



Research Article

Undrained shear strength of polypropylene fiber reinforced alluvial clay

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ABSTRACT

Construction of civil engineering structures on weak soil without taking necessary precautions may be risky. Alluvial soil that has not completed its geological formation has a high void ratio and contains organic material therefore, the strength properties of these soils should be examined carefully. In this study, the undrained shear strength (cu) behavior of natural and polypropylene (PP) fiber-reinforced alluvial clays was investigated with a laboratory Vane shear test. To examine the moisture content effects on cu behavior of alluvial clay, samples were prepared in 0.50 liquid limit (LL), 0.75 LL, and LL water contents. The PP fibers used were 6 and 18 mm long, they mixed with soil 0.1, 0.5, and 1% by dry weight of the sample. The Vane shear tests were performed at two different depths to investigate the overburden pressure effect. The increase in water content caused a significant decrease in cu. The laboratory results indicated that the cu of PP reinforced (1% and 18 mm PP) alluvial clay deposits prepared in 0.5LL, 0.75LL, and LL water contents were 56.6, 20.7, and 8.4 kPa, respectively. The increase in PP fiber content increased the cu of alluvial clay deposits. The length of fiber was directly proportional to cu values. The effect of fiber was more pronounced in long fiber added samples. The cu of natural and 1% fiber reinforced (6 mm and 18 mm) samples prepared in the same water content were 27.4, 29.1, and 55.7 kPa. The cu increased with increasing penetration depth.

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INTRODUCTION

Shear strength is one of the essential geotechnical parameters used in the design procedure of geotechnical constructions like retaining walls, foundations, and embankments, and is determined using a variety of laboratory and in-situ tests. Due to the action of rapid loading (or unloading) on clayey soils, the water content and the volume of the soil remain constant, and excess pore water pressure is generated. In such a case, the shear strength is called the

undrained shear strength (cu). Undrained shear strengths are influenced by several factors including sample disturbance, anisotropy, over consolidation ratio, deformation state, strain rate, and sample size. The determination of this parameter is significant, and it can be measured by using a variety of laboratory and in-situ tests. In laboratory conditions, Unconsolidated-Undrained (UU) triaxial, Unconfined Compression (UCS), and Vane Shear Tests (VST) can be conducted to define this parameter. Besides, it can be determined from field VST and calculated by empirical

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correlations using SPT – CPT data. Among these, the VST is the most effective and suitable method for specifying the undrained shear strength of very soft-hard clays in terms of being a cheaper and quicker method compared to the complexed mechanism of the triaxial shear test or time-consuming in-situ tests. It is also recommended by ASTM D4648 [1] as an effective tool to examine the strength of anisotropy in both directions of soil samples. The VST which can be performed either in the laboratory or in the field is commonly used for measuring the undrained strength of undisturbed, fully saturated clay and cohesive soils at low shear strength due to its simplicity, speed, and relative cost [2–4]. Although it has many advantageous features, there are a limited number of studies in the literature regarding VST. Wilson et al. [5] researched the effect of several factors such as vane rotation rate, insertion disturbance, soil anisotropy, and structure on the vane-measured strength of soft clays and they reported the main information about the factors affecting the interpretation of VST values. They concluded that the resistance developing during the VST in soft clays is affected by these mechanisms and more mechanical properties of soil can be retrieved through the test.

Many reinforcement methods have been applied in the previous studies to alter the undesirable engineering properties of problematic soils such as organic soils, soft clays, loose sands, alluvial deposits. Improvement of the engineering properties of the soil by adding randomly distributed fibers has started at least 5000 years from now [6]. In most geotechnical engineering projects, using fiber-reinforced soils attracts more attention and approval. The mixing fibers into the soil increase the shear, compressive, and tensile strength reduces the swelling and brittleness. Currently, many researchers have examined the behavior of reinforced clays by using discrete fibers [7–13].

The advantages of this material are low cost, easy to execute, and has a high melting point. Also, polypropylene does not react or absorb the soil moisture because it is a chemically inert and hydrophobic material [7].

The determination of the undrained shear strength of low permeability soils is an interesting subject and has been studied by many researchers in various methods. Furthermore, there are many studies concerning the improvement of strength properties of soils using different types of additives. Ozkul and Baykal [8] studied the impact of the fiber on the undrained shear strength of the kaolinite clay. Consolidated – undrained (CD) triaxial tests were performed with clay and clay – fiber samples. The tire fiber was mixed with 10% by dry weight of clay. The samples were prepared in two different compaction energies (standard and modified). Three different confining pressures (100, 200, and 300 kPa) were applied. It was observed that undrained shear strength values increased with the tire fiber addition for both compaction energies. The undrained shear

strength was between 100 and 485 kPa for standard compaction, between 440 and 1080 kPa for modified compaction. Mollamahmutoglu and Yilmaz [14] investigated the shear strength behavior of polypropylene fiber reinforced high plasticity clay. The consolidated – undrained (CU) triaxial tests were performed on fiber-reinforced clay with contents of 0.1, 0.2, 0.3, and 0.4% by dry weight of soil. The specimens were prepared in accordance with the maximum dry unit weight and optimum moisture content. The test results revealed that cohesion decreased, internal friction angle increased with the fiber content increasing. Cohesion values were ranged between 28–212 kPa, the internal friction angle took values from 4.9° to 21.4° . Pradhan et al. [11] inspected the change in shear strength of the soil reinforced with polypropylene fibers. The strength characteristics of fiber-reinforced soil, as well as unreinforced soil, were investigated by using several tests such as California Bearing Ratio (CBR), unconfined compression, and direct shear tests. The test results proved that the peak and residual shear strength of soil samples are increased concerning the inclusion of randomly distributed polypropylene fibers. Maliakal and Thiyyakkandi [9] used randomly distributed coir fibers to better understand the effect on the shear strength of clay by conducting a series of consolidated – undrained triaxial tests. It was reported that the inclusion of fibers increased the shear strength of clay remarkably, therefore it is convenient to mix soil with fibers in-situ conditions. Yilmaz [15] analyzed the fly ash and polypropylene fiber effect on the strength behavior of Ankara clay. The clay soil was mixed with fly ash (10 and 30%) and polypropylene fiber (1%). Unconsolidated – undrained triaxial tests were conducted with 28 days of cured samples. When the polypropylene fiber was added, undrained shear strength values increased from 115.3 to 124.3 kPa for 0% fly ash, from 180.2 to 260.2 kPa for 10% fly ash, from 246.2 to 266.2 kPa for 30% fly ash. Diab et al. [13] analyzed the undrained shear strength behavior of clay blended with natural hemp fibers. The fibers were mixed with soil 0.5, 0.75, 1.0, 1.25 and 1.5% by dry weight of soil. The unconsolidated – undrained triaxial tests were conducted to specify undrained shear strengths. The specimens were prepared in different water contents (14, 18, and 20%) with Standard Proctor compaction energy. The undrained shear strength values were determined between 160 and 880 kPa. Also, the test results revealed that when the fiber content increased up to 1.25% more strength is gained, yet less is obtained with the water content increases.

In the literature, researchers have studied the relation between water content and undrained shear strength of different types of soils. Mohamad et al. [16] examined moisture content effect on the undrained shear strength of older alluvium soil that is widely spread in Malaysia. It was concluded that the increase in water content has a great impact on the reduction of shear strength. The cohesion values of dry and saturated samples were reported to decrease from

21.04 kPa to 9.54 kPa. Kuriakose et al. [17] studied to obtain a relation between the undrained shear strength of clays and the water content. Laboratory Vane shear tests were conducted with clay samples obtained from four different sites (Parur, Kumbalam, Maradu, Elamkulam). They generated two correlations in-between Water Content Ratio (WCR) – undrained shear strength and liquidity index (IL) – undrained shear strength. According to test results, the undrained shear strength decreased as the water content increases.

A very limited number of studies have investigated the change in the undrained shear strength with respect to depth. Bartetzko and Kopf [18] studied how porosity and undrained shear strength of marine sediments are affected by depth. The values of undrained shear strength were evaluated by an automated Vane shear system, hand-held Torvane, and pocket penetrometer in Ocean Drilling Program (ODP) site. At the end of the test, the undrained shear strength values were found between 0 – 439 kPa. When the depth increased, the undrained shear strength values increased, and porosity decreased. Li et al. [19] observed the change of undrained shear strength with depth. The data were collected from four different sites (Port Huron, Baton Rouge, Kringalik Plateau, Ontario). The results showed that undrained shear strength improved with the increase in depth. Researchers proposed four different correlations for the undrained shear strength with respect to both depth and effective unit weight.

When the studies about the fiber-reinforced soil's behavior are investigated, it is commonly concluded that fiber should be long enough to activate fiber-soil interaction since the fabric of the composite does not allow such an interaction in short lengths. In another case, if the fiber diameter is smaller than the grain size by at least one order of magnitude, fibers may slip during the deformation, thus they cannot take any load [20, 21]. A number of studies have revealed that the increase in shear strength of soils can be enhanced further by longer fiber additions. In general, the length of fibers in the aforementioned studies was ranged between 6–25 mm [22–24]. The chosen fiber lengths were selected according to the dimension of the soil sample used in the study. Since Standard Proctor Mold in the study is large enough to allow a homogeneous mixing area of fiber-soil mixture, it is decided to use fiber length up to 18 mm.

Cigli-Balatcik (Izmir, Turkey) is a newly developing region that generally contains alluvial clay soils under the quick-undrained loading condition due to the rapidly increasing demand on the constructions. Thus, the objective of this study is to investigate undrained shear strength characteristics of natural and polypropylene (PP) fiber-reinforced alluvial clays taken from this region. The laboratory VSTs were conducted using two different lengths (6 mm and 18 mm)



Figure 1. The top view from the region of Cigli – Balatcik.

of polypropylene fibers with different ratios (0.0, 0.1, 0.5, and 1.0% by dry weight). To investigate the water content effects on undrained shear strength, samples were prepared and tested in three different water contents (LL, 0.75LL, and 0.5LL). Overburden pressure was also taken into account and tests were performed at two different depths (2H and 3H). The undrained shear strength behavior of natural and reinforced alluvial clays was defined with 126 VSTs. Test results were statistically analyzed by the methods of two-way ANOVA and the Student–Newman–Keuls as a post hoc test to search for the relationship between variables and undrained shear strength.

MATERIALS AND METHODS

Alluvial Clay Deposit

Alluvial clay deposits were obtained from Cigli – Balatcik region located at the north of Izmir, surrounded by Mene-men from the north, the Gulf of Izmir from the south (Turkey). The alluvial clay samples were taken from a construction site at Izmir Kâtip Celebi University (Fig. 1). Alluvial deposits have a broad spectrum in terms of both the condition and the type of the soil. According to the mechanical properties, alluvial deposits are classified as the so-called transition soils or intermediate soils. Alluvial deposits containing a significant amount of organic matter carried by a stream have high porosity. They have a low bearing capacity so that they are considered problematic soil in geotechnical engineering.

Polypropylene Fiber

Synthetic fibers are commonly used to improve the strength of soil or concrete by a micromechanical interaction mechanism between particles [7, 20]. The monofilament fibers

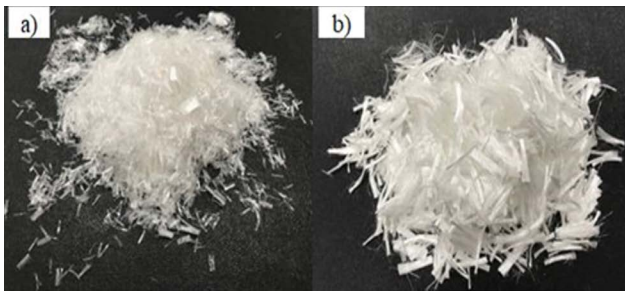


Figure 2. (a) 6 and (b) 18 mm polypropylene fibers.

used for sample preparation are commercially available synthetic polypropylene fibers. The fiber lengths were 6 mm and 18 mm, the diameter was 0.023 mm, and the specific gravity was 0.91. PP fibers used in the laboratory tests have been shown in Figure 2.

Physicochemical and mechanical properties obtained from the manufacturer company for polypropylene fibers are summarized in Table 1.

Polypropylene fibers were added to alluvial deposits at 0.1, 0.5, and 1% by dry weight. The content of fibers in soil samples is calculated by using Equation 1.

$$\rho_f = \frac{W_f}{W_s} \quad (1)$$

where ρ_f represents the fiber-reinforced ratio, W_f and W_s indicate the weight of fiber and air-dried soil, respectively. In this study, ρ_f values were chosen as 0, 0.1, 0.5 and 1%, variables, and the sample properties were summarized in Table 2.

Since the fibers are hydrophobic chemically, they need only be mixed long enough to ensure the dispersion in material [24].

Geotechnical Index Properties

The geotechnical index properties of alluvial deposits were designated by laboratory tests following ASTM Standards. To define the liquid limit of alluvial clay, the Casagrande device was used, and the Multipoint method (Method A) was followed according to ASTM D4318 [25]. The water content at which a 3.2 mm diameter soil sample crumble while rolling between the two fingers is called the plastic limit of the soil and in this study, it was determined with the traditional hand rolling method which is detailly defined in ASTM D4318 [25]. Besides, the Standard Proctor test was conducted to find the water content and dry unit weight at the optimum compaction effort. The compaction curve of the alluvial clay deposit was determined according to the ASTM D698, Method A [26]. The identification of specific gravity of alluvial soil samples was determined based on ASTM D854 [27] instructions utilizing a water pycnometer. Therefore, the density or phase relationships of soil samples could be determined. The classification of alluvial deposits was specified by interpreting grain size distribution analysis according to ASTM D2487 [28], Unified Soil Classification System (USCS).

Table 1. The physicochemical and mechanical properties of PP fibers

Type	Properties
Fiber type	Monofilament
Material	100% virgin PP
Appearance	Individual fiber
Cross-section	Round
Specific gravity	0.91
Softening point (°C)	150
Melting point (°C)	160
Length (mm)	6 & 18
Young modulus (MPa)	3000 – 3500
Tensile strength (MPa)	600 – 700
Alkali effect	Stable
Color	Transparent

Table 2. The variable parameters in the study

PP length (mm)	pf (100%)	Moisture content	Penetration depth
6 and 18	0.0	0.50LL	2H/3H
		0.75LL	2H/3H
		LL	2H/3H
	0.1	0.50LL	2H/3H
		0.75LL	2H/3H
		LL	2H/3H
	0.5	0.50LL	2H/3H
		0.75LL	2H/3H
		LL	2H/3H
	1.0	0.50LL	2H/3H
		0.75LL	2H/3H
		LL	2H/3H

Vane Test

The laboratory VSTs were performed to determine the undrained shear strength of natural and PP reinforced alluvial deposits based on ASTM D4648 [1].

Sample Preparation

Natural and fiber-reinforced alluvial clay samples were prepared in 0.5LL, 0.75LL, and LL moisture contents. To obtain uniform and consistent samples same procedures were applied such as mixing, placement, rodding, compaction and smoothing. Mixtures were prepared in a benchtop laboratory mixer with 4.7 lt capacity. Polypropylene was added and mixed thoroughly using a mechanical mixer at a speed of 142 rpm for 15 min to prevent clumping (local aggregation) and balling and to obtain homogeneous fiber-reinforced soil. Standard Proctor molds having 10.3 cm diameter and 11.6 cm height with a compaction effort of 596 kJ/m³ were used to achieve predetermined unit weight values. The samples were prepared with a similar compaction procedure such that the unit weights remained within a certain range (16–18 kN/m³). Since fibers are not able to absorb water, the added

Table 3. Guide for spring detection [30]

Spring No.	General soil description	Maximum shear stress (kN/m ²)
1	Very soft (Weakest)	20
2	Soft	40
3	Soft to firm	60
4	Firm (Stiffest)	90

Table 4. Geotechnical index properties of alluvial deposits

Geotechnical indices	Results
Liquid limit (LL), %	58.6
Plastic limit (PL), %	27.5
Plasticity index (PI), %	31.1
Specific gravity, (G _s)	2.58
Fine content (-No.200), %	91
Max. dry unit weight (γ _{dry,max}), kN/m ³	15.4
Optimum moisture content (w _{opt}), %	26.8
Unified Soil Classification System (USCS)	CL

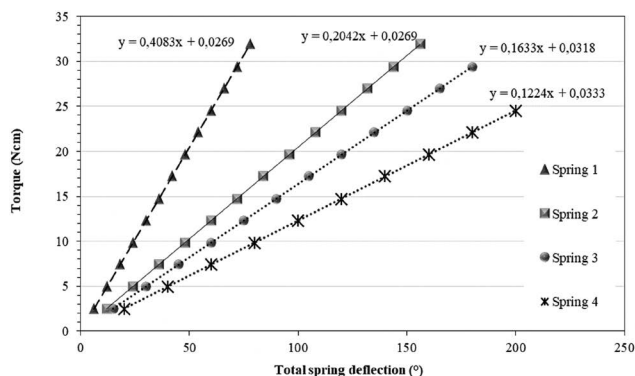


Figure 3. Calibration curves of springs.

fiber amount did not affect the available unit weight. The degree of saturation value of the samples in LL, 0.75LL, and 0.5LL water contents were determined as 98.14, 96.82, and 95.31% respectively. To prevent moisture loss, Vane tests were conducted immediately after samples were prepared.

The Arrangement of the Vane Apparatus

Vane device consists of many parts such as spring, Vane blade, vertical shaft, hand knob, pointer, circular graduated scale, and secondary scale. The number of torsion springs shall be chosen according to the probable soil strength as it is indicated in Table 3.

After the trial tests, spring No.4 was concluded to be suitable for alluvial soils. The spring was calibrated to ensure proper operation of the Vane device by following the instructions suggested by ASTM D4648 [1]. At the end of the calibration process, the calibration curve for each spring was plotted and from that curve, the spring constant values were determined (Fig. 3).

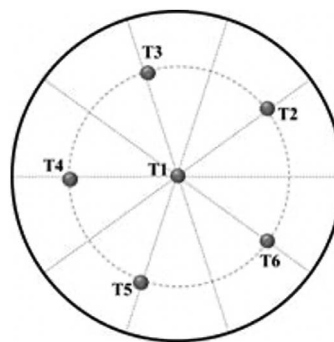


Figure 4. Test points configuration of samples.

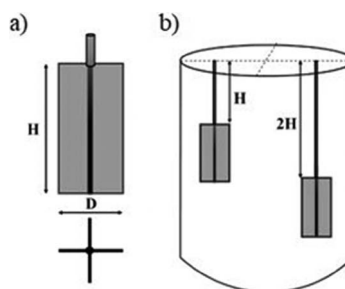


Figure 5. (a) Miniature Vane blade geometry (b) penetration depths of Vane blades (2H and 3H).

Testing of Samples

Undrained shear strengths of reconstituted (remolded) specimens were determined by using a miniature vane test device according to Method A (Conventional Calibrated Torque Springs). Six points were selected on the surface of the sample (T1, T2, T3, T4, T5, and T6). The configuration of the test points is shown in Figure 4.

According to the ASTM D4648 [1], the Vane must be penetrated the sample at least twice the height of the blade. In other words, the depth of penetration should be twice the height of the Vane blade at a minimum. Experiments were performed at two different depths (2H; [T1, T2, T4] and 3H; [T3, T5, T6]) to investigate the effects of penetration (overburden pressure) on undrained shear strength. Miniature Vane blade geometry has shown in Figure 5a. The penetration depths were selected as 2 and 3 times of Vane blade height measured from the top of the mold surface by taking care of its possible minimum value as recommended in the ASTM D4648 [1] and schematically demonstrated in Figure 5b.

The experiment starts by inserting the Vane blade to the desired point in the sample (2H or 3H). The initial reading is recorded and then the handle is rotated counterclockwise to apply torque to spring at a constant rate of 60 to 90°/min. (Fig. 6). The upper part of the spring starts to rotate at a constant speed, while the lower part remains constant. Torque and angular displacements are saved every 5 seconds and recorded with the video camera to prevent misreading. When the applied torque passes the shear resistance of the soil, the bottom of the spring starts to rotate [1]. The record-



Figure 6. Test points and test steps.

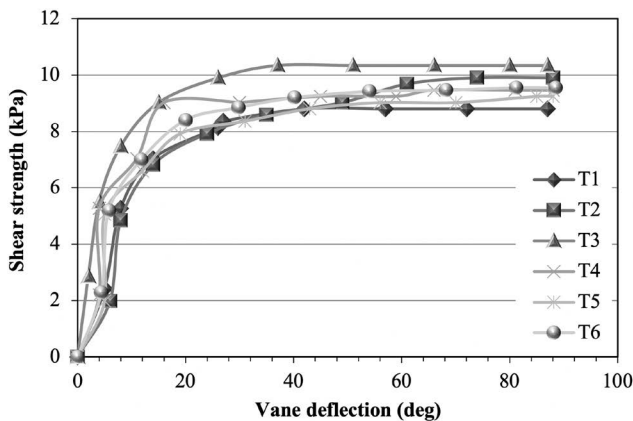


Figure 7. The undrained shear strength – Vane deflection relation of natural samples.

ing continues until the spring deflection remains constant. This procedure is followed for six test points with different depths. The test points and test steps are shown in Figure 6.

The data obtained from the torque displacement scale and spring deflection angle were converted into torque values by multiplying the angle with the spring constant (Equation 2).

$$T = k \times \Delta \tag{2}$$

where: T = torque applied (Nm), k = spring constant (Nm/°), Δ = spring deflection (°). The undrained shear strength (c_u) of the soil was calculated by Equation 3.

$$c_u = T/K \tag{3}$$

where: c_u = Undrained Shear Strength (Pa), K = Vane blade constant (m^3), $K = \pi r D^2 \times (\frac{H}{2} + \frac{H}{6})$

Statistical Analysis

The VST results are analyzed statistically by using two-way ANOVA (SPSS 12.0, SPSS GmbH, Germany) and the Student–Newman–Keuls methods. Significant differences between groups were stated at p-values at least <0.05. (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

RESULTS AND DISCUSSIONS

In this part, the geotechnical index properties of alluvial clay obtained from laboratory tests were given. The laboratory Vane shear test results were summarized for natural

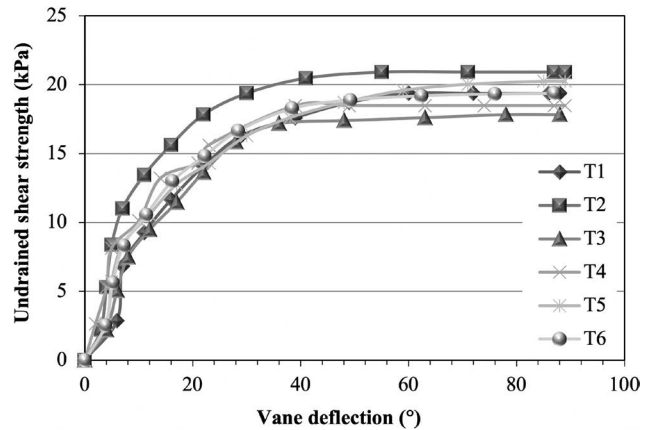


Figure 8. The undrained shear strength – Vane deflection relation of PP reinforced samples.

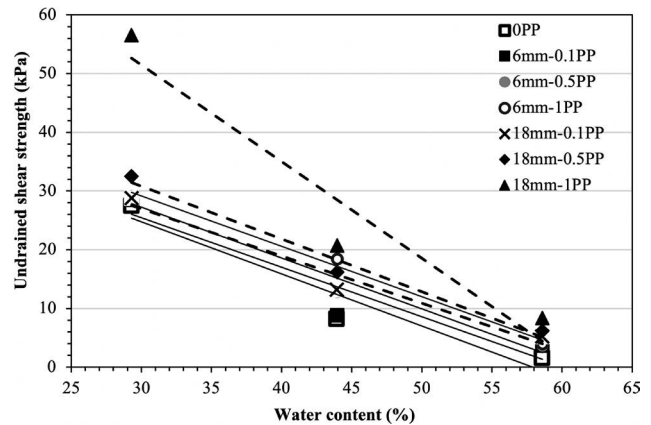


Figure 9. The undrained shear strength – water content relation of natural and reinforced alluvial soil.

and PP added samples. Also, the test results were supported by statistical analysis.

Geotechnical Index Properties Results

The geotechnical index properties of alluvial clay deposits were determined with laboratory tests according to ASTM Standards. The test results are displayed in Table 4. The particle size distribution analysis and consistency limits test results revealed that the soil can be categorized as low plasticity clay (CL) according to USCS.

Vane Shear Test Results

In this study fiber length, water content, fiber content, and penetration depth were examined as factors affecting the undrained shear strength behavior of alluvial clay deposits. A total of 126 experiments were performed with 18 natural and 108 reinforced samples. Undrained shear strength - Vane deflection relation has shown in Figures 7 and 8. Curves were plotted for six different test points and two different depths (2H; [T1, T2, T4] and 3H; [T3, T5, T6]). Since the VSTs were performed with reconstituted (remolded) alluvial clay samples, peak shear stress was not observed.

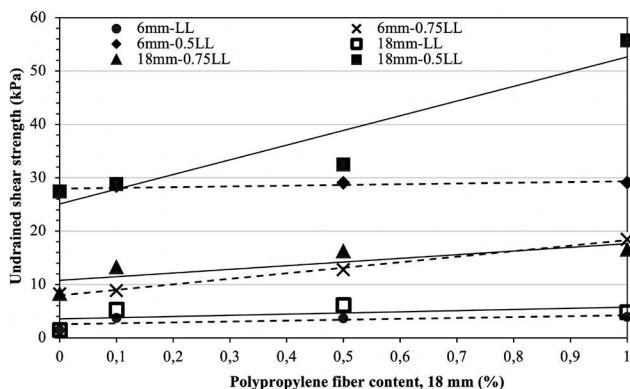


Figure 10. The undrained shear strength – PP fiber content relation of natural and reinforced alluvial soil.

Thus, the maximum shear stress was equal to ultimate shear stress and tests were terminated at 90° deflection.

The PP fiber effect on the undrained shear strength behavior of alluvial clay deposits can be compared with Figures 7 and 8. The average undrained shear strength of the natural alluvial sample prepared in 0.75 LL water content was 9.14 kPa (Fig. 7). On the other hand, the average undrained shear strength of reinforced alluvial samples (0.5% PP) prepared in the same water content was 18.80 kPa (Fig. 8). The undrained shear strength behavior of fine-grained soil is directly related to water content [17, 29–32]. The undrained shear strength-water content relation of natural and PP reinforced alluvial soils is presented in Figure 9. The test results clearly showed that when the water content increased, a significant decrease in undrained shear strength was obtained. The undrained shear strengths of PP reinforced (1% and 18 mm PP) alluvial clay deposits prepared in 0.5LL, 0.75LL, and LL water contents were 56.6, 20.7, and 8.4 kPa, respectively. This can be explained that in fine-grained soils, intermolecular bond in-between water causes cohesion of particles [33, 34]. Therefore, cohesion varies with soil water content, particle size, and compaction of soils. When the water content is raised, the adhesion decreases due to the further separation of the clay particles, thereby reducing the shear strength. Similarly, as the soil particles start to come closer, owing to continuous reduction in water content, the bonding between solid particles builds up and contributes to the shear resistance of soil in friction [31, 35].

To improve the undrained shear strength properties of alluvial clays polypropylene reinforced fibers were used with three different contents and results are demonstrated in Figure 10. The test results have stated that when the polypropylene fiber content is raised, the undrained shear strength of alluvial clay deposits has increased, too. As the soil is sheared, fibers extended in the soil body, which increases the tensile strength of the PP fiber reinforced soil and increases the shear strength because of the extensible nature of the fibers [36–38]. Discrete fibers in a randomly distributed position lock the soil grains together and form a single coherent matrix that helps

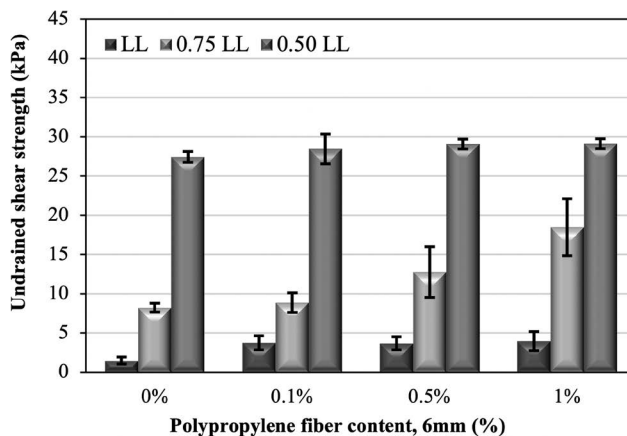


Figure 11. Undrained shear strength of alluvial deposits reinforced with 6 mm PP fiber.

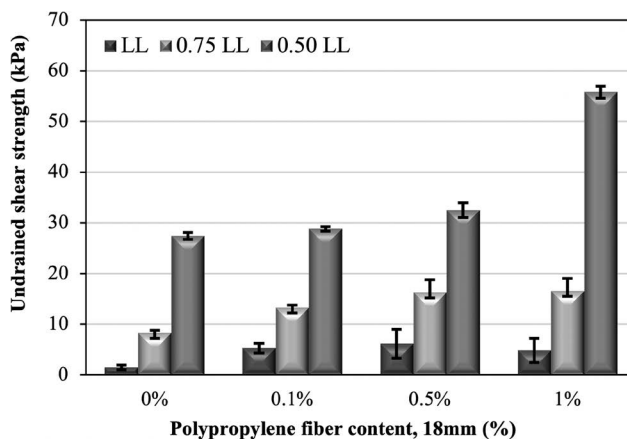


Figure 12. Undrained shear strength of alluvial deposits reinforced with 18 mm PP fiber.

limit the displacement of the particles. The grooves and pits formed on the fiber surface are thought to form a lock and improve the interaction between the soil matrix and the PP fiber surface. The effect of interlocking is more pronounced when fiber content has risen so that an increase in the shear strength of samples with a high fiber content is obtained [12]. Especially in samples with low water content (0.5LL), the fiber of 18 mm length played a more effective role than 6 mm length on undrained shear strength. The undrained shear strengths of natural and 1% fiber reinforced (6 mm and 18 mm) samples prepared in the same water content (0.5LL) were 27.4, 29.1, and 55.7 kPa, respectively.

The undrained shear strengths of natural and fiber-reinforced samples prepared at different moisture contents and various fiber contents have been shown in Figures 11 and 12. The test results indicated that the water content crucially influenced the undrained shear strength. The increase in moisture content adversely affects the undrained shear strength. The test results were indicated that the PP fiber effectively influenced the undrained shear strength parameter.

The positive impact of PP fiber additive on undrained shear strength was more evident in long fiber samples. While the undrained shear strength of natural alluvial clay was 27 kPa, samples with 6 mm and 18 mm long PP fibers in 1% were 29 kPa and 56 kPa, respectively. After compaction, the PP fiber is covered with interconnected soil particles. Some of the particles are bonded to the PP fiber surface after the fiber has been pulling out. This shows that in the shearing procedure of soil, the interface of the soil structure is disturbed and disconnected. Therefore, the interface friction is highly dependent on the resistance shown by soil particles to rotation and regulation when shear occurs [39, 40].

The VSTs were performed at two different depths to examine the influence of overburden pressure on the undrained shear strength. The test results revealed that the undrained shear stress improved with increasing penetration depth. The penetration depth was more effective in samples with high water content. In other words when the overburden pressure increased the undrained shear strength is increased too (Fig. 13).

The samples with high water content have higher undrained shear strength increases due to penetration depth. The undrained shear strength of natural samples prepared in LL water content, tested at 2H and 3H depths were 1.47 kPa and 2.42 kPa, respectively.

According to 126 VST results useful correlations were derived between effective overburden stress ($\gamma'z$) – undrained shear strength (c_u) and moisture content (w) – undrained shear strength (c_u). These correlations were given in Equation 4 and Equation 5.

$$c_u = 0.14 \times \gamma \times z + 13.3 \quad (4)$$

$$w = 104.88 \times c_u^{-0.37} \quad (5)$$

Statistical Analysis Results

In this study, each sample was tested at least three times to check repeatability and obtained test results were statistically analyzed. The undrained shear strength of natural alluvial clays decreased with increasing water content. These results were supported by statistical analysis ($c_{u(LL)}$ [1.47±0.46; $p < 0.001$], $c_{u(0.75LL)}$ [8.23±0.55; $p < 0.001$], $c_{u(0.5LL)}$ [27.43±0.67; $p < 0.001$]) kPa. Test results have clearly shown that polypropylene fiber reinforcement positively affected the undrained shear strength of the sample prepared in the same water content. Additionally, the PP fiber was more effective in samples with high water content ($c_{u(6mm_0.1\%)}$ [3.74±0.88; $p < 0.001$], $c_{u(18mm_0.1\%)}$ [5.28±0.0.96; $p < 0.001$]).

Literature Comparison

When the results of the current study are compared with the studies conducted in the literature [40–42], it was observed that the undrained shear strength tends to increase with the addition of polypropylene fiber (Fig. 14). It was

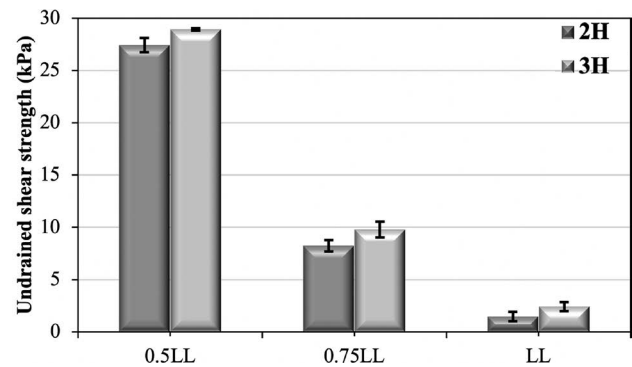


Figure 13. Undrained shear strength of natural alluvial deposits at depth 2H and 3H.

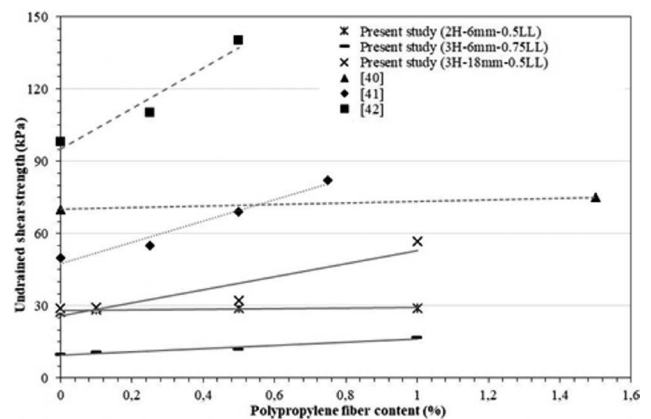


Figure 14. Comparison of literature and current study results.

also found that the increase was sharply up to certain fiber content, then a less increase.

In addition, it was observed that the increase in undrained shear strength was higher in studies using soils with high plasticity [41–42]. On the contrary, in studies using soils with low plasticity (i.e., present study), the increase in undrained shear strength was found to be slightly less [40].

CONCLUSIONS

In this study, the undrained shear strength behavior of natural and PP fiber-reinforced alluvial clay deposits obtained from Balatcik – Cigli (Izmir, Turkey) was investigated. VSTs were performed considering the effects of water content, fiber length, fiber content, and penetration depth on the undrained shear strength. Firstly, the effect of water content on the undrained shear strength was examined for natural alluvial deposits. Afterward, the soil was improved by the addition of two different lengths of PP fiber with a variety of proportions in specified water contents. A total of 126 experiments were performed with 18 natural and 108 reinforced samples. Test results were supported by statistical analysis. The laboratory test results indicated that,

- The increase in water content caused a significant decrease in undrained shear strength. The undrained shear strengths of PP reinforced (1%- and 18-mm PP) alluvial clay deposits prepared in 0.5LL, 0.75LL, and LL water contents were 56.6, 20.7, and 8.4 kPa, respectively.
- The increase in polypropylene fiber content increased the undrained shear strength of alluvial clay deposits. The interlocking effect increases with increased fiber content, which leads to an increase in the shear strength of samples with high fiber content.
- Especially in samples with low water content (0.5LL), the fiber of 18 mm length played a more effective role than 6 mm length on undrained shear strength. The undrained shear strengths of natural and 1% fiber reinforced (6 mm and 18 mm) samples prepared in the same water content (0.5LL) were 27.4, 29.1, and 55.7 kPa, respectively.
- The undrained shear strength increased with increasing penetration depth. The penetration depth was more effective in samples with high water content. The undrained shear strength of natural samples prepared in LL water content, tested at 2H and 3H depths were 1.47 kPa and 2.42 kPa, respectively.
- The length of fiber was directly proportional to undrained shear strength values. The effect of fiber was more pronounced in long fiber added samples.
- The equations derived from test results can be used to determine the undrained shear strength in the preliminary design stage of the projects.
- Statistical analysis results confirmed the consistency of the test results.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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