



Experimental Investigation of the Mechanical Properties of Polypropylene Fiber-Reinforced Clay Soil and Development of Predictive Models: Effects of Fiber Length and Fiber Content

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Abstract

This study investigated the mechanical properties of a low-plasticity clay soil reinforced with polypropylene (PP) fiber in various contents (0.05%, 0.10%, 0.15%, and 0.20%) and lengths (6, 12, and 19 mm). The reinforced specimens were subjected to unconsolidated-undrained (UU) triaxial compression tests under three different confining pressures (50, 100, and 200 kPa). The optimum fiber contents in specimens reinforced with 6-, 12-, and 19-mm PP fiber were determined as 0.15%, 0.15%, and 0.20%, respectively. As a result, the highest values regarding deviator stress at failure (σ_{dev}), energy absorption capacity (EAC), and shear strength parameters occurred in specimens containing 0.20% PP (19 mm). As a result of the reinforcement process, the most remarkable improvements in the σ_{dev} , cohesion, internal friction angle, and EAC values of the natural soil are 59.95%, 21.80%, 63%, and 34.70%, respectively. Linear and nonlinear relationships between σ_{dev} and fiber length, fiber content, and confining pressure were investigated by multiple linear regression and artificial neural network methods. Equations were generated to predict σ_{dev} of a low-plasticity clay soil reinforced with PP fiber and were made available to geotechnical researchers.

Keywords Polypropylene fiber · Soil reinforcement · Artificial neural network · Multiple linear regression

1 Introduction

In geotechnical engineering applications, geotechnical engineers frequently use traditional reinforcement techniques to increase the bearing capacity and reduce settlements in soils with low bearing capacity or high compressibility to prevent damage to lightweight structures, channel beds, retaining structures built on clays with high swelling pressure, to eliminate the risk of liquefaction in sandy soils, and to increase the durability of soils under freeze–thaw cycles. Researchers need alternative reinforcement materials due to the high cost of traditional reinforcement materials, consumption of renewable resources, and damage to the environment. Recently, there has been an increasing interest in fiber materials that have low cost and high strength, do

not require high-energy consumption, and are environmentally friendly. Additionally, geotechnical researchers have increased their research on using waste materials to stabilize soils to contribute to waste management. Using synthetic fiber elements such as nylon and PP as plastic products in soil reinforcement applications contributes to reducing waste. For all these reasons mentioned above and due to its high strength and Young's modulus, non-biodegradability, low cost, and easy accessibility, PP fiber was preferred as the reinforcement material in this study. The studies carried out for glass fiber-reinforced soils [1–7], for PP fiber-reinforced soils [8–24], for polyvinyl alcohol fiber-reinforced soils [25–27], for polyvinyl chloride fiber-reinforced soils [28], for nylon fiber-reinforced soils [29–32], and for polyester fiber-reinforced soils [33–35] are some of the studies conducted on soils reinforced with synthetic fibers. The literature studies have shown remarkable improvements in the engineering properties of soils with the addition of synthetic fibers. Apart from soil reinforcement applications, PP fiber is also utilized in composite structures, concrete, roads, tunnels, precast concrete, and special mortars [36, 37]. Since reinforcement of soils with fibers is a relatively new method, the

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literature research on the reinforcement of clay soils with PP fibers still needs to be developed. Few studies examined the behavior of a low-plasticity clay soil reinforced with PP fiber under triaxial stress conditions, considering the microstructure. Additionally, there is no study in the literature to predict the effects of fiber parameters and test conditions on the strength of reinforced soils. Therefore, this study discusses the effects of fibers on the engineering properties of clay soils with low plasticity. The effects of PP fiber addition of various lengths and contents on the stress–strain behavior, σ_{dev} , EAC, and shear strength parameters of local clay soil with low plasticity were investigated. For this purpose, reinforced and unreinforced specimens were sheared under different confining pressures (σ_3) in an unconsolidated-undrained triaxial compression test. In addition, MLR and ANN equations were created to predict the reinforced soil's σ_{dev} . They were presented to geotechnical researchers to give a preliminary idea.

2 Materials and Method

The amount of improvement that will occur in the engineering properties of the soil as a result of the addition of random, discrete, and flexible fibers into the soil varies depending on many factors such as soil properties, fiber characteristics, fiber amount, distribution and orientation of the fiber, type, shape and structure of the fiber, mixing and compression method used in the preparation of the fiber–soil composite, and field/laboratory conditions [38–41]. This study investigated the effects of PP fiber addition on the mechanical properties of a low-plasticity clay soil by UU triaxial compression test. For this purpose, the effects of confining pressure, one of the test conditions of the triaxial compression test and fiber parameters such as fiber content and fiber length on the strength of the clay soil used in this study, were investigated.

2.1 Natural Soil

The natural soil used in the experiments was taken from Burdur, Turkey, with geographical coordinates N 37°24'12.3084" and E 30°07'06.0312". The soil sample's engineering properties were determined per ASTM standards. The existing soil falls into the low-plasticity inorganic clay soil (CL) range on the plasticity card according to the unified soil classification system (USCS). The properties of the soil are given in Table 1.

2.2 Polypropylene Fiber

PP fibers are one of the most preferred synthetic fibers due to their low cost, corrosion resistance, high acid and alkali

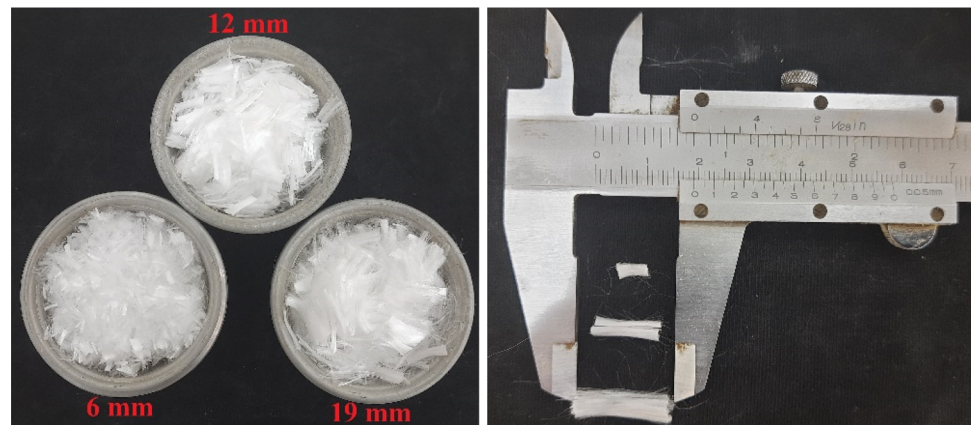
Table 1 Clay soil's properties

Property	Symbol and unit	Value	Test standard
<i>Atterberg limits</i>			
Liquid limit	LL (%)	35	ASTM D 4318
Plastic limit	PL (%)	19	
Plasticity index	PI (%)	16	
<i>Compaction characteristics</i>			
Maximum dry unit weight	γ_{kmax} (g/cm ³)	1.73	ASTM D 698
Optimum water content	w_{opt} (%)	15	
Percentage of soil finer than 75 μ m (%)	FM (%)	98.8	ASTM D 422
Specific gravity	G_s (—)	2.73	ASTM D 854
<i>Swelling parameters</i>			
Swelling index	S_I (%)	10.67	ASTM D 4546
Swelling pressure	S_{Pr} (kPa)	73.35	
<i>Shear strength parameters</i>			
Cohesion	c_u (kPa)	133	ASTM D 2850
Internal friction angle	ϕ_u (°)	14.6	

resistance, high tensile strength, hydrophobic and chemically inert material, and non-toxicity [12, 42–45]. For this reason, PP fiber was chosen as one of the synthetic fiber varieties in this study. PP fiber with 6-, 12-, and 19-mm lengths was obtained from a local supplier (Fig. 1). The properties of PP fiber are given in Table 2.

2.3 Specimen Preparation

Soil was kept in an oven at 105 ± 5 °C for 1 day. The water and dry clay soil corresponding to their respective w_{opt} and γ_{kmax} values were measured. The required fiber content (F_C) was established as a percentage of the dry soil weight. Before mixing, the amounts of soil, water, and fiber required for each specimen were divided into three, and the mixing process was carried out in three separate porcelain bowls. The literature uses methods such as drum mixer, mechanical stirring, and manual and mortar mixer to prepare fiber–soil mixtures. In this study, the manual mixing method was preferred because it can be observed whether uniform and equal fiber distribution is achieved in the soil during the mixing process and because it is practical in small works such as laboratories. First, fibers and dry clay soil were mixed in a porcelain bowl. Then, water was added to this mixture. The mixture was mixed by hand until the water and fiber were evenly distributed in the soil (only water was added to the

Fig. 1 PP fibers with different lengths**Table 2** Properties of PP fiber

Fiber	Tensile strength (MPa)	Density (g/cm ³)	Young's modulus (GPa)	Length (mm)	Diameter (μm)
PP	450–700	0.91	3–3.5	6–12–19	18–20

soil to prepare unreinforced specimens). Three parts were mixed to ensure maximum uniform fiber distribution [46]. Three separate mixtures were mixed into a single bowl to ensure maximum uniform fiber distribution in the soil. The mixture was placed inside locked bags within a closed box for 18 h to achieve uniform water distribution. This mixture was then statically compressed, and cylindrical specimens with a height of 10 cm and a diameter of 5 cm were prepared for the triaxial compression test.

2.4 Triaxial Compression Test

This study carried out unconsolidated-undrained triaxial compression tests on all specimens according to ASTM D 2850. Fiber contents were determined by conducting trial–error tests on PP-reinforced specimens in the triaxial compression device. In addition, since it is difficult to prepare a homogeneous fiber–soil mixture due to the clumping of fibers at fiber contents greater than 0.2%, 0.2% was used as the maximum fiber content in this study. Cylinder specimens prepared by adding 6-, 12-, and 19-mm PP fibers at 0.05%, 0.10%, 0.15%, and 0.20% by weight were placed on the base of the triaxial cell by enclosing it with a rubber membrane. The magnitude of the confining pressure is a parameter that directly affects the strength of the soil, and 50, 100, and 200 kPa were used in this study. After applying the confining pressure, approximately 10 min were waited to allow the specimen to stabilize under the relevant confining pressure. Under the relevant confining pressure, the specimens were loaded axially at an axial strain rate of 1 mm/min, and tests were carried out up to 15% strain. The deviator stress acting on the specimen and the corresponding axial strain were recorded during the test.

3 Test Results and Discussion

This section investigated stress–strain behavior, EAC, shear strength parameters, and scanning electron microscope images of reinforced and natural soil specimens. Pictures of the sheared specimens are given in Fig. 2, and it was generally observed that bulging failure occurred in all specimens.

3.1 Stress–Strain Behavior Analysis

The stress–strain curves of specimens containing 0.05%, 0.10%, 0.15%, and 0.20% of 6-mm, 12-mm, and 19-mm lengths of PP fibers are presented in Fig. 3.

Unreinforced soil specimens exhibited strain-softening behavior, and increased confining pressure decreased the softening degree. Hardening behavior occurs in fiber-reinforced specimens, unlike unreinforced specimens. All specimens generally show ductile behavior. Axial deformations where maximum deviator stresses occur in reinforced specimens increased compared to the natural soil. In all specimens, σ_{dev} increased as confining pressure increased (Fig. 3).

It was observed that the stress–strain curves were similar in all specimens, up to approximately 1–3% strain. After these strain levels, as the axial strain increases, the effect of the reinforcement material emerges. As the axial strain applied to the soil specimens increases during the test, it exerts a force on the embedded fibers in the soil. The elasticity modulus of the PP fibers is 3 GPa, much larger than the soil's modulus. Since the difference between the elasticity modules of the soil and the fiber material is very large, inconsistent deformations occur between the soil and the fibers during the experiment. In this case, the fibers are in tension [47–49]. Therefore, as the axial deformation increases, the



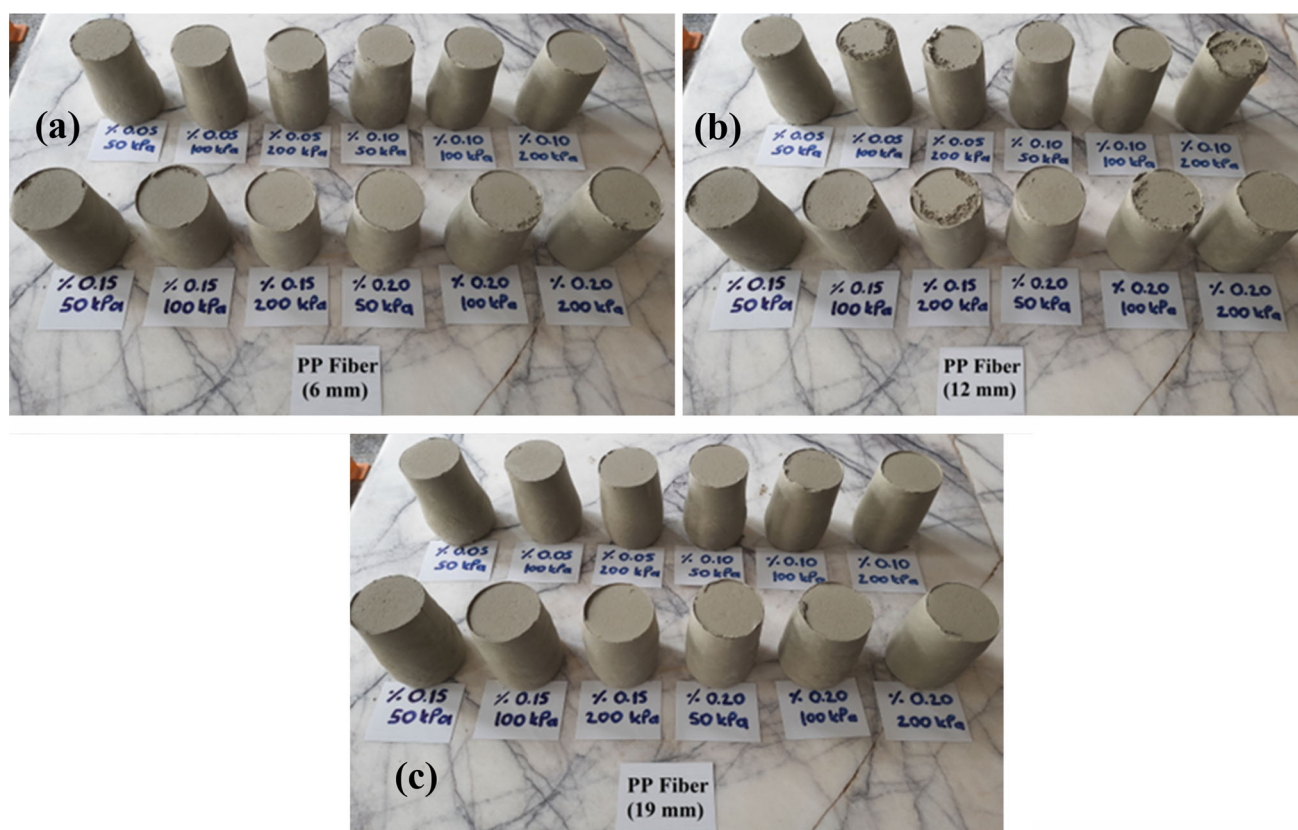


Fig. 2 Reinforced specimens, **a** with 6-mm PP fiber, **b** with 12-mm PP fiber, and **c** with 19-mm PP fiber

frictional and/or adhesion forces at the fiber–soil interface and the tensile strength of the fibers are mobilized. In this way, the deformation of the soil particles near the fibers is limited, and the reinforced soil acts as an integrated structure [50, 51]. When PP fiber-reinforced soil is subjected to an axial load, the soil matrix bears the load at strain levels less than 1–3%. As a result, it can be said that a specific axial strain is necessary to mobilize the tensile properties of reinforcement material; the reinforcement effect is notably limited at low axial strain levels but increases as the axial strain increases [52]. When observing Fig. 3, it becomes apparent that the initial elasticity modulus of the soil remains unaffected by both the fiber content and length.

3.2 Effect of Fiber Content

3.2.1 Effect of Fiber Content on Deviator Stress at Failure

Figure 4 illustrates the effect of fiber percentage on the reinforced soil's σ_{dev} .

Figure 4a, b shows that for all confining pressures, σ_{dev} increases as the amount of PP fiber increases up to 0.15% and decreases with the addition of fiber greater than 0.15%. It was obtained that for all confining pressures, as the fiber content

increased up to 0.2%, the σ_{dev} of the soil reinforced with 19-mm PP fiber increased continuously (Fig. 4c). Accordingly, the optimum fiber contents for σ_{dev} in specimens reinforced with 6-, 12-, and 19-mm PP fibers were determined as 0.15%, 0.15%, and 0.2%, respectively. Compared to the natural soil, the σ_{dev} in the soil containing the optimum amount of 6-mm PP fiber increased by 19%, 25.84%, and 33.51% for confining pressures of 50, 100, and 200 kPa, respectively. The improvements in σ_{dev} in specimens reinforced with 12-mm PP fiber at optimum content were calculated as 28.84%, 28.03%, and 40.98% for 50, 100, and 200 kPa confining pressures, respectively. In specimens reinforced with 19-mm PP fiber at the content of 0.20%, increases of 49.83%, 44.37%, and 59.95% were observed for confining pressures of 50, 100, and 200 kPa, respectively. Incorporating the optimum fiber content into the soil limits the reinforced soil's bulging, enabling the fiber–soil composites to resist relatively large axial stresses, even at large axial strains [53].

3.2.2 Effect of Fiber Content on Shear Strength Parameters

The undrained shear strength parameters of reinforced specimens prepared using fibers of different lengths and contents are shown in Fig. 5.

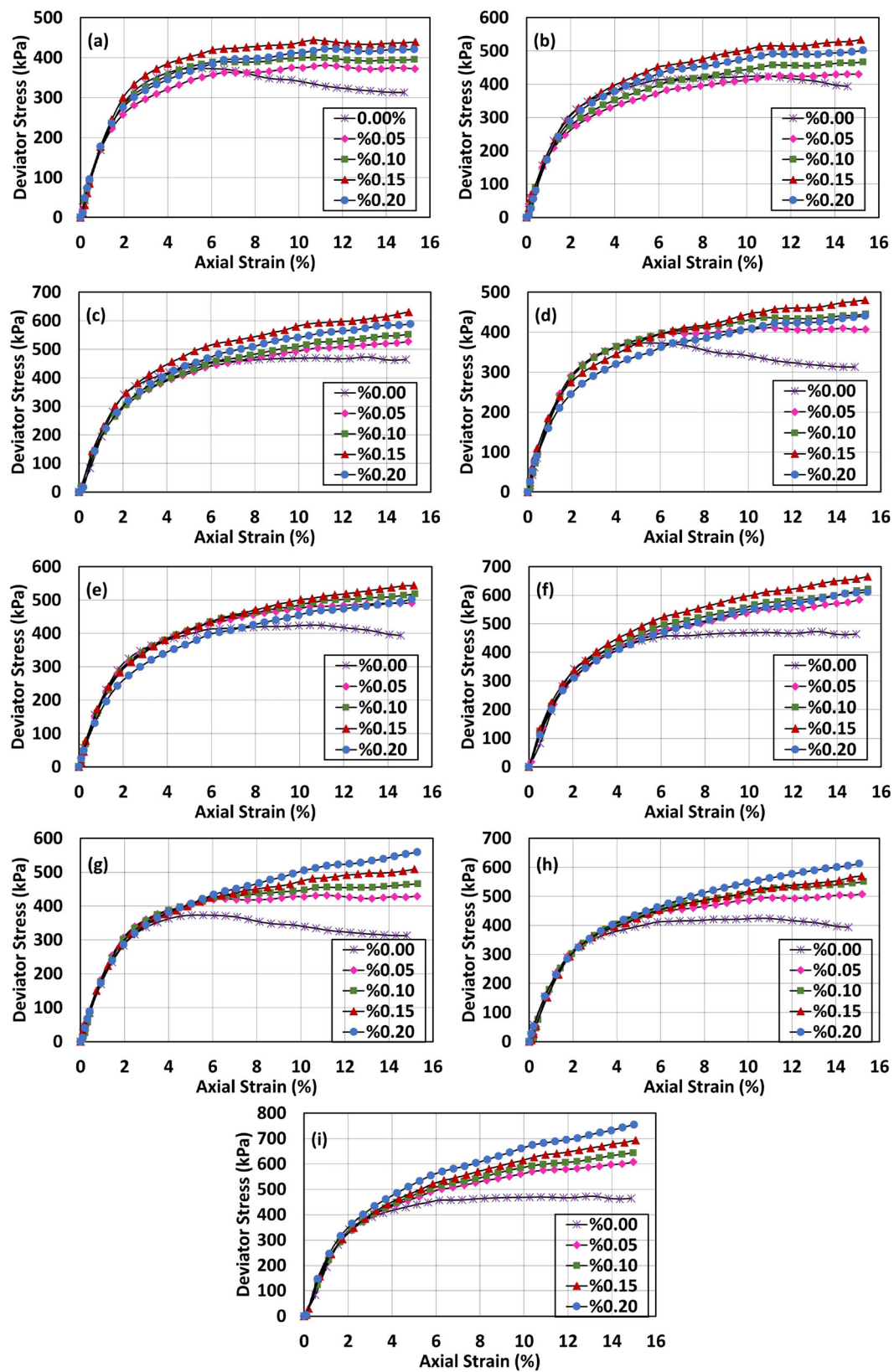


Fig. 3 Stress–strain curves for various PP fiber contents, **a** 6 mm–50 kPa, **b** 6 mm–100 kPa, and **c** 6 mm–200 kPa, **d** 12 mm–50 kPa, **e** 12 mm–100 kPa, and **f** 12 mm–200 kPa, **g** 19 mm–50 kPa, **h** 19 mm–100 kPa, and **i** 19 mm–200 kPa



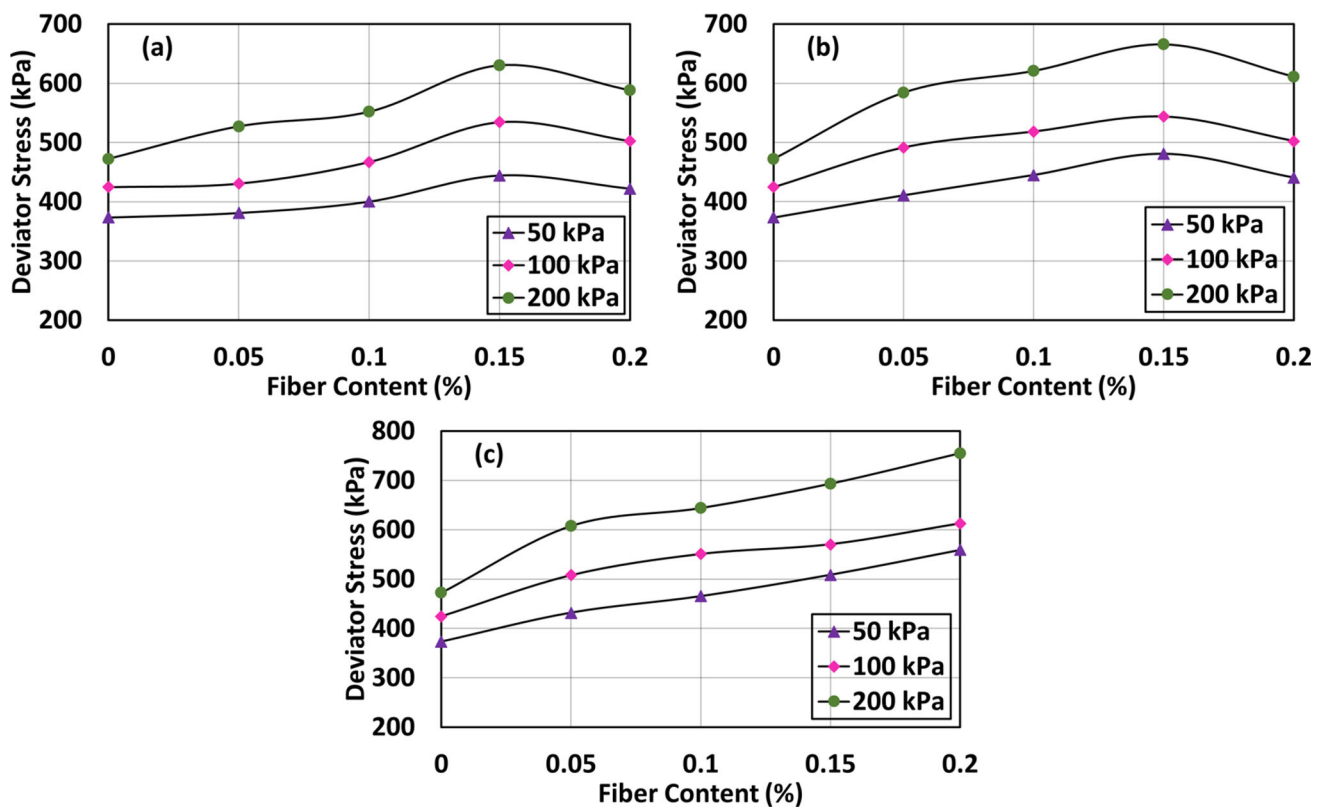


Fig. 4 σ_{dev} -fiber content relationship for **a** 6-mm PP fiber, **b** 12-mm PP fiber, and **c** 19-mm PP fiber

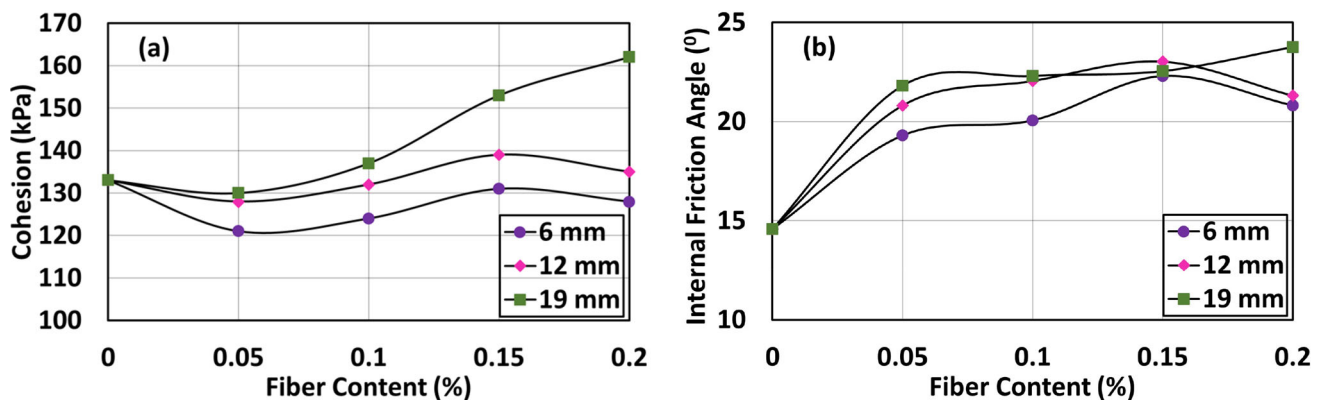


Fig. 5 **a** Cohesion and **b** internal friction angle values for different fiber contents

In all specimens, when the fiber content was 0.05%, the cohesion decreased compared to that of the natural soil (Fig. 5a). It was concluded that in specimens containing 6- and 12-mm PP fibers, cohesion increased as the fiber content increased from 0.05 to 0.15% and decreased again with fiber content greater than 0.15%. In specimens reinforced with 19-mm PP fiber, it was obtained that cohesion increased continuously with increasing fiber content after 0.05% (Fig. 5a). In specimens containing 6- and 12-mm fibers, the internal friction angle increased to 0.15% fiber percentage. After

this value, it decreased with the increase in fiber percentage. In specimens reinforced with 19-mm fiber, continuous enhancement of the internal friction angle was observed with the increasing fiber content, as depicted in Fig. 5b. As a result, when 0.20% of 19-mm PP fibers were added into the soil, the highest cohesion (162 kPa) and internal friction angle (23.75°), and therefore the highest shear strength, were obtained. In this situation, where the highest improvement was observed, the increases in the natural soil's cohesion and internal friction angles were calculated as 21.8% and 63%, respectively.



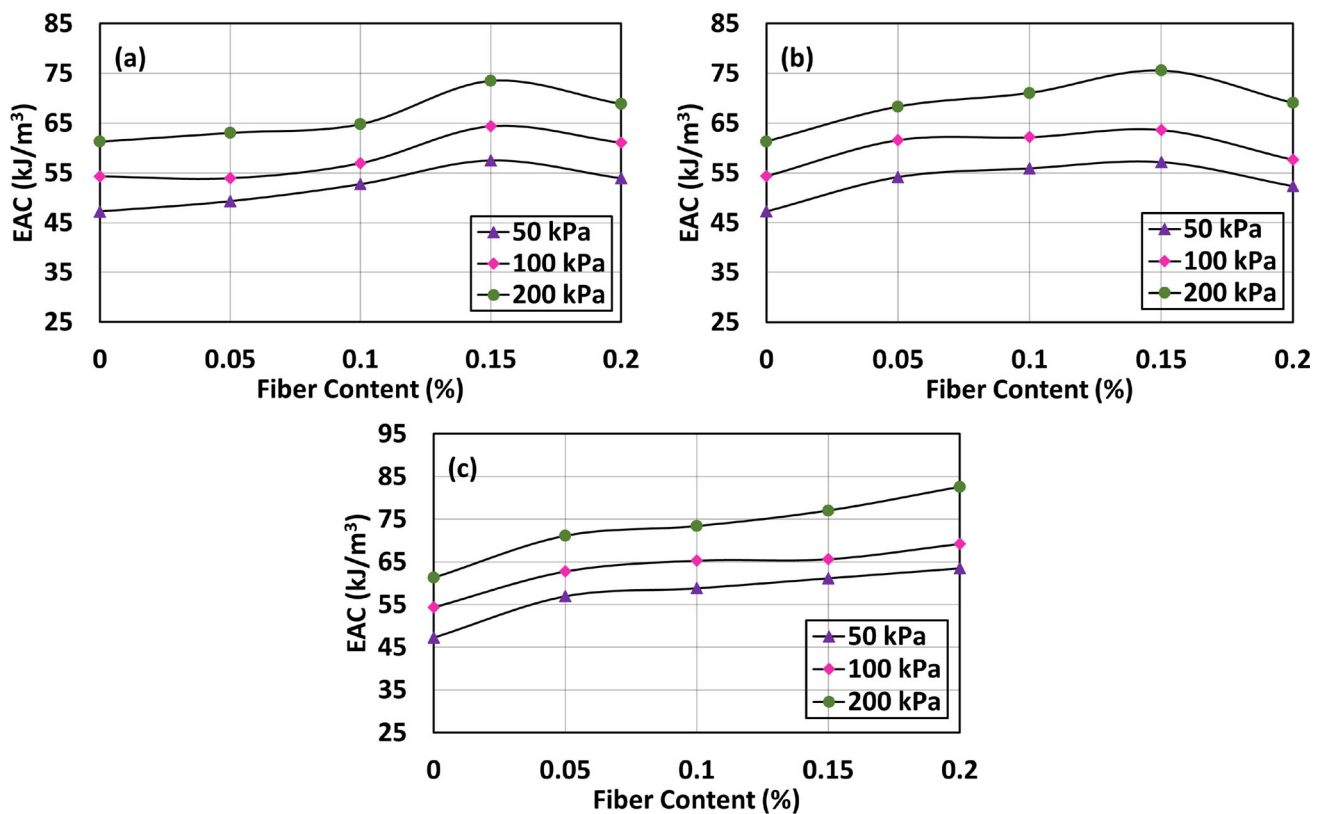


Fig. 6 EAC of clay soil reinforced with **a** 6-mm PP fiber, **b** 12-mm PP fiber, and **c** 19-mm PP fiber

3.2.3 Effect of Fiber Content on EAC

EAC was calculated from the area under the stress–strain curves up to 15% strain. As the EAC increases, the material's ductility increases [41]. The effects of different amounts and lengths of PP fiber on the EAC of clay soil are shown in Fig. 6.

EAC exhibits an ascending trend as the fiber content rises to the optimal level and diminishes with higher fiber percentages. Consequently, ductility rises as the fiber percentage increases to optimum but diminishes when exceeding the optimum fiber content.

3.3 Effect of Fiber Length

3.3.1 Effect of Fiber Length on Deviator Stress at Failure

Figure 7 illustrates the effect of fiber length (L) on the σ_{dev} of reinforced soil specimens. The results indicate that the length of the fibers has a notable influence on the strength of the specimens. σ_{dev} increased with increasing fiber length for all confining pressures and fiber percentages. The most significant improvements in deviator stress compared to the unreinforced soil occurred in specimens containing 19-mm PP fiber at a content of 0.20%. For this case, the σ_{dev} is

559.203, 612.915, and 755.252 kPa for 50, 100, and 200 kPa, respectively, and the increases in σ_{dev} compared to that of the pure soil are 49.83%, 44.37%, and 59.95%, respectively. Compared to specimens containing the optimum amount of PP (6 mm) and PP (12 mm) fibers, these increases are 25.91%, 14.72%, and 19.81% and 16.29%, 12.76%, and 13.46%, respectively.

3.3.2 Effect of Fiber Length on Shear Strength Parameters

Figure 8 depicts the impact of fiber length on shear strength parameters. When Fig. 8a is examined, it is noticed that, in specimens reinforced with 6-mm PP fiber, the cohesion decreases for all fiber contents compared to the unreinforced soil. As the fiber length exceeded 6 mm, a continuous increase in cohesion was observed for all fiber contents. Furthermore, the internal friction angle demonstrated a general upward trend as the fiber length increased for all fiber contents, as depicted in Fig. 8b.

3.3.3 Effect of Fiber Length on EAC

Figure 9 displays the influence of fiber length on the EAC of clay soil reinforced with PP fiber under varying confining pressures. The effect of fiber length on the alteration of



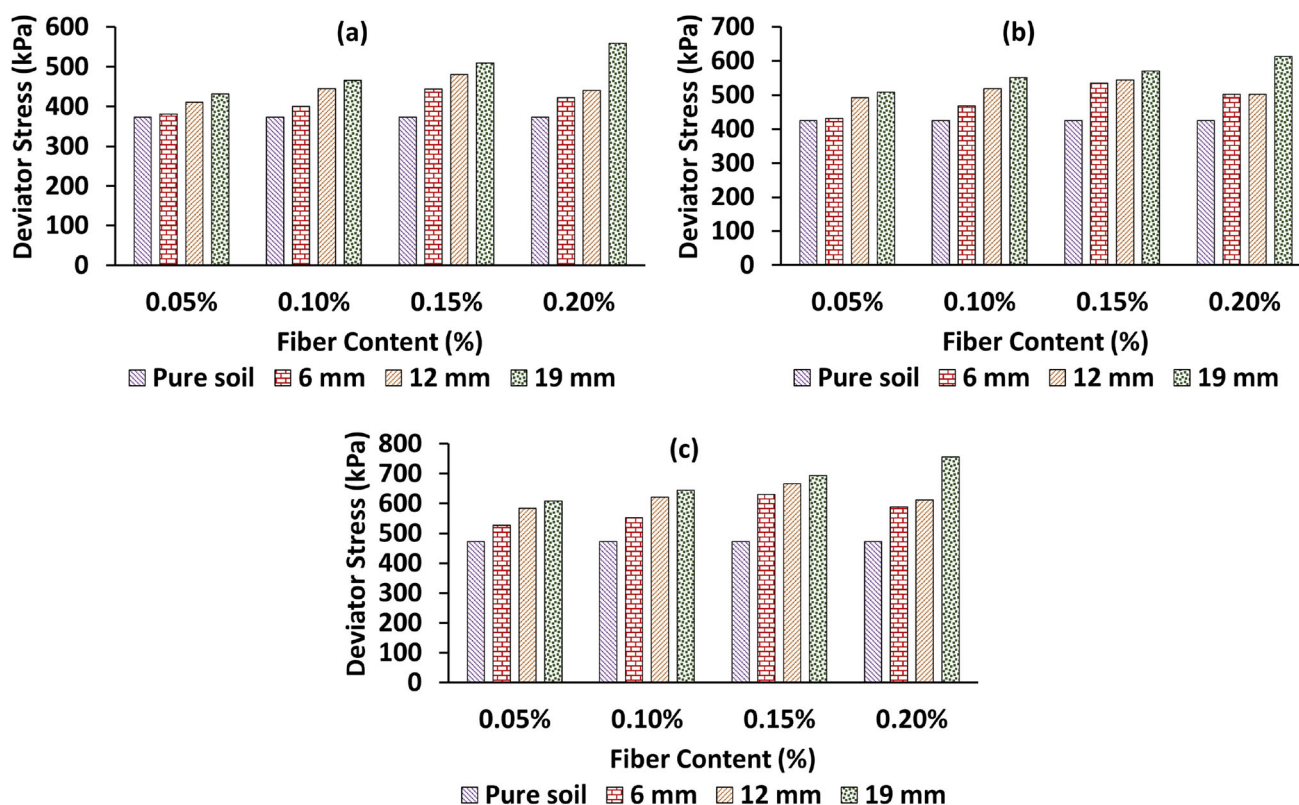


Fig. 7 Effect of fiber length on σ_{dev} for a 50 kPa, b 100 kPa, and c 200 kPa

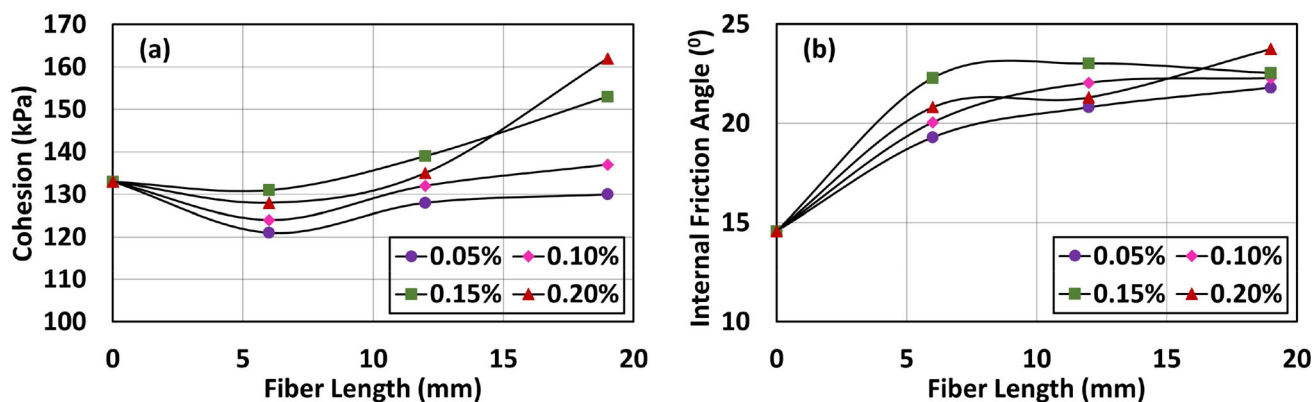


Fig. 8 a Cohesion and b internal friction angle values for different fiber lengths

EAC was observed to be irregular. However, it was concluded that the EAC increased with the presence of fiber material in the soil compared to that of the unreinforced soil (47.259, 54.340, and 61.309 kJ/m³ for 50, 100, and 200 kPa confining pressures, respectively). This shows that soil specimens containing fibers exhibit more ductile behavior than natural soil. In the EAC–fiber length curves for different confining pressures, the highest EAC for each fiber content occurred in specimens containing 19-mm PP fiber. It was observed that the highest EAC (63.503, 69.227, and 82.583 kJ/m³ for confining pressures of 50, 100, and 200 kPa, respectively)

was obtained in the specimens prepared by adding 0.20% of 19-mm PP fibers. As a result, specimens containing 19-mm PP fiber exhibited more ductile behavior than all other specimens, and the most ductile behavior occurred in specimens reinforced with 19-mm PP fiber at a content of 0.20%. The highest improvements in EAC compared to unreinforced soil were calculated as 34.37%, 27.40%, and 34.70% for confining pressures of 50, 100, and 200 kPa, respectively.



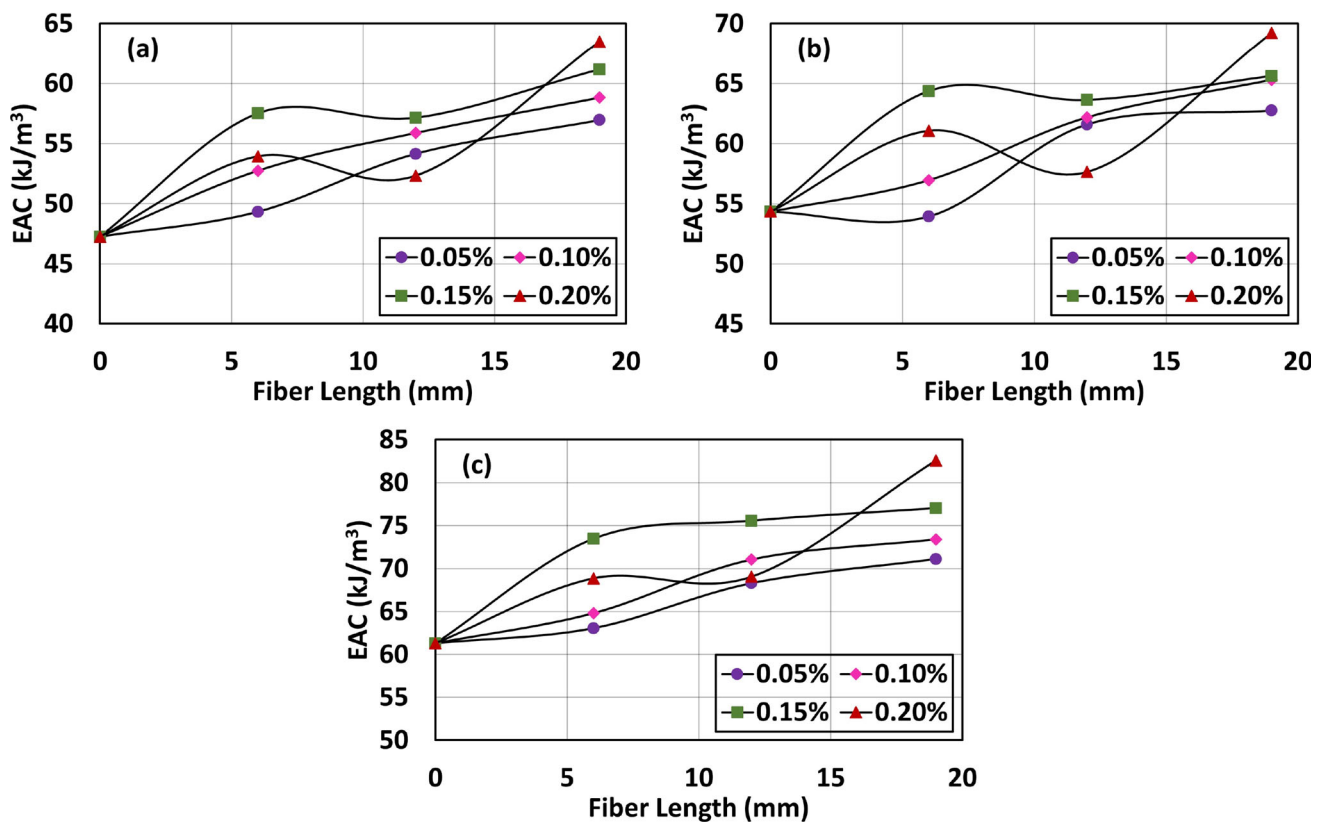


Fig. 9 Effect of fiber length on the EAC of reinforced soil, **a** 50 kPa, **b** 100 kPa, and **c** 200 kPa

3.4 Fiber–Soil Interaction Mechanism

Figure 10 presents the specimens' scanning electron microscope (SEM) images. In Fig. 10a, the natural soil is depicted. SEM images of specimens mixed with fibers below the optimal content, at the optimal percentage, and above the optimal content are displayed in Fig. 10-b, d, Fig. 10-e, and Fig. 10-c, respectively.

Provided the fibers are evenly distributed in the soil, the interaction between the soil particles and the fibers and the interaction among soil particles significantly affects the soil's strength when the fiber–soil composite is under load. Frictional and/or adhesion forces occur at the interface between fibers and soil particles within the fiber–soil composite under axial load, limiting the movement of the soil particles. In addition, the flexible PP fibers in the soil bend, wrap the soil particles, and restrict the deformation of the soil particles under load. Bending flexibility allows the fibers to be randomly distributed in the soil matrix, forming many curved structures. As the fibers within the soil undergo tension, the concave side of the bent fiber applies to squeeze stress on the soil particles. This results in a constraining effect on the soil particles, effectively decreasing soil deformation [48, 49, 52]. Moreover, the fibers interweave within the soil to create

a three-dimensional network, effectively limiting the movement of soil particles. Thus, the load is distributed over a larger area [52]. After analyzing the experimental findings and examining SEM images of the reinforced specimens, it became evident that a specific fiber length and content were required for the natural soil to achieve its optimal strength. It becomes apparent that when the fiber content is below the optimal amount, there is an insufficient total contact area between soil particles and fibers. As a result, fibers cannot establish a network structure within the soil, limiting soil strength enhancement. In cases where the fiber content exceeds the optimal level, the fibers tend to cluster together rather than achieve a uniform distribution. Thus, there is an increase in fiber–fiber contact rather than fiber–soil contact, resulting in a decrease in strength. It is easier to distribute short fibers uniformly into the soil. Adding and mixing short fibers into the soil can be done simply, as in lime, cement, or other additives that provide an isotropic increase in the strength of the reinforced soil [54]. However, using short fibers in soil reinforcement applications has some disadvantages. Due to the limited contact area between fibers and soil particles, when the fiber–soil composite is subjected to loading, the fibers are simply pulled out from the soil matrix, the reinforcement element cannot create an effective bending in the reinforced specimen, and the fibers cannot constitute a



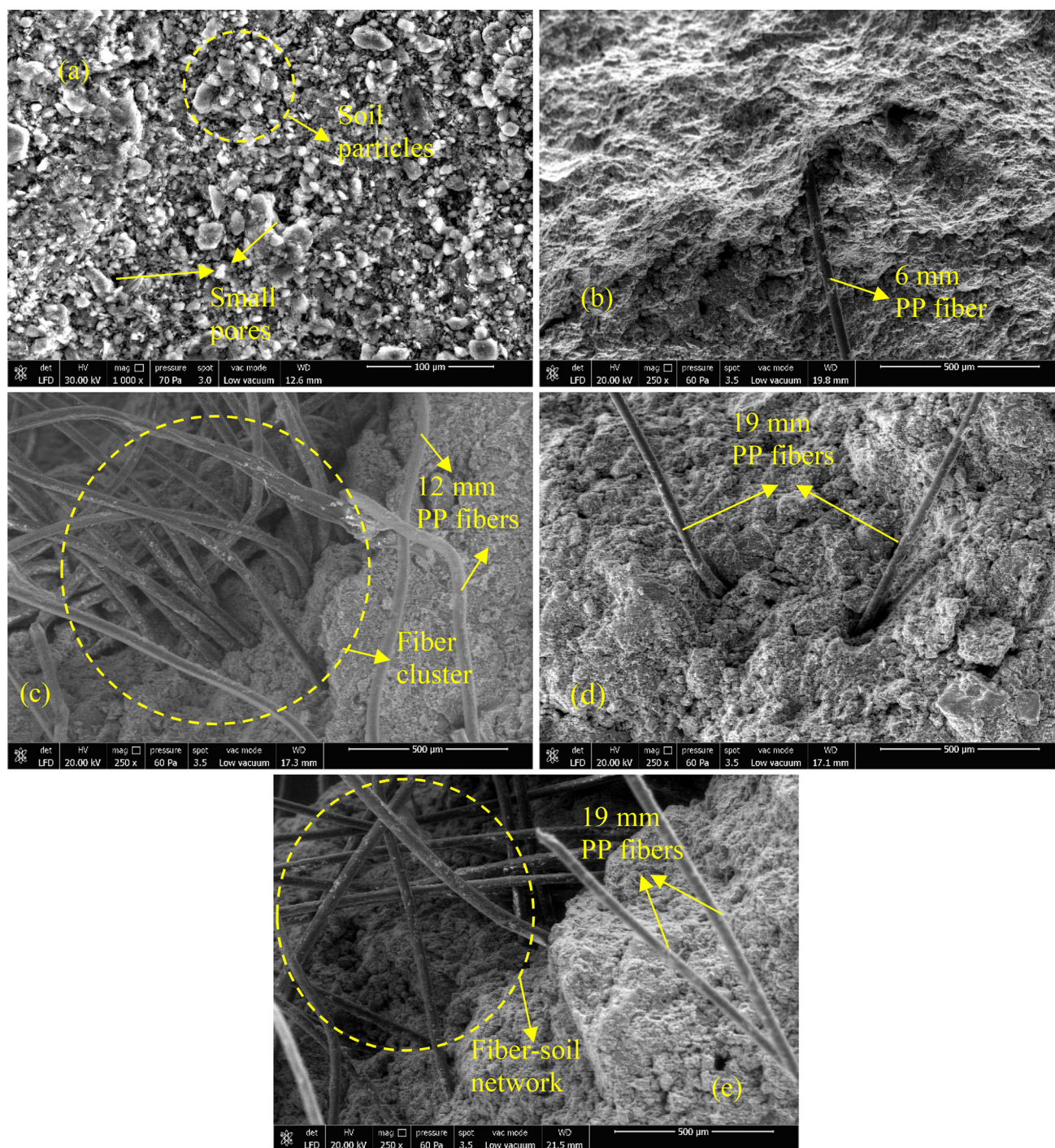


Fig. 10 SEM of the soil containing **a** 0.00%, **b** 0.05% 6-mm PP, **c** 0.20% 12-mm PP, **d** 0.05% 19-mm PP, and **e** 0.20% 19-mm PP images

three-dimensional network within the composite [52]. In the clay soil reinforced with PP fiber of optimum length (19 mm), the randomly distributed individual fibers within the soil matrix act as a three-dimensional network interlocking with smaller clay particles, which limits the displacement of the fiber–soil composite during loading. In addition, the fact that

long and flexible fibers bend and wrap around the soil particles sufficiently compress them and limit their deformation is another factor that contributes significantly to improving the strength of the reinforced specimen [50].

Table 3 Descriptive statistics of the data used in ANN and MLR

Phase	Symbol	Unit	Min	Max	Mean	Standard deviation	Skewness coefficient	Kurtosis coefficient
Training	F_c	%	0	0.200	0.110	0.060	0.177	−1.166
	L	mm	0	19	10.240	4.990	0.311	−0.402
	σ_3	kPa	50	200	108	61.123	0.652	1.243
	σ_{dev}	kPa	373.233	665.653	498.199	76.264	0.447	−0.430
Validation	F_c	%	0.100	0.200	0.143	0.042	0.272	−1.817
	L	mm	6	19	17.143	4.549	−2.041	7.000
	σ_3	kPa	50	200	135.714	58.029	0.022	−2.071
	σ_{dev}	kPa	400.077	755.252	603.900	105.606	−0.534	1.013
Testing	F_c	%	0	0.200	0.107	0.082	−0.229	−2.152
	L	mm	0	19	9.714	7.420	−0.091	−1.677
	σ_3	kPa	50	200	128.571	64.681	0.040	−2.351
	σ_{dev}	kPa	424.549	611.214	527.129	65.806	−0.098	−1.424

3.5 ANN and MLR Analysis

This section employed the MLR and ANN methods to investigate the linear and nonlinear relationships between the σ_{dev} and fiber length, fiber content, and confining pressure. Descriptive statistics values of these data are shown in Table 3.

Multilayered ANNs are commonly utilized as modeling tools because they accurately predict nonlinear relationships among various parameters. Additionally, in multilayered ANN, the network can be trained solely using input–output data pairs without making assumptions or simplifying the problem [55]. In the literature, one hidden layer was generally used in ANN analyses to avoid the overfitting problem [56–63]. For this reason, a multilayer perceptron network structure containing a hidden layer was preferred in this study. In ANN applications, the optimum number of neurons is determined by trial and error [64]. In studies carried out within civil engineering, the number of neurons is generally between 2 and 10, and using more than 10 neurons in the hidden layer does not significantly affect the network's performance [65]. In this study, ANN models were created using data from PP fiber-reinforced specimens. These models' input and output layers consist of three neurons (F_c , L , and σ_3) and one neuron (σ_{dev}), respectively. Tangent sigmoid and linear transfer functions were employed in the hidden and the output layers, respectively. The Levenberg–Marquardt algorithm [57, 66, 67] was utilized for training ANN models; of the total 39 data, 60% was reserved for training, 20% for validation, and the other 20% for testing. Commonly used indicators of mean absolute percentage error (MAPE) and determination coefficient (R^2) were chosen to evaluate the network's performance. The analyses were conducted by varying the number of neurons in the hidden layer,

ranging from 2 to 10. ANN models were determined in which the highest R^2 and lowest MAPE values were calculated by performing 100 relearning in each model. As a result, Table 4 presents the R^2 and MAPE values, which indicate the performance of each network with different structures in predicting training, validation, and test data. As shown in Table 4, the performance of all ANN models is acceptable since R^2 values are generally greater than 0.80. However, it was observed that the best performance was achieved if eight neurons were used in the hidden layer (Fig. 11). The prediction equation for this ANN model, which produces predictions closest to the actual values, is given in Eq. 1.

$$\sigma_{dev} = \frac{111.79239}{1 + e^{(N_1)}} + \frac{45.28486}{1 + e^{(N_2)}} + \frac{81.27903}{1 + e^{(N_3)}} + \frac{228.29582}{1 + e^{(N_4)}} + \frac{156.78118}{1 + e^{(N_5)}} - \frac{128.87778}{1 + e^{(N_6)}} + \frac{52.80452}{1 + e^{(N_7)}} - \frac{101.06301}{1 + e^{(N_8)}} + 217.89694 \quad (1)$$

$$N_1 = 50.6098F_c - 0.37657L - 0.00783\sigma_3 - 5.71912 \quad (1a)$$

$$N_2 = -4.2431F_c + 0.63152L - 0.04279\sigma_3 + 2.02136 \quad (1b)$$

$$N_3 = -15.34676F_c + 0.44986L - 0.09776\sigma_3 + 9.56325 \quad (1c)$$

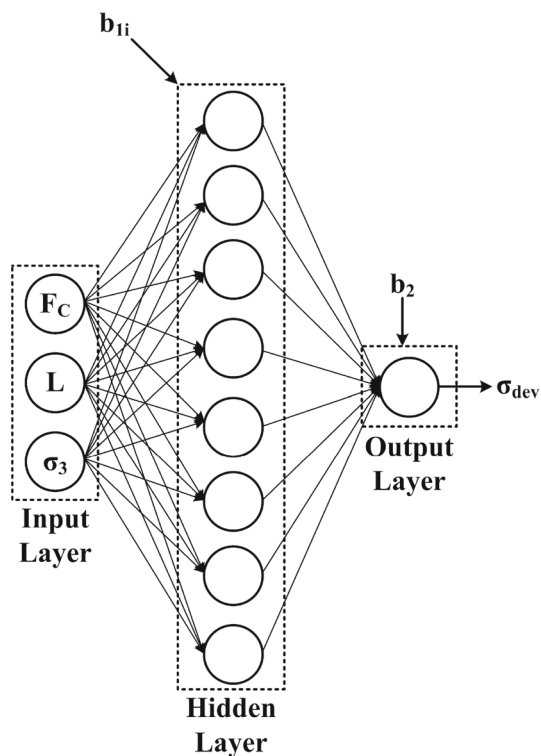
$$N_4 = 1.0166F_c - 0.26805L - 0.00771\sigma_3 + 3.91899 \quad (1d)$$

$$N_5 = -46.16876F_c - 0.19499L - 0.00289\sigma_3 + 8.00194 \quad (1e)$$



Table 4 Performances of ANN models

Model no	Number of neurons in the hidden layer	ANN results					
		Training		Validation		Test	
		R^2	MAPE	R^2	MAPE	R^2	MAPE
1	2	0.974	1.972	0.890	4.215	0.635	5.642
2	3	0.993	1.041	0.890	4.477	0.786	4.312
3	4	0.998	0.572	0.936	4.009	0.836	4.221
4	5	1.000	0.004	0.945	5.204	0.872	4.520
5	6	1.000	0.118	0.948	3.264	0.880	4.203
6	7	1.000	0.000	0.938	6.058	0.800	7.590
7	8	1.000	0.000	0.962	2.247	0.850	3.503
8	9	1.000	0.001	0.851	8.508	0.845	6.998
9	10	1.000	0.025	0.933	4.117	0.869	5.970

**Fig. 11** Structure of ANN models that give the best predictions

$$N_6 = -36.01336F_C - 0.50665L - 0.00617\sigma_3 + 11.68928 \quad (1f)$$

$$N_7 = -47.92464F_C - 0.19205L + 0.05124\sigma_3 - 2.67001 \quad (1g)$$

$$N_8 = 11.5908F_C - 0.24822L + 0.0761\sigma_3 - 2.08126 \quad (1h)$$

Researchers can get a preliminary idea by using this equation to predict the σ_{dev} under unconsolidated-undrained

loading conditions. At this stage, researchers should make calculations without exceeding the lower and upper limit values of the variables used in this study in creating prediction equations.

This study also investigated an MLR relationship, considering the fiber percentage, fiber length, and confining pressure values as independent variables and the σ_{dev} as the dependent variable. To test the success of the determined regression equation and compare it with the success of the ANN model in predicting training, validation, and test data, the data in the regression analysis were divided into 60% training, 20% validation, and 20% test data. A linear regression equation was derived using the training data to establish the relationship between the independent and dependent variables. Then, the success of this equation in predicting validation and test data was tested. Furthermore, the outputs from the regression equation were compared with those generated by the ANN model that exhibited the most accurate predictions.

Some assumptions need to be tested before MLR can be used. The most critical assumptions are outliers, multicollinearity, normal distribution of errors, and homoscedasticity. Tests carried out to check whether these conditions are met are given below:

1. Outliers should not exist within the variables.

The interquartile range (IQR) method was used to detect outliers. The IQR value is calculated from the difference between the third (Q_3) and first (Q_1) quartiles in a data set.

According to this method, lower (T_{min}) and upper (T_{max}) bounds are calculated from the following equations:

$$T_{min} = Q_1 - 1.5(IQR) = Q_1 - 1.5(Q_3 - Q_1) \quad (2)$$



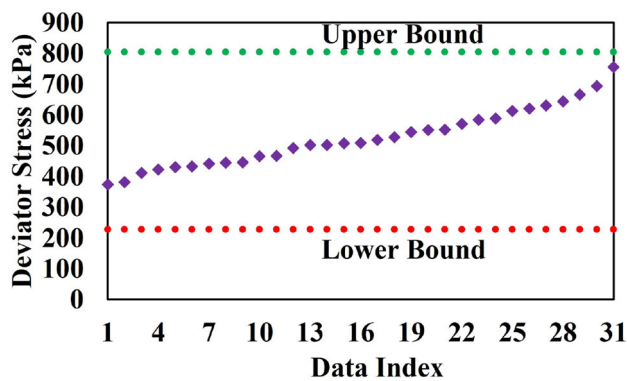


Fig. 12 Outliers according to the lower and upper limits of σ_{dev}

$$T_{\max} = Q_3 + 1.5(IQR) = Q_3 + 1.5(Q_3 - Q_1) \quad (3)$$

The lower and upper bounds for σ_{dev} are shown in Fig. 12. When Fig. 12 was examined; there were no outliers in the experimental results of specimens containing PP fiber.

2. All variables must have a normal distribution.

Although some researchers state that all dependent and independent variables should exhibit normal distribution as an assumption of linear regression, many researchers [66, 67] instead state that the normal distribution of errors is sufficient. However, testing the normality of variables beforehand can sometimes be a useful indicator that the distribution of errors will also be normal. The kurtosis and skewness coefficient values were utilized to get an initial idea of whether the training data used in the regression analysis were normally distributed (Table 3). The fact that the skewness and kurtosis coefficients of a data set are zero indicates that the data of the relevant variable are normally distributed. However, since the skewness and kurtosis values are generally different from zero in many applications, acceptable ranges for kurtosis and skewness coefficients were suggested in the literature to check the normality of the data. In this context, one recommended range is ± 2.00 [68–70]. Table 3 shows that the kurtosis and skewness coefficients of the dependent and independent variables (training phase) involved in the linear regression analysis fall within the mean of ± 2.00 . As a result, it can be said that the dependent and independent variables exhibit normal distribution.

3. There should be no multicollinearity between independent variables.

Evaluation can be made by looking at the correlation coefficient between independent variables to test multicollinearity (Table 5). The absolute value of the correlation coefficient, being less than 0.8, suggests the absence of

Table 5 Correlation coefficients between variables

	σ_{dev}	F_C	L	σ_3
σ_{dev}	1.000	0.307	0.123	0.867
F_C	0.307	1.000	−0.028	0.060
L	0.123	−0.028	1.000	−0.210
σ_3	0.867	0.060	−0.210	1.000

Table 6 Normality test

	Shapiro–Wilk		
	Statistics	Degrees of freedom	α
Standardized error	0.967	25	0.570

multicollinearity among the independent variables [71, 72]. However, researchers typically employ the variance inflation factor (VIF) to assess multicollinearity. A VIF value of 1 signifies no significant relationship between the independent variables, while a VIF value falling between 1 and 5 indicates a moderate level of correlation among the independent variables. A VIF value greater than 5 indicates a multicollinearity problem among the independent variables in the regression model [71, 72].

Table 5 shows that the correlation coefficients between F_C - L , σ_3 - F_C , and L - σ_3 are −0.028, 0.060, and −0.210, respectively, and have values much lower than 0.8. In addition, the VIF values of each independent variable were calculated to be very close to 1 (Table 8). As a result, it was observed that there was no multicollinearity problem among the independent variables included in the regression analysis.

4. Errors should be normally distributed.

Kolmogorov–Smirnov and Shapiro–Wilk tests are widely used in the literature for normality tests. If the number of data is greater than or equal to 30, the Kolmogorov–Smirnov test should be used, and for data less than 30, the Shapiro–Wilk test should be used. Additionally, the data's normality can be evaluated using Q–Q graphs. The Shapiro–Wilk test was used for the 95% confidence interval to investigate the normality of the errors, and the results are presented in Table 6. Additionally, the distribution of standardized errors obtained from MLR analysis is shown in the Q–Q graph below. As a result, the significance coefficient (α) obtained from the Shapiro–Wilk test is greater than 0.05, and the standardized errors are scattered very close to the line in the Q–Q graph (Fig. 13), indicating that the errors comply with the normal distribution.



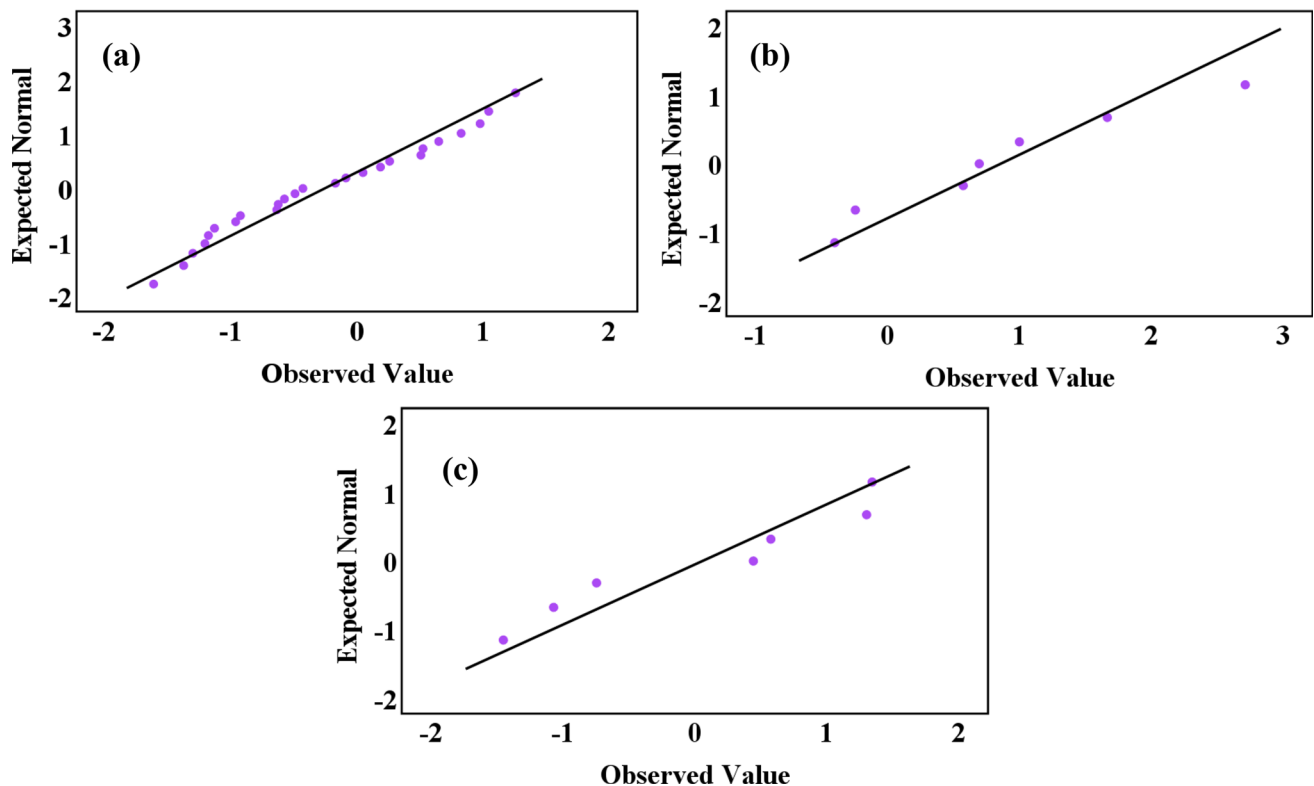


Fig. 13 Q – Q plot for standardized errors for **a** training data, **b** validation data, and **c** test data

5. Homoscedasticity

MLR assumes that errors have constant variance at each point in the linear model. The simplest way to determine whether this assumption is met is to plot standardized errors versus predicted values (Fig. 14). For homoscedasticity to occur, the points in this graph must be randomly distributed. In other words, the errors corresponding to the predictions should not exhibit a functional behavior. When Fig. 14 is examined, it can be seen that this condition is also met.

MLR analyses were performed with the SPSS Statistics Program, and the "Enter Method" was used. The results of the prediction model are presented below. The regression analysis model summary is presented in Table 7, while Table 8 shows the coefficients for the corresponding model.

Table 7 indicates that the adjusted R^2 value is relatively high. The standardized coefficients in Table 8 indicate how much the dependent variable changes when the independent variable varies by one unit of standard deviation. For example, if the fiber content and length are kept constant and the confining pressure increases by one standard deviation, the value of the σ_{dev} increases by $0.919 \times \text{standard deviation}$. Accordingly, considering their effects on deviator stress, we found that the order from the highest to the lowest value is σ_3 , L , and F_C . Additionally, Table 8 shows that the significance coefficient for all independent variables is less than

0.05. This implies that all the independent variables have a significant effect on the dependent variable. As a result, the equation below gives the σ_{dev} of a low-plasticity clay soil reinforced with PP fiber.

$$\sigma_{dev} = 331.295F_C + 4.941L + 1.147\sigma_3 + 287.308 \quad (4)$$

For example, for $F_C = 0.075\%$, $L = 10$ mm, and $\sigma_3 = 75$ kPa, using Eqs. 1 and 4, deviator stress is calculated as 453.728 kPa and 447.590 kPa, respectively. For $F_C = 0.175\%$, $L = 15$ mm, and $\sigma_3 = 150$ kPa, the deviator stress values calculated from Eqs. 1 and 4 are 639.030 kPa and 591.450 kPa, respectively.

3.5.1 Comparison of the Performances of ANN and MLR Models

Statistical indicators (R^2 and MAPE) of the ANN and MLR models that provide the best predictions are given in Table 9 for the training, validation, and testing stages. In addition, the best predictions obtained from ANN and MLR analyses were compared with the actual values (Fig. 15a). When the R^2 and MAPE values of the MLR and ANN models in Table 9 are compared, it is observed that the ANN model gives higher R^2 and lower MAPE. In Fig. 15a, it becomes evident that the ANN model provides predictions closer to

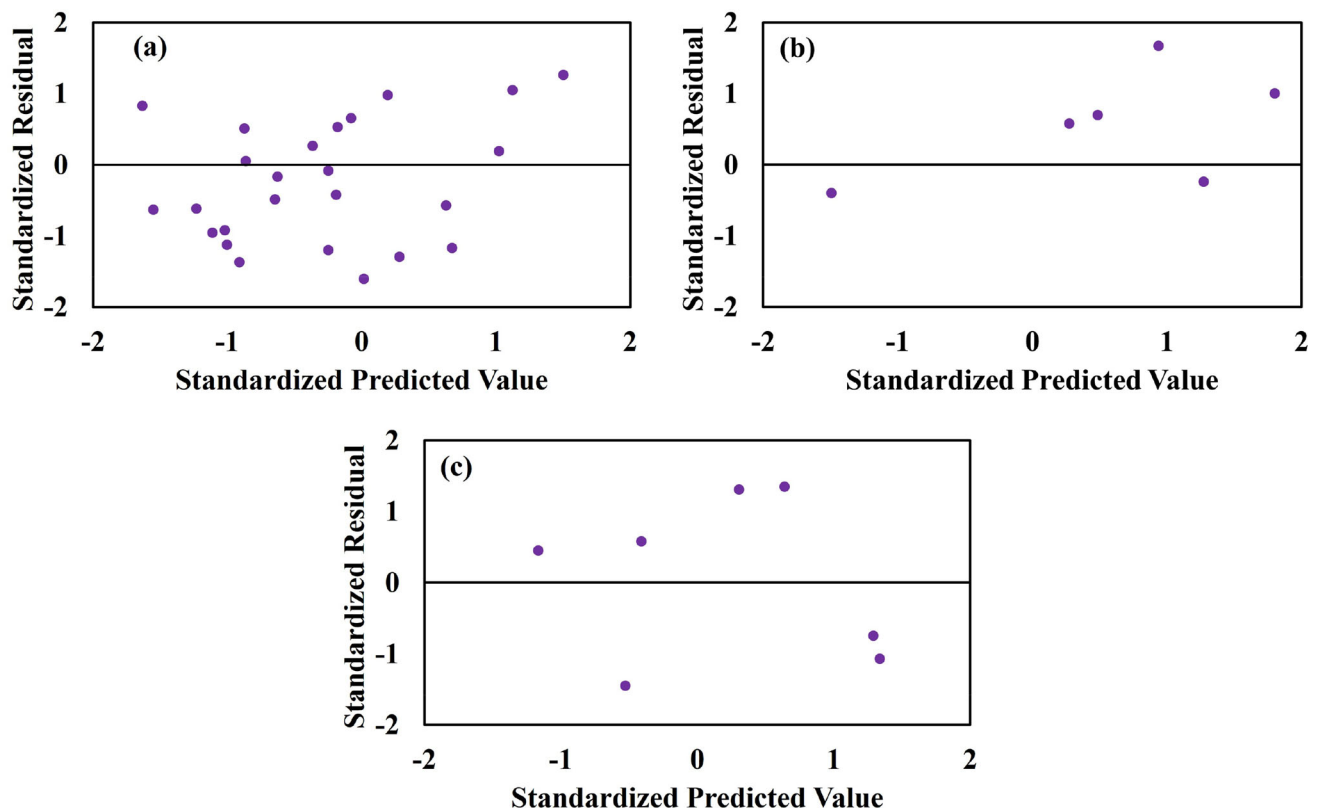


Fig. 14 Control of homoscedasticity for **a** training data, **b** validation data, and **c** test data

Table 7 Model summary

Model	R	R^2	Adjusted R^2	Standard error of the estimate
PP	0.957	0.917	0.905	24.021

Table 8 Regression coefficients

	Unstandardized coefficients	Standardized coefficients	t	α	VIF
Constant	287.308		16.342	< 0.001	
F_C	331.295	0.261	4.130	< 0.001	1.004
L	4.941	0.323	5.018	< 0.001	1.046
σ_3	1.147	0.919	14.244	< 0.001	1.049

Table 9 Statistical indicators of predictive models

	MLR			ANN		
	Training	Validation	Test	Training	Validation	Test
R^2	0.917	0.956	0.797	1.000	0.962	0.850
MAPE	3.850	4.815	6.904	0.000	2.247	3.503

the actual values. Cumulative frequency analysis was performed to understand how often the errors of the σ_{dev} values estimated by Eqs. 1 and 4 are a certain value. The cumulative frequency distributions of errors are presented in Fig. 15b [73, 74] to compare the success of the predictive equations

created by ANN and MLR analyses. Cumulative frequency calculations were made using all data (39 σ_{dev} data). For example, for a 2% error, the ANN model gave a cumulative frequency of 84.62%, while for MLR, this value was approximately 23.08%. In other words, while the probability



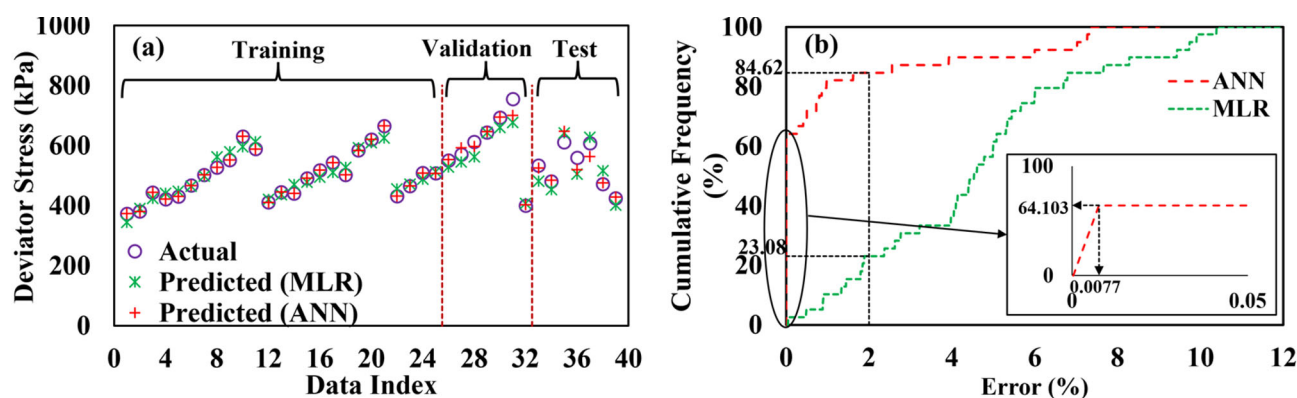


Fig. 15 **a** Comparison of ANN and MLR predictions with actual values and **b** cumulative frequency distribution of errors

of observing an error of less than 2% in the predictions made with the ANN equation (Eq. 1) is 84.62%, this probability is 23.08% in the predictions made with the MLR equation (Eq. 4). Accordingly, it can be said that the ANN equation provides the best predictions as it gives the highest cumulative frequency for a lower error range compared to MLR.

4 Conclusions

This study used the UU triaxial compression test to investigate the mechanical characteristics of low-plasticity clay soil reinforced with PP fibers of various contents and lengths. Furthermore, prediction equations were created using MLR and ANN methods using data from reinforced soil. The main conclusions drawn from this study are summarized below.

1. The stress–strain behavior of the unreinforced soil, strain softening, changed to strain hardening due to reinforcement.
2. Adding different contents and lengths of PP fiber into the soil did not affect the initial stiffness of the natural soil. Therefore, PP fiber reinforcement did not affect the clay soil's stiffness at small deformation levels.
3. It was observed that the type of failure was not affected by the presence of fiber in the soil, and all specimens were subjected to bulging failure.
4. Considering the increases in σ_{dev} of the natural soil, it was observed that the optimum fiber contents for PP (6 mm), PP (12 mm), and PP (19 mm) were 0.15%, 0.15%, and 0.20%, respectively.
5. Improvements increased with increasing confining pressure in reinforced specimens. In reinforced specimens, σ_{dev} generally increased with increasing fiber length. Compared to other reinforced specimens, the highest increases in the σ_{dev} of the natural soil occurred when 19-mm PP fibers were used at 0.20% by weight.

These increases for 50, 100, and 200 kPa confining pressures were measured as 49.83%, 44.37%, and 59.95%.

6. Higher internal friction angles were obtained in specimens reinforced with the optimum content of PP fiber compared to others. Accordingly, the internal friction angles of the specimens reinforced with the optimum content of PP (6 mm), PP (12 mm), and PP (19 mm) fibers increased by 52.97%, 57.99%, and 63.00%, respectively, compared to those of the unreinforced soil. The changes in the cohesion of the specimens containing the optimum amount of PP (6 mm), PP (12 mm), and PP (19 mm) compared to the unreinforced soil were calculated as -1.5% , 4.51% , and 21.80% , respectively. As the fiber length increased in specimens containing PP fiber, the internal friction angles measured for all fiber percentages generally increased. As a result, the highest shear strength parameters occurred in specimens reinforced with 19-mm PP fiber at the content of 0.20%. The shear strength of reinforced specimens consists of internal friction angle and cohesion. Considering the changes in the shear strength parameters of the reinforced samples, the internal friction angle was observed to be relatively more dominant than cohesion.
7. The EAC of all reinforced specimens reached values significantly higher than those of the natural soil. This shows that the ductility of the soil is significantly increased by adding different lengths and contents of PP into the soil. The highest EAC and, therefore, the highest ductility occurred in the soil specimens containing the optimum amount of PP fibers. It has been observed that EAC generally increases with increasing fiber length for all confining pressures. The highest EAC values were measured in specimens containing 19-mm PP at 0.20% by weight.
8. The fiber's content and length directly affect the interaction between fibers and soil particles in the fiber–soil composite. The contact area between the fibers and soil

particles is relatively small in the fiber–soil composite containing less than the optimum amount of fibers. This causes the increases in the strength of the soil to be small. If the soil is reinforced with PP fibers above the optimum amount, the fibers embedded in the soil matrix cannot be distributed uniformly; they form clusters, so fiber–fiber contact increases rather than fiber–soil contact. When short fibers are used in soil reinforcement, the contact area between fibers and soil particles is small. For this reason, the fibers are easily pulled out from the soil when the fiber–soil composite is exposed to a load. Besides, the fibers cannot interweave and form a three-dimensional fiber–soil network structure due to their short length. As a result, the improvements caused by short fibers in the strength of the natural soil are relatively small.

9. Compared to all other specimens, the most remarkable improvements in σ_{dev} , cohesion, internal friction angle, and EAC occurred in specimens containing 19-mm PP fiber at the content of 0.20%.
10. ANN and MLR predictive models were developed using PP fiber-reinforced specimen data. A nonlinear prediction equation was generated from the ANN model, providing the highest compatibility with the actual results. As an alternative, a regression equation was created from MLR analyses. Researchers can benefit from the prediction equations created in this study to estimate the σ_{dev} of a low-plasticity clay soil reinforced with PP fiber for different fiber contents, fiber lengths, and confining pressure conditions.

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Declarations

Conflict of interests The authors have no competing interests to declare that are relevant to the content of this article.

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