed once placed into the water and mixed.

Table 2 Physical and hydraulic geotextile properties

Material	Polypropylene (PP)
Fabric structure	W, MF
AOS (mm)	0.42
Permittivity (s^{-1})	0.37
Mass per unit area (g/m^2)	585
Thickness (mm)	1.04
Tensile strength (kN/m)	96 × 70

Obtained from Khachan et al. [17]

W woven, *MF* monofilament, *AOS* apparent opening size

The prepared slurry sample was then mixed using a Phipps and Bird PB-700 four paddle jar tester at a rate of 300–320 rpm for 5 min without flocculants. The mixing rate was decreased to a range of 260–270 rpm to allow for soil flocs to form with the addition of the polymer. Concentrated polymer was added to the sample in increments of 10 mL (43.3 ppm polymer per increment per unit of total volume) and allowed to mix for 1 min to ensure complete distribution of the flocculant in the slurry. The jar tester was stopped after mixing and the settling rate was observed for 2 min. Two minutes of settling was chosen due to the fact that most dewatering in geotextile tubes occurs instantly and any observed changes in turbidity after 2 min were negligible. The turbidity of the supernatant was taken at the end of the settling time and measured using a Hach 2100 N Turbidimeter. The removed supernatant was returned to the sample and mixed for 15 s before adding the next dose. This process was completed until 45 mL total of concentrated polymer was added to the sample. The change in turbidity versus the polymer dose was then plotted to determine the optimum dose.

Pressure Filtration Test

Pressure filtration tests (PFTs) were conducted to compare dewatering behavior of slurry with and without fibers. Due to the fact that there is no existing standard for the PFT, an identical preparation of each slurry sample for the jar test procedure was followed [3, 6, 19]. The prepared slurries of soil and fibers were initially mixed for 5 min before adding polymer. A similar mixing procedure for polymer additions to the jar test was used. This procedure was slightly simpler and shorter, though, in which three equal increments of polymer (12.7 mL determined from the optimum dose tests) were added followed by 1 min and 20 s of mixing.

After the mixing phase, the subsequent polymer dose was added without stopping the mixing between increments. This was repeated until all three increments were added, with a total combined mixing time with polymers of 4 min. The slurry created for the PFT had a volume of 577 mL.

The PFT setup is shown in Fig. 2. Immediately after the mixing and polymer addition phase, the slurry was poured into the top of the cylindrical reservoir (72 mm diameter, 170 mm height, and 600 mL volume capacity). At the base of the cylindrical reservoir is a cylindrical baseplate and geotextile filter which allows dewatering of the slurry while retaining the flocculated slurry. The cap was attached to the top of the reservoir which has an inlet for an applied pressure. The pressure was set at 34.5 kPa (5psi) in order to match the pressure within the geotextile tubes during filling and dewatering. The pressure was applied without releasing the downspout nozzle for a total of 15 s to allow an initial filter cake to form. The downspout nozzle was released and the change in volume over time (dewatering rate) was measured using a 500 mL graduated cylinder. At the end of the PFT, the filter cake was immediately taken from the reservoir and the filter cake height was measured. The samples were weighed in their wet form and then were oven dried for 24 h to measure its moisture and solids content.

Fall Cone Test (FCT)

Once the filtration process was completed in the PFT, the filter cake was tested with a 60 g and 60° cone Matest Penetrometer to measure the shear strength from a drop height of 0 mm (Fig. 3b). FCT were performed in accordance with Wood (1990) and Monfared, who followed the procedure described in liquid limit standards and industry testing standards [20–23]. The penetration depth of the cone was measured and the depth was correlated with shear strength using the following equation [20]:

$$S_{\mathrm{u}} = \frac{k * m * g}{d^2}$$

where S_{u} is the shear strength (kPa), k is the cone factor (unitless), m is the mass of the cone (grams), g is the force of gravity (m/s^2), and d is the penetration depth (mm). A k-value of 0.29 was used because it is the widely accepted value, as suggested by Wood (1990) [20], for this empirical coefficient for a cone of this selected mass and shape.

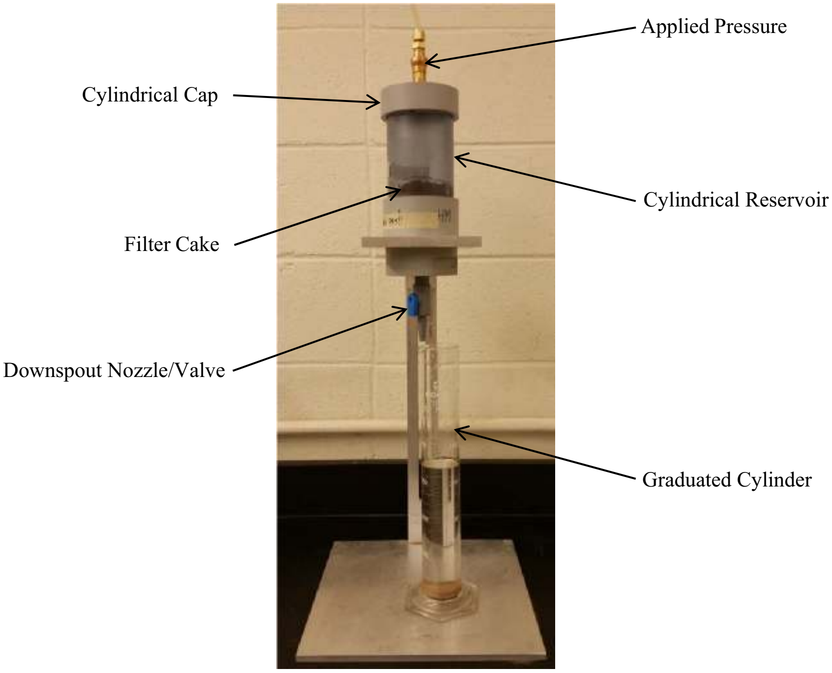
Lab Vane Test

After the FCT penetration depth was measured, the filter cake's shear strength was measured at different locations of the filter cake using a Farnell lab vane (Fig. 4). The entire vane was inserted into the filter cake so that the extents of the vane were flush with the top surface in position near the center. The lab vane was rotated at a rate of one revolution per 2 s until the filter cake could no longer resist the shearing. The rotational angle in which the filter cake resisted the lab vane shear was recorded and correlated with the filter cake shear strength using the following formula provided by the manufacturer:

$$S_{\mathrm{u}} = \theta * C$$

where S_{u} is the shear strength (kPa), θ is the rotational angle (degrees), and C is the correlation factor, which is

Fig. 2 PFT test set up



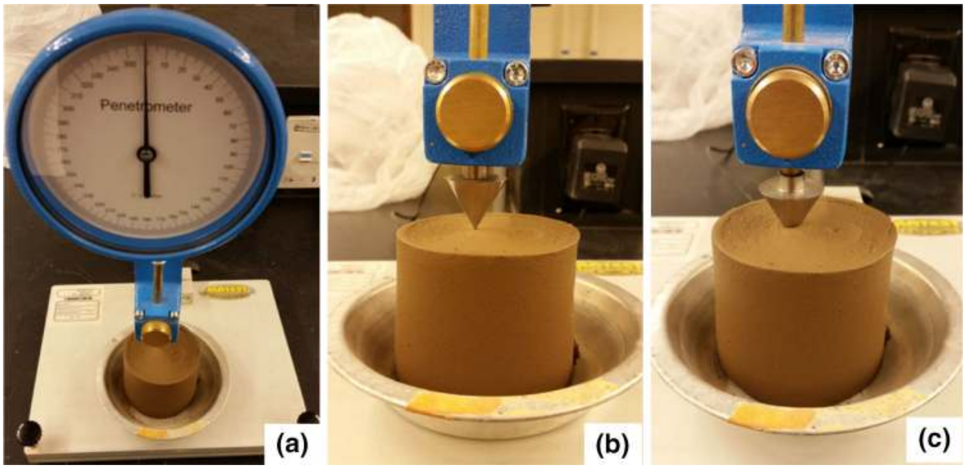


Fig. 3 Fall cone test set up and penetration—no fibers condition

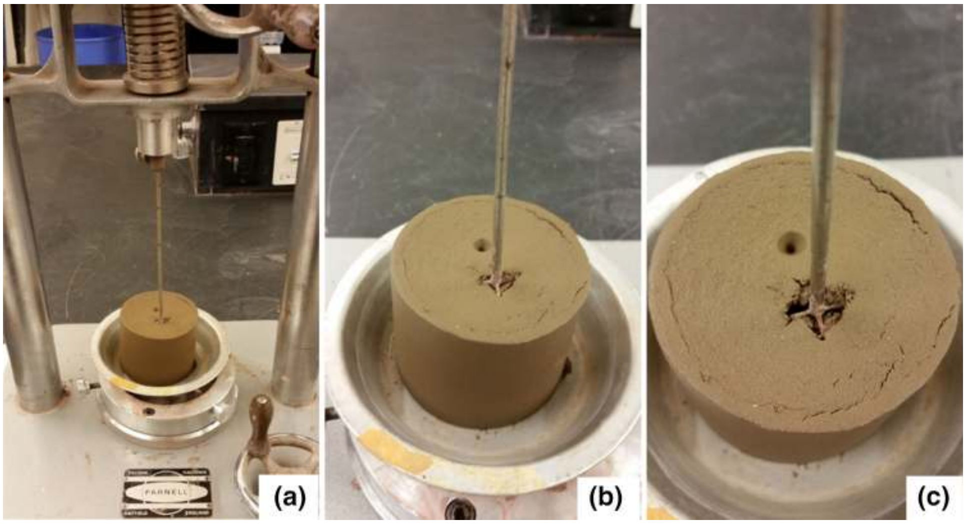


Fig. 4 Lab vane test set up—no fibers condition

0.359 (kPa/degree). It should be noted that the correlation equation above is dependent on the specific geometry of the vane used and is specific to the lab vane spring constant. The correlation factor was obtained from a calibration curve supplied by Leonard Farnell Company.

Unconsolidated Undrained Test

Unconsolidated undrained (UU) tests were conducted in order to measure the shear strength of the slurry after dewatering. A smaller sample in terms of total volume was required in order to fit in the GeoTac Automated Test Acuator set up (Fig. 6). This device required a sample with a height of 72 mm and a 36 mm diameter. Therefore, a modified PFT has been developed at Syracuse University to accommodate these new dimensions. The details are provided in Fig. 5.

190 mL of DI water were added into a 600 mL glass beaker. 95 g of Tully fines was added to the water and fibers mixture. When fibers were used, the respective amount of fibers (0.48 g) was added to the water and stirred with a stirring rod to disperse the fibers in the water. The slurry was mixed in the Phipps and Bird PB-700 four paddle jar tester at a speed of 310–320 rpm for 5 min. The speed was reduced to 260–270 rpm (to allow the flocs to form) and three equal increments of 4.8 mL polymer concentrate were added, followed by a period of mixing for 1 min and 20 s between each addition. The jar tester was stopped for 45 s after the addition and mixing phase to ensure the sample had reached an optimum turbidity and the fibers were completely mixed in the slurry.

The test set up for the modified PFT filtration works identically to the PFT test set up by allowing for water filtration through a geotextile, while the slurry flocs remain behind, creating a filter cake. Inside of the cylindrical reservoir is a latex triaxial membrane. This membrane allowed for quick and easy removal of the filter cake from the cylindrical reservoir to the UU test set up once the

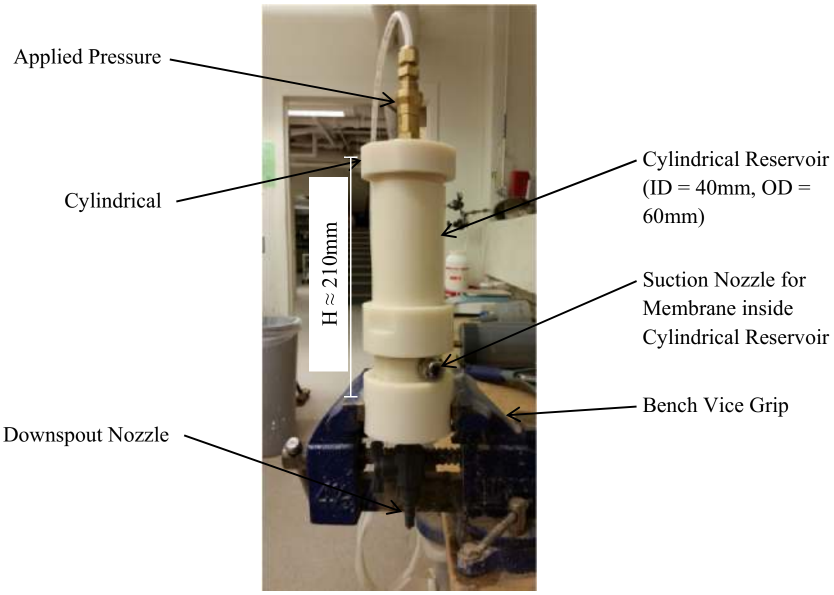


Fig. 5 Unconsolidated undrained filtration test set up

filtration process was complete to create minimal disturbances in the filter cake. The plastic end caps were placed on both sides of the filter cake and attached to the member extents using rubber O-rings (Fig. 6). The sample was then moved to the UU test set up (Fig. 6).

The cell pressure was set at 34.5 kPa to simulate the average stress a soil specimen would encounter within a filled geotextile tube. The specimen was loaded at a strain rate of 2 %/min for 15 min. During this test, the deviator stress and axial strain were measured to create stress–strain relationships, as well as to measure the ultimate shear strength of the filter cakes.

Results and Discussion

Optimum Dose Results

Jar test results were used to obtain the optimum polymer dose for slurries with and without fibers. The optimum dose for a given sample corresponds to turbidity below 20 nephelometric turbidity units (NTU), a measure of the cloudiness of a fluid, in the supernatant. A turbidity of 20 NTU was chosen based on best construction practices and technology available to minimize turbidity, for which 20 NTU is acceptable. Figure 7 shows the range at optimum corresponding to a turbidity level of 20 NTU. For each combination, a high and low is plotted represented by the small black dashes. The larger black dash corresponds to the average polymer dose for each combination.

As it can be seen from Fig. 7, the average ranges between 155 and 175 ppm. In order to avoid changing the optimum polymer dose for each condition, a common dosage of 165 ppm was selected. The selected optimum dose of 165 ppm is within 6 % of the individual optimum doses for the slurries with fibers conditions. Moreover, the optimum dose also falls within the limits of the no fibers condition.

As the fiber length increases, the optimum dose range and average polymer dose for the range stays within 5 % of each other, indicating that fiber length does not have a significant impact on the optimum dose. However, the addition of fibers does significantly affect the optimum dose compared to no fibers slurries, with a maximum decreases in average optimum polymer dose of 17 and 19 % between nylon (18 mm) and jute fibers, respectively. The optimum polymer dose of 165 ppm was converted to an equivalent volume of concentrated polymer for the pressure filtration test and UU test to ensure the optimum polymer dose was achieved in each scenario with varying slurry volumes.

Pressure Filtration Test (PFT) Results

Three PFT tests were conducted for each combination to evaluate test reproducibility. From this test, dewatering rate and final filter cake properties were evaluated. These two properties were chosen as they have the most importance to dewatering applications.

Filter Cake Properties

Three different filter cake properties were measured after each PFT test—filter cake height, percentage of solids, and fiber dispersion. The filter cake height is important to geotextile tube dewatering application because the smaller the height achieved after each test indicates a more

Fig. 6 UU test filter cake preparation and set up

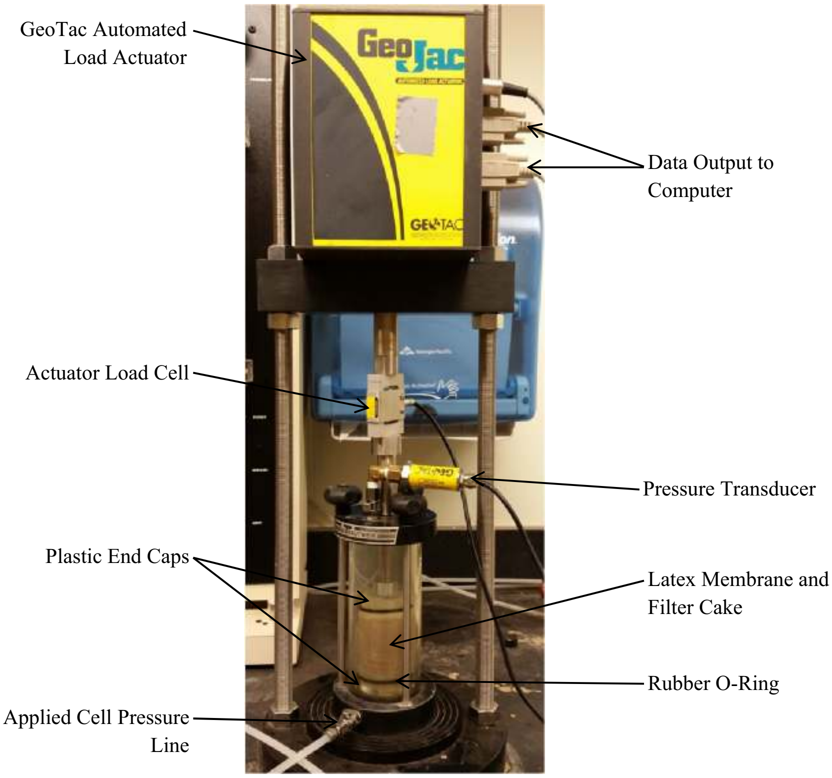
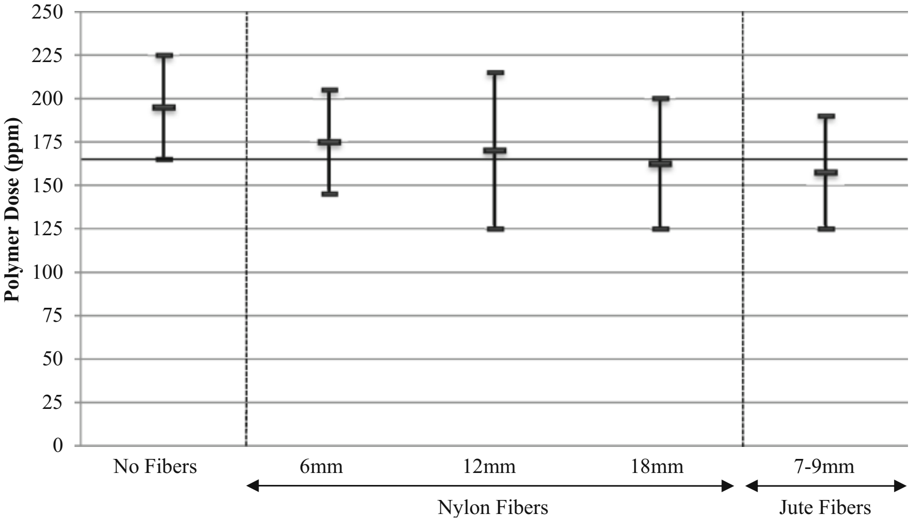


Fig. 7 Polymer dose range with supernatant less than 20 NTU by condition



compact sample with a smaller overall volume. Filter cake samples after PFT test are shown in Fig. 8.

As shown in Fig. 8, the uniformity of each sample decreases with fiber additions. This created issues with measuring the exact filter cake height; the best approximate average height of the filter cake was measured in the case where no definitive average height was present. The height of the sample, however, did not significantly change due to the addition of fibers and did not vary significantly between fiber lengths.

Solids percentage is also critical in dewatering applications for similar reasons as the filter cake height. A higher solids percentage indicates a greater amount of drained water. The higher the dewatered volume, the more slurry (in terms of solids volume) can be placed into geotextile tubes. Therefore, by increasing solids content, the efficiency of dewatering with geotextile tubes increases. Table 3 shows the average filter cake height, percentage solids, and water content for each condition.

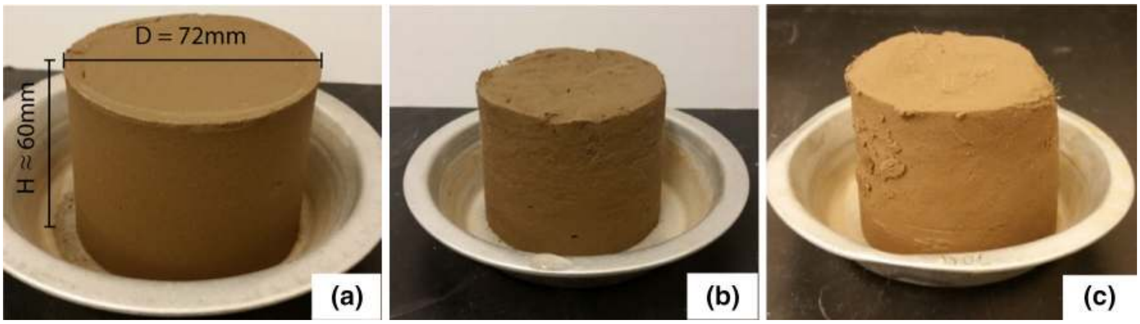


Fig. 8 PFT filter cake samples—no fibers (**a**), 18 mm fibers (**b**), and jute fibers (**c**)

While the filter cake height decreases slightly between the no fibers condition and the fibers condition (3.8 % maximum between no fibers and 18 mm fibers), this change in height is not significant. Moreover, an increase in percentage of solids of 1–2 % between the no fibers condition and fibers condition is negligible. However, the difference in the solids and water content between the nylon fibers and jute fibers can be explained by the nylon fibers hydrophobic characteristics and the jute fibers affinity to water. It is expected that the jute fibers would produce identical results in terms of solids and water content if they were not able to absorb water.

The dispersion of fibers in the PFT filter cakes are shown in Fig. 9. As this figure suggests, the dispersion of fibers of different lengths did not vary. Each filter cake observed similar dispersion trends, where the fibers are randomly distributed in the samples, as assumed throughout this study.

Dewatering Time

Dewatering time is one of the most critical aspects of geotextile tube dewatering. The faster the flocculated sediments settle and dewater, the quicker the next geotextile tube can be filled. The dewatering results of slurries with fibers (nylon and jute) are presented in Fig. 10.

The initial dewatering phase, regardless of the sample containing fibers or not, is relatively the same for the first 15 s, as shown by the green vertical line. This is due to the fact that the filter cake was not observed to have been formed with in the first several seconds. Therefore, the water was simply dewatering through the geotextile until the filter cake started to form after this initial phase. After this phase, there seems to be a clear division in dewatering rates between the no fibers, nylon fibers, and jute fibers conditions (red vertical line). The total amount of water removal remained constant for each condition at roughly 340 mL (black horizontal line). However, dewatering times were influenced by the fibers.

Figure 10 indicates that adding fibers to the slurry significantly decreases the dewatering time by 41 % with nylon fibers (160 s) and 49 % with jute fibers (137 s) compared to the no fibers condition (271 s). However, no distinct correlation between the fiber length and dewatering time was found. The average dewatering times of slurries with different lengths does not vary by more than 9 %. This suggests that fiber length does not influence the dewatering time, but simply that the addition of fibers improves dewatering times by increasing the void spaces (permeability) at the fiber-soil interface. This can be due to the fact the total volume of fibers is the same (0.5 % by mass of soil). There are more total 6 mm fibers in samples compared to the 12 and 18 mm fibers but this did not influence the results.

The results also show that the jute fibers performed better as compared to the nylon fibers in terms of dewatering time. The minimum decrease in the dewatering time between the two fiber types was 14 % (jute fiber and 18 mm nylon fiber), while the maximum increase was 22 % (jute fiber and 6 mm nylon fiber). This difference is

Table 3 Average filter cake properties

Condition	Filter cake height[a] (mm)	Solids content (%)	Water content (%)
No fibers	57.4	65.2	53.3
6 mm RC fibers	56.1	66.4	50.7
12 mm RC fibers	56.5	67.2	48.9
18 mm RC fibers	55.2	67.4	48.5
8 mm jute fibers	56.1	65.7	52.4

[a] The best approximate filter cake height was measured due to irregularities of the top surface

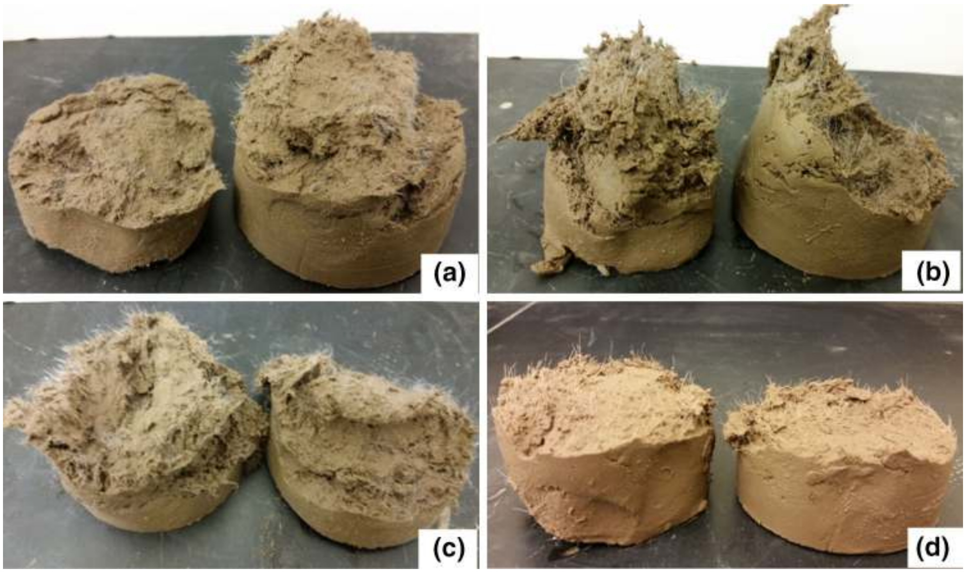


Fig. 9 Dispersion of fibers in PFT filter cakes—6 mm (**a**), 12 mm (**b**), 18 mm (**c**), and jute fibers (**d**)

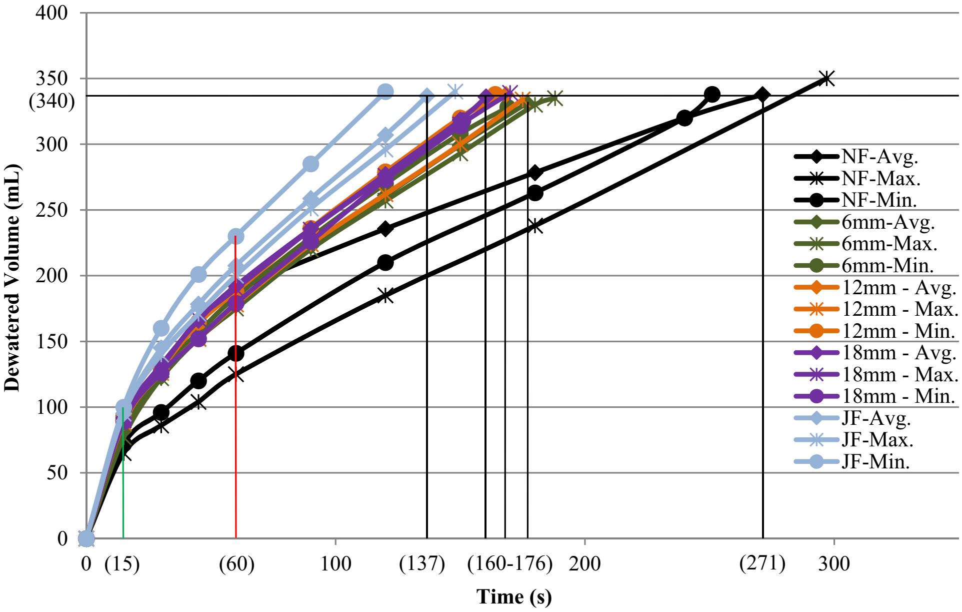


Fig. 10 Dewatering rates for no fibers, nylon fibers and jute fibers

could be attributed to the fact that the jute fibers have a larger diameter, and thus surface area, compared to the nylon fibers (Fig. 1). Therefore, there is a larger area in which particles can attach to the fiber surface, creating more void spaces in the jute fiber compared to nylon fiber.

Shear Strength Results

One of the main objectives of this study was to investigate the role of fibers on the shear strength of the dewatered filter cake. Increasing shear strength of filter cakes allows the cake to sustain more stresses while reducing the stresses in the geotextile tube. This may reduce the likelihood of geotextile rupture or failure. Furthermore, increasing the shear strength of filter cakes creates better stability of filled geotextile tubes which reduces risks associated with geotextile tube stacking commonly used in industry to preserve on or off site space.

Three methods were used to measure the shear strength of filter cakes: lab vane (LV), fall cone test (FCT), and unconsolidated undrained (UU) tests. The LV and FCT are widely used tests but often produce less reliable results compared to more complicated tests, such as triaxial tests. The UU triaxial test was used in order to measure the shear strength of the filter cakes. This test is more reliable than LV and FCT tests, but requires much more time, efforts, and complicated equipment.

Lab Vane Test (LV)

Several attempts were made to measure the shear strength of the filter cake using the lab vane. The lab vane did not give reliable test results. In this test, the fibers would resist the penetration of the vane into the soil, thus creating a very disturbed sample and test result. The results from the LV test of filter cakes with fibers had very high shear strength values compared to the no fibers condition (due to the insertion resistance of the fibers) and compared to the FCT and UU test results. For this reason, the lab vane test results were not accepted. Figure 11 shows test specimens under the LV tests. The no fibers condition had little disturbance from the lab vane penetration as expected (a). However, the fibers condition samples were affected by the fibers resisting the lab vane penetration (b). In some instances, the lab vane penetration would even collapse the soil into the sample (c).

Fall Cone Test (FCT)

The fall cone test was used only on PFT filter cakes after dewatering. The tests were performed on the top surface which is the weakest portion of the cake; the strength is expected to increase from top to bottom within the filter cake due to the increase in the overlying sediment weight. Table 4 shows the average penetration depth of the cone into the filter cake. The penetration depth was correlated to the shear strength (see "Fall Cone Test" in Test Methods section).

The FCT results suggest that fiber additions increase the shear strength of the sample by a maximum of 162 % in the case of the 12 mm fibers and a minimum of 51 % in the case of the jute fibers compared to the no fibers case. Therefore, it can be concluded that the addition of fibers do improve the shear strength of the filter cake. This could be due to the creation of interlocking soil-fiber matrices.

These results also suggest that there is an optimum fiber length (12 mm) which provides the greatest strength increase. After an increase in fiber length greater than 12 mm, the average shear strength of the filter cakes decreased by 21 % with the 18 mm fibers condition. This could be due to the fibers being too long in which they begin to interact with themselves, as opposed to interacting solely with the soil particles.

Table 4 Average FCT penetration and shear strength

Condition	FCT penetration (mm)	Shear strength (kPa)[a]
No fibers	6.8	3.7
6 mm RC fibers	4.7	7.7
12 mm RC fibers	4.2	9.7
18 mm RC fibers	4.7	7.7
8 mm Jute fibers	5.5	5.6

[a] See "Fall Cone Test" in Test Methods section for shear strength correlation equation

The jute fibers did not increase shear strength as much as the nylon fibers. One possible reason for this is because the jute fibers have a higher specific gravity compared to the nylon fibers. Thus, the jute fibers would settle quicker in the slurry during the dewatering phase, causing less fiber dispersion in the filter cake in comparison to the nylon fibers. Less dispersion would then cause the shear strength in the top layer to be less than that of nylon fibers conditions. Moreover, since the jute fibers have a higher specific gravity compared to the nylon fibers, there are significantly less fibers in the filter cake in terms of volume. Therefore, there are less unique soil-fiber interlocking matrices in jute fiber specimens, which could lead to a lower shear strength value.

Unconsolidated Undrained (UU) Test

Unconsolidated undrained tests produced much more reliable results compared to the lab vane and fall cone test, and thus, are much more widely accepted. The stress–strain relationships from the UU tests are presented in Fig. 12. The shear strength of each test was taken as half of the deviator stress.

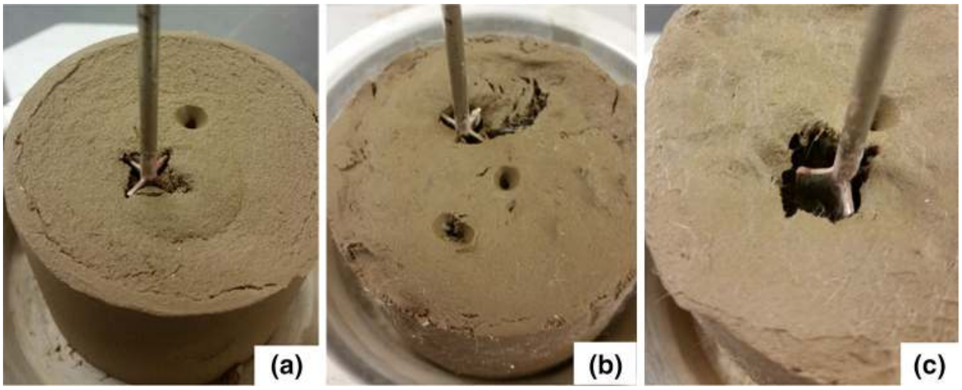


Fig. 11 Lab vane penetration with fibers (**a**) and without fibers (**b**) and (**c**)

Due to the fact that there was no point where the deviator stress was a maximum (the deviator stress continued to increase with strain in each test), a strain limit of 15 % was selected as the maximum deformation a sample could undergo, marked by the vertical black line. This value was chosen assuming that it is the maximum strain filter cakes can achieve without causing stability issues with geotextile tubes.

The initial portion of each curve is relatively the same for each condition for the first 0.5 % (roughly) of strain. After this strain value is reached, the filter cakes undergo nonlinear strain in which the fibers help to resist the deformation, leading to increases in shear strength. Ideally, the longer fibers cause higher strength gains because the fibers create more soil–fiber interactions helping to resist shearing forces under axial loads. However, it is believed that the longer fibers interact with themselves, causing limited strength gains.

There is a significant strength gain due to fiber additions as compared to the no fibers condition. A maximum individual strength gain of 100 % was achieved with the 12 mm fibers compared to the no fibers condition. Furthermore, the 12 mm fibers condition was by far the most consistent where there was low variability between tests. The 18 mm fiber condition, on the other hand, was the least repeatable, with fluctuations in shear strength up to 50 % between its own test results. This inconsistent performance could be due to the fact that the longer fibers do not disperse as evenly as shorter fibers, causing them to interact with themselves.

The trends from the UU tests match very closely with the trends from the FCT results. The 12 mm fibers case has the highest average strength gain in both tests, followed by 18, 6 mm, and jute fibers conditions. Moreover, the average shear strength of each condition (half of the deviator stress) is similar to its corresponding FCT shear strength value. One outlier may be the 12 mm fibers which had an average shear strength of 7.6 kPa from the UU results and 9.7 kPa shear strength from the FCT results, which is a difference of 22 %. However, the same overall trend between the UU and FCT results still remains in which both tests indicated that 12 mm fiber filter cakes had the highest shear strength. On the other hand, while jute fibers showed slightly higher average shear strength values under the UU tests (6.2 kPa) compared to the FCT tests (5.6 kPa), they still had the lowest average shear strength compared to all other fiber addition filter cakes.

Conclusions

The optimum polymer dose with a high molecular weight and charge density cationic polymer was measured on 33 % Tully fines slurries with and without fibers. Three different characteristics of filter cakes were investigated in this study with and without fibers: filter cake properties, dewatering time, and shear strength. The shear strength was measured in three different ways using the fall cone test, lab vane test, and unconsolidated undrained triaxial

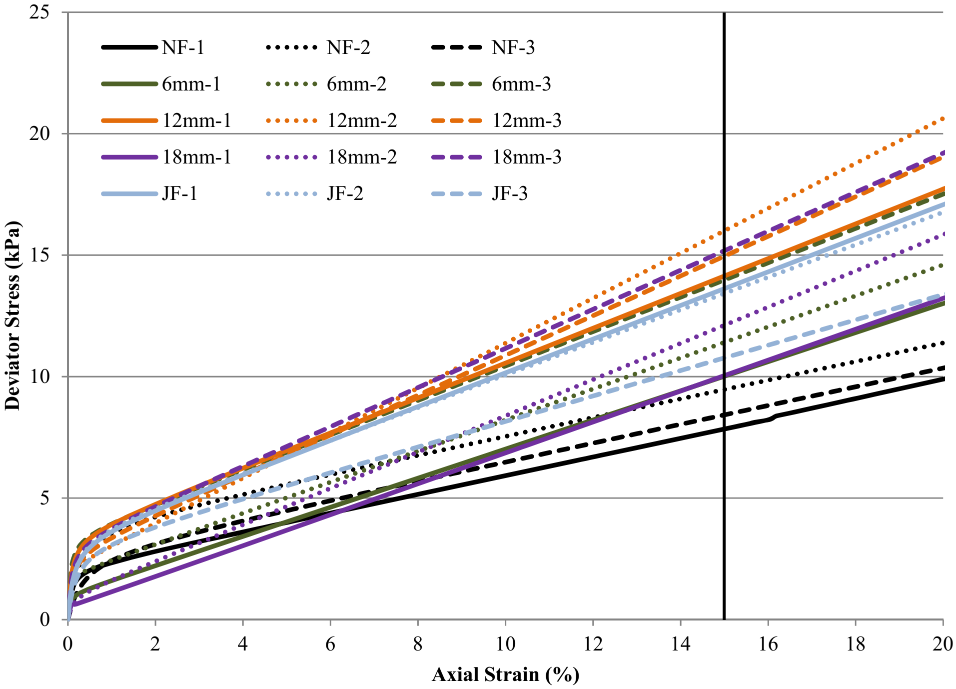


Fig. 12 Stress–strain relationship of UU test results

test. These four aspects of slurries and filter cakes, optimum polymer dose, filter cake properties, dewatering time, and shear strength, are crucial to dewatering and geotextile applications which can save time, money, and effort by reducing material consumption, equipment and energy usage, as well as to minimize manpower. The following conclusions can be made based on the results and observations of this investigation:

- There is a decrease in required polymer dose to reach the optimum level between fibers and no fibers slurries. This decrease was observed to be as much as 17 % with nylon fibers (18 mm) and 19 % with jute fibers.
- The dewatering time significantly decreases with the addition of fibers. Decreases of as much as 41 and 49 % were seen with nylon and jute fibers, respectively, compared to no fiber filter cakes. However, the fiber length did not have an effect on the dewatering rate. One possible explanation for variations in dewatering rates between the nylon and jute fibers, however, could be provided by the fact that jute fibers have a larger diameter and overall surface area which allows for more soil–fiber interactions [9]. These interactions increase the void spaces through which water can pass and, therefore, expedite the dewatering rate.
- There is a significant shear strength increase between the filter cakes with fiber additions and filter cakes with no fibers. FCT and UU results indicated shear strength increases up to 162 and 100 %, respectively, compared to no fibers filter cakes. These increases in strength are very comparable to that of Kumar et al. [6]. The shear strength was observed to increase in filter cakes with fibers up to 12 mm lengths. After this fiber length, the shear strength decreased in the 18 mm fibers in both the FCT and UU tests. This finding is similar to that of Ahmad et al. [4], who observed limited strength gains after a certain fiber length.
- There is a trade-off between shear strength and dewatering rate for jute fibers compared to nylon fibers. Jute fibers tend to have faster dewatering rates than nylon fibers, but do not have as high of a strength gain. The optimum polymer dose and filter cake properties did not vary significantly between nylon and natural fibers.

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References

1. Khachan MM, Bader RA, Bhatia SK, Maurer BW (2011) Comparative dewatering performance of slurries conditioned with synthetic polymers versus eco-friendly polymers. Geotechnical Special Publication, Geo-Frontiers 2011, Dallas, pp 3050–3058
2. Koerner RM, Koerner GR (2010) Performance tests for the selection of fabrics and additives when used as geotextile bags, containers, and tubes. Geotech Test J 33(3):1–7
3. Satyamurthy R, Bhatia SK (2009) Effect of polymer conditioning on dewatering characteristic of fine sediment slurry using geotextiles. Geosynth Int 16(2):83–96
4. Ahmad F, Bateni F, Azmi M (2010) Performance evaluation of silty sand reinforced with fibres. Geotext Geomembr 28(1):93–99
5. Freitag DR (1986) Soil randomly reinforced with fibers. J Geotech Eng 112(8):823–826
6. Kumar A, Walia BS, Mohan J (2006) Compressive strength of fiber reinforced highly compressible clay. Constr Build Mater 20(10):1063–1068
7. Maurer BW, Gustafson AC, Bhatia SK, Palomino AM (2012) Geotextile dewatering of flocculated, fiber reinforced fly-ash slurry. Fuel 97:411–417
8. Michalowski RL, Čermák J (2003) Triaxial compression of sand reinforced with fibers. J Geotech Geoenviron Eng 129(2):125–136
9. Ranjan G, Vasan RM, Charan HD (1996) Probabilistic analysis of randomly distributed fiber-reinforced soil. J Geotech Eng 122(6):419–426
10. Tang C, Shi B, Gao W, Chen F, Cai Y (2007) Strength and mechanical behavior or short polypropylene fiber reinforced and cement stabilized clayey soil. Geotext Geomembr 25(3):194–202
11. Biswas S, Ahsan Q, Cenna A, Hasan M, Hassan A (2013) Physical and mechanical properties of jute, bamboo, and coir natural fiber. Fiber Polymers 14(10):1762–1767
12. Sinha E, Panigrahi S (2009) Effect of plasma treatment on structure, wettability of jute fibers and flexibility strength of its composite. J Compos Mater 43(17):1791–1802
13. ASTM D 1140. Standard test methods for determining the amount of material finer than 75-μm (No. 200) sieve in soils by washing. ASTM International, West Conshohocken
14. ASTM D 422. Standard test method for particle-size analysis of soils. ASTM International, West Conshohocken
15. ASTM D 4318. Standard test methods for liquid limit, plastic limit, and plasticity index of soils. American Society for Testing and Materials, West Conshohocken
16. ASTM D 2487. Standard practice for classification of soils for engineering purposes (unified soil classification system). American Society for Testing and Materials, West Conshohocken
17. Khachan MM, Bhatia SK, Bader RA, Cetin D, Ramarao BV (2014) Cationic starch-based polymers as an alternative to synthetic polymers in geotextile tube dewatering of dredged sediments. Geosynth Int 21(2):119–136
18. ASTM D 2035. Standard practice for coagulation–flocculation jar test of water. ASTM International, West Conshohocken
19. Liao K, Bhatia SK (2005) Geotextile tube: filtration performance of woven geotextiles under pressure. In: Proceedings of NAGS 2005/GRI—19 cooperative conference, Las Vegas, pp. 1–15
20. Wood DM (1990) Soil behavior and critical state soil mechanics. Cambridge University Press, Cambridge

21. Azadi MRE, Monfared SR (2012) Fall cone test parameters and their effects on the liquid and plastic limits of homogeneous and non-homogeneous soil samples. Electron J Geotech Eng K 17:1615–1646
22. Lee LT (2001) In situ expedient test methods to determine geotechnical properties of dredged materials. DOER Technical Notes Collection (ERDC TN-DOER-N12), U.S. Army Engineer Research and Development Center, Vicksburg
23. BS 1377-2 (1990) Methods of testing for soils for civil engineering purposes, British Standards Institution