Journal of King Saud University – Engineering Sciences (2025) 37:14
https://doi.org/10.1007/s44444-025-00011-z

ORIGINAL PAPER

Installation of polyethylene terephthalate (PET) columns to promote the soil-bearing capacity of soft kaolin clay

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Received: 28 January 2025 / Accepted: 24 May 2025

Abstract
The reuse of disposal waste like polyethylene terephthalate (PET) plastic in a modified stone column method in ground improvement offers a reliable, sustainable, and cost-effective approach. The method is aimed at rectifying the problem of soft clay soil in terms of its engineering properties, which often lead to severe issues including soil settlement, soil particle dispersion, high compressibility, soil bulging, and erodibility. Previous studies have suggested the utilization of PET plastic in treating kaolin through stone column installation, but there is no direct examination including a comprehensive statistical analysis. This research examines kaolin, PET plastic, and kaolin reinforced with PET columns by implementing the relevant geotechnical means. It focuses on particle size distribution, Atterberg limits tests, relative density test, specific gravity test, standard Proctor test, permeability test, unconfined compressive strength test, and unconsolidated undrained triaxial test. By assessing the shear strength parameters of the control and reinforced samples, the influence of the number of columns, column diameter, column height, area replacement ratio, height penetration ratio, column height to column diameter ratio, volume replacement ratio, and confining pressure were considered. The results obtained from the investigation of PET reinforcement in single and group categories confirmed the enhancement of kaolin shear strength parameters, with optimum improvement of 48.42% and 56.53% at a penetration height of 100 mm coherent to the observed parameters. Hence, the results not only testify to the effectiveness of single and group PET columns but also highlight the environmental benefit of PET material in promoting sustainable construction.

Keywords Soft clay soil · Ground improvement · Soil bearing capacity · Granular column · Polyethylene terephthalate · Sustainable

1 Introduction

In civil engineering, ground modification and improvement processes are crucial to enhancing the geotechnical properties of the soil prior to construction, in order to meet stability requirements. In highly populated areas, one of the most commonly encountered problems involves construction projects on soft clay soil. Clay is a naturally occurring material that is formed through the erosion of rock and geological weathering (Shen et al. 2024). The most common types of clay minerals are smectites, illite, and kaolin minerals (Mohammed et al. 2021). As reported by Buckner et al. (2016), the presence of water with the combination of major materials such as kaolinite and micas results in the formation of clay. To categorize a soil as kaolin, the amount of kaolinite with the general formula of $Al_2Si_2O_5(OH)_4$ must be greater than 50%, with a general particle size less than 2 μm (Chandrasekhar and Ramaswamy 2002; Yang et al. 2023). Some clay may be composed entirely of kaolinite, which is the highest-purity clay. Generally, clay is problematic for engineering purposes, where soft clay soils are primarily associated with settlement, soil particle dispersion, soil erosion, and structural damage due to inadequate strength. Thus, soft clay soils are treated to alter their engineering properties and enhance their strength (Kabeta 2022). Bahumdain et al. (2022) reported that the United States spends approximately USD 100 million annually in maintenance costs for unstable bridge structures due to the settlement

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Published online: 04 July 2025

of poor soil. From a financial and safety perspective, researchers have proposed different methods to treat problematic soft clays, such as ground improvement and soil stabilization. For the ground enhancement approach, Shen et al. (2023) and Jun Shen et al. (2025) reported that the use of prefabricated drains beneath the soft soil enhances the soil bearing capacity. Similarly, Syamsul et al. (2023) reported the use of a geosynthetic membrane to encapsulate reinforcing columns, which reduces the undulation of sensitive soil, preventing further liquefaction of multiple soil layers. Likewise, this membrane acts as an intermediate support for the smooth transmission of axial load throughout the reinforcement (Hasan et al. 2021). In contrast, Rezaei-Hosseinabadi et al. (2022) proposed a method for stabilizing soft soil by using stabilizing agents such as lime and calcium chloride to alter the physical and chemical properties of the clay. This method was supported by Phanikumar and Ramanjaneya Raju (2020), who improved the shear strength of kaolin via the combination of lime sludge and cement, facilitating the binding of soil particles by the pozzolanic reaction. In addition, a soil–cement stabilizing approach was applied by Rehman et al. (2025) to decrease the plasticity index and reduce the risk of shrinkage. Similarly, biopolymers such as agar and guar gum have been applied to enhance the shear strength parameters of sandy soil, where the cohesion value was dramatically increased through the formation of adherent hydrogels in the soil particles (Maleki et al. 2025). In addition to clayey soil enhancement, the engineering properties of subgrade soil were stabilized via the addition of eggshell powder, comprising 96% calcium carbonate (Yang et al. 2025). The moisture content present in the eggshell powder facilitates calcination, substantially enhancing the soil strength through the conversion of eggshell to quicklime (CaO) and hydrated lime ($Ca(OH)_2$). All of these studies have confirmed that both geotechnical approaches are effective for enhancing the workability of clayey soil.

With advances in ground improvement, several common techniques have been modified, including vibro substitution with stone columns and encased stone columns (Souza et al. 2023). These techniques can create a reinforced ground with either partially or fully penetrated columns beneath the soil, depending on the column design. Bin Hasan et al. (2014) used partially and fully penetrated bottom ash columns to improve the soil, minimize settlement, and increase the coefficient of compressibility. Furthermore, the improvement of soil characteristics has also been used extensively to resist lateral loading and facilitate consolidation (Wang et al. 2022). Rezaei-Hosseinabadi et al. (2022) reported that a modified stone column results in better shear strength enhancement, as the performance of steel slag composite is better than sand composite. Regardless of the type of substituent used, the performance of a stone column is strongly influenced by the width, length, column arrangement, column intervals, and the condition of the underlying soil (Jun Shen et al. 2024). Mohanty and Samanta (2015) conducted a numerical study and found that the thickness of the first layer of soil influences the performance of stone columns, while Menon et al. (2021) demonstrated that a stone column can withstand twice the exerted pressure as compared to non-reinforced ground. Although the use of granular columns can improve the soil's characteristics, sustainable development has always been a concern when it deals with non-renewable resources. This issue can be resolved by using recycled materials and industrial waste. Previous studies have utilized bottom ash, furnace slag, polypropylene (PP), and polyethylene terephthalate (PET) for civil engineering purposes, specifically in advanced concrete and soil enhancement (Hasan et al. 2021; Meenakshi and Mohini, 2020; Mohammed et al. 2021; Shen et al. 2023). The results of these studies highlight the value of employing green material or potential waste for ground remediation based on the column installation approach.

With regard to the cost and environmental concerns, these have a significant role in the exploitation of existing renewable resources such as PET disposal waste. The use of of PET plastic as a renewable source is of particular value in construction applications, since it is cost-effective and environmentally friendly (Moses et al. 2016). Numerous studies have reported that PET fiber of different sizes produced a better-quality product, for instance, in improving concrete ductility and enhancing the cohesion and friction angle of soil (Meenakshi and Mohini 2020; Moses et al. 2016). As reported by Malafatti-Picca et al. (2023), approximately 360 million tons (Mt) of polymers are manufactured globally, and about 400 million PET bottles are produced annually. This shows the correct predicted values, where plastic production was recorded at only 204 Mt, and increased by almost 50% to 300 Mt in 2013. Of the manufactured PET products, it is estimated that 8 to 9 Mt will be discarded in the oceans, thus necessitating the development of effective strategies to manage these disposed plastics. In Malaysia, a study report shows that the rate of plastic recycling is only about 8.4%, while 75.8% of plastics are disposed of in open spaces and landfills (EPA 2020). Similarly, Malaysia has generated about 0.94 Mt of unmanaged disposed plastic, of which 14–39% has been washed into the ocean, endangering marine life (Jambeck et al. 2015). Hence, due to the enormous quantity of plastic, researchers have proposed that plastic materials could be managed properly through microbial analysis of polymers (Malafatti-Picca et al. 2023), and act as a sustainable material in the mixture of asphalt for pavement and concrete for structures.

PET plastic is a long-chain polymer belonging to the generic group of polyesters. Terephthalic acid and ethylene glycol are both generated from oil feedstock and act as intermediates for the production of PET. The typical PET plastic is durable and shows no breakage in the unnotched impact strength test at low temperatures (Moses et al. 2016). This strength is attributable to the second polymerization stage that PET undergoes, which removes all the volatile impurities, making it tough and creep-resistant (Moses et al. 2016). PET plastic may be utilized as a substitute for cementitious material, and as an alternative to non-renewable coarse aggregate in soil improvement applications (Ferreira et al. 2021). According to Meenakshi and Mohini (2020), ground PET fiber has a particle size of 1.18 mm, which is suitable for the category of coarse aggregate, where it can increase the soil friction angle by reducing the vertical and horizontal deformation of granular columns (Ferreira et al. 2021). As noted by Sulyaman et al. (2016), the reuse of PET plastic or different types of plastic adds economic value, increases the green index of a structure, and prevents environmental pollution.

Consequently, there are myriad advantages to utilizing PET plastic, especially in the construction industry. The replacement of a certain portion of traditional construction material represents the greatest potential usage, preventing the accumulation of plastic waste from human consumption. The research data prove to society that PET plastic can be used as an alternative, reducing the rate of resource exploitation. Focusing on the geotechnical industry, the utilization of PET plastic in soil and ground improvement has generated momentum among researchers as well as industry players, where this application must come with a complete and systematic set of data regarding the engineering properties of PET plastic in association with kaolin clay. Past research has shown that PET plastic can be used as alternative material based on certain parameters (Ferreira et al. 2021); however, no studies have examined the use of PET plastic specifically for ground improvement in treating problematic clay, and no statistical analysis has been examined. Therefore, the current work addresses the installation of single and group PET columns to treat soft clay soil by assessing the rate of shear strength improvement through the unconfined compression test (UCT). In addition, the function of these columns is assessed via the triaxial test and unconsolidated undrained (UU) test to determine the soil friction angle and cohesion. Therefore, three hypotheses are proposed: (1) the installation of PET columns regardless of the category (single or group) can modify the engineering properties of soft clay soil; (2) the installation of PET columns regardless of the category (single or group) can resolve the water accumulation issue through the enhancement of the shear strength of soil; and (3) a systematic model can be generated to represent the relationship between the relevant independent variables. To test these hypotheses, the objectives of the study are to (1) examine the engineering properties of the materials used (kaolin clay and PET plastic); (2) assess the undrained shear strength of kaolin clay after the installation of single and group PET columns; and (3) generate regression equations to correlate the shear strength parameters of kaolin clay reinforced with various dimensions of single and group PET columns at varied effective confining pressure.

2 Materials and methods

2.1 Materials

The materials used in the study were PET plastic and kaolin clay S300, as shown in Fig. 1. PET plastic sand was obtained from Glowmore Express Sdn Bhd (Selangor, Malaysia), which is the largest recycling plastic material company in Southeast Asia and the leader in the recycling industry in Malaysia. The company supplies different types of raw plastics worldwide, such as polypropylene (PP) and PET plastic. PET plastic was purchased at a unit cost of RM 1.00 (≈ 0.23 USD)/kg, and the current research utilized around 2 kg to complete the entire experimental work, because several trials were undertaken.

As mentioned, kaolinite is a clay mineral composition generally found in white powder form. It is hydrophilic and can be easily turned into a slurry solution when mixed with water, turning the color to gray-white. The kaolin powder was purchased from Kaolin (M) Sdn Bhd (Puchong, Selangor). Kaolin powder grade S300 was purchased at a rate of RM 1.20 (≈ 0.28 USD)/kg, and the total utilized was around 12 kg to prepare identical soft clay samples using the compaction method in a specific mold.

3 Setup of experimental procedures

3.1 Preparation of required material

The engineering properties of the materials and column samples including Atterberg limits, particle size distribution (PSD), specific gravity, compaction properties, coefficient of permeability, relative density, angle of shearing resistance, shear strength, and soil friction angle were analyzed according to American Society for Testing and Materials (ASTM) standards and British Standards (BS) in Table 1. Kaolin powder S300 in air-dried condition was mixed with 20.0% water by volume per the compaction curve. The uniformity of the process was ensured by using the same mass of kaolin (280 g), which was thoroughly mixed in a tray and then poured in three layers into a standard-size mold. The process proceeded with the compaction of kaolin, where each layer was hit with five blows using a 3.1 kg customized steel hammer. The mold was specifically designed for column preparation, with a diameter of 50 mm and height of 100 mm (Fig. 2a).

Fig. 1 Manufacturing companies for PET plastic and kaolin clay

Regarding the preparation of PET materials, the labels attached to the PET containers were removed, and the materials were washed with clean water and dried under sunlight for 24 h to remove the water molecules and impurities that were stuck on the PET surface before proceeding to the grinding process by the recycling center (see Fig. 2b). The PET plastic was randomly ground into into several sizes, and dry sieving was then carried out. According to the sieve analysis standard, the largest amount of PET plastic retained on the respective sieve size was recorded, which was 1.18 mm. This value was referenced to previous findings, in which Shen and Hasan (2025) reported using the same grain size of PET material, and Haider et al. (2023) found that the size of PET should not be greater than 2 mm because it will influence the column dimension ratio and the boundary limit of the specimens. This is coherent with the current study, as it considers the ratio of D/d, which is discussed in sub Section 3.3. Furthermore, the relative density of PET plastic used to fill the hole of the columns for obtaining the shear strength, soil friction, and cohesion from the unconfined compression test (UCT) and unconsolidated undrained triaxial test was 0.48 Mg/m^3 or 56.59%, based on the minimum, maximum, and in situ dry density. The PET column samples were prepared in general with a height of 100 mm and a diameter of 50 mm in a standard-size mold, which was further modified based on the hole drilling design process.

The PET column diameter varied from 10 to 16 mm, and the design was considered according to the diameter of PET plastic. The largest particles retained on the 1.18 mm sieve

Table 1 Test standards and methods used to test materials and column samples

Material	Test	Standard/method
Kaolin	Atterberg limit	
	- Liquid limit	BS 1377: Part 2: 1990: 4.3
	- Plastic limit	BS 1377: Part 2: 1990: 5.3
	Particle size distribution	
	- Hydrometer	BS 1377: Part 2: 1990: 9.6
	Compaction	
	- Standard compaction	BS 1377: Part 4: 1990: 3.3
	Specific gravity	BS 1377: Part 2: 1990: 8
	Permeability - Falling head	BS 1377: Part 5: 1990
Polyethylene terephthalate	Particle size distribution	
	- Sieve	BS 1377: Part 2: 1990: 9
	Specific gravity	BS 1377: Part 2: 1990: 8
	compaction - Standard compaction	BS 1377: Part 4: 1990: 3.3
	Permeability	
	- Constant head	BS 1377: Part 5: 1990
	Relative density	BS 1377: Part 4: 1990: 4
Kaolin [reinforced with polyethylene terephthalate column(s)]	Unconfined compression	ASTM D 2166
	Unconsolidated undrained triaxial	BS1377: Part 7: 1990

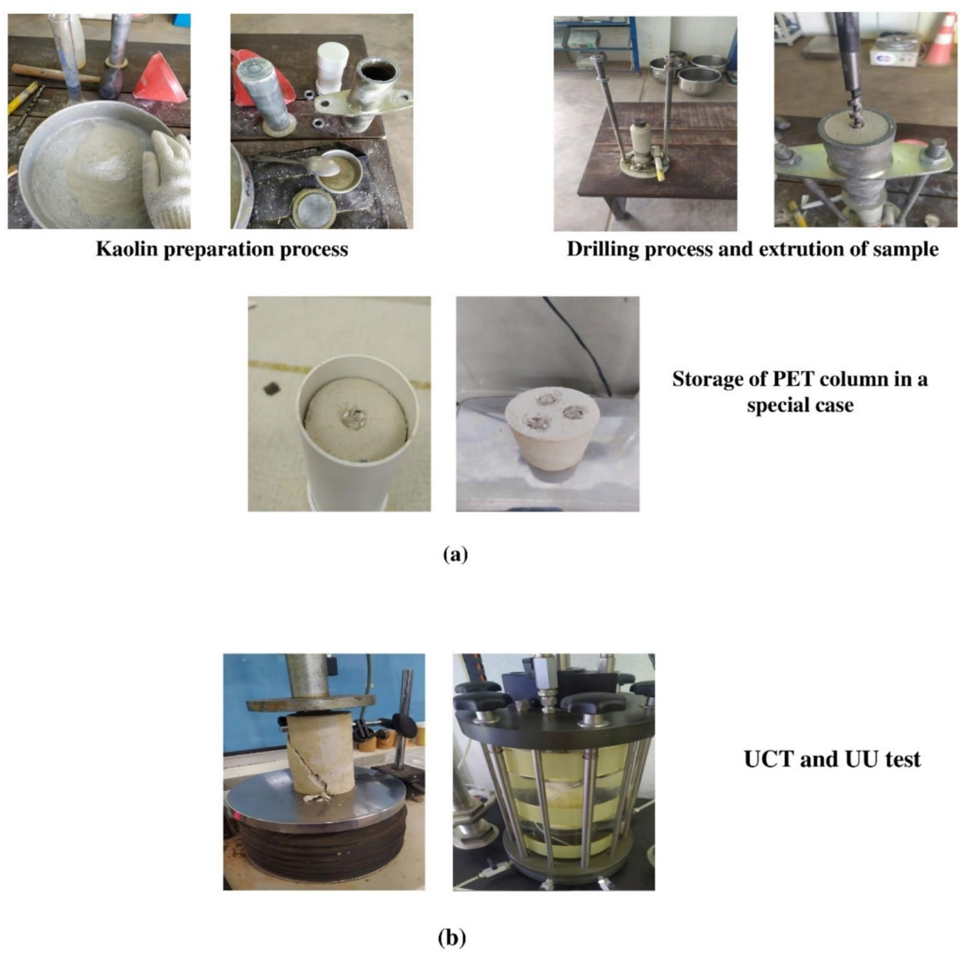


Fig. 2 Flowchart of the (**a**) preparation of the kaolin sample for the PET column, (**b**) examination of the unreinforced and reinforced kaolin sample

were obtained from the sieve analysis test using sieve sizes from 0.063 mm to 6.30 mm. The PET plastic retained on the 1.18 mm sieve was collected, the substitution method was applied to replace the drilled kaolin quantity after the drilling process that produced the desired diameter, and the estimated quantity of PET plastic (1.18 mm) was computed based on the in situ density of PET plastic, as illustrated in Table 2.

3.2 Installation of PET column

The process began with the mixing of the kaolin and compacting the samples in the mold, where the unreinforced samples (no PET column) were produced (see Fig. 2a). The reinforced samples were kept in the mold while drilling was conducted to prevent the cracking of the sample; customized drill bits of 10 mm or 16 mm were used to drill the holes in the sample. The drilling depth was either 60 mm or 80 mm for the partially penetrating column and 100 mm for the fully penetrating column. After the drilling process, the measured quantity of PET plastic, as indicated in Table 2, was poured into the drilled hole using the raining method, which prevents material waste during pouring, ensuring the accuracy of PET weight in the sample. The reinforced sample was then extruded and transferred to a special case to store for at least 24 h to stabilize the moisture content inside the sample. By repeating the above procedures, the disturbance of kaolin clay was reduced, obtaining identical PET columns.

3.3 Detailed configuration of the PET column

Figure 3 shows the configuration of the single and group PET columns. The design is classified into two categories: (1) center placement of a single PET column and (2) triangular arrangement of PET columns. The center design features a PET column with equal spacing between the upper, bottom, left, and right boundaries (Fig. 3a). The triangular pattern for 10 mm PET columns shows a distance of approximately 7.5 mm between the PET column and the outer edges of the sample. The 16 mm PET columns shorten the distance to 3 mm, with a distance of 4.5 mm from the outer edge (Fig. 3b). This ensures that the lateral load can be expediently transmitted within the defined boundary, in either centric or triangular formation. Subsequent assessments consider the ratio of the PET column, including area replacement ratio (A_{rr}), height penetrating ratio (H_{pr}), column height-to-column diameter ratio (H_{dr}), and volume replacement ratio (V_{rr}).

The ratio of the PET column width to the PET particle diameter *D*/*d* is also important. Different *D*/*d* ratios have different effects on the performance of PET columns due to the air voids that exist between the PET plastic. The current study obtained *D*/*d* ratios varying from 8.47 to 13.56, but a previous study proposed a ratio of the prototype as the test model. The width of the column varied from 10 to 16 mm, where the ratio lies within the range. Due to the limits of a small-scale laboratory, the increased column width is not practical, as this may cause the test model to fail. The computed A_{rr} values obtained for the single samples ranged from 4.00% to 10.245%, while that for the group samples ranged from 12.00% to 30.72%. The direct penetrated PET reinforcement, or the H_{pr}, has the same ratio of 0.6 and 0.8 for the partially penetrating column, and 1.0 for a fully penetrating column for both categories.

Table 2 Mass of PET required with respect to the column volume and density

Column diameter (mm)	Column height (mm)	Volume (mm^3)	Density (g/ cm^3)	Mass of PET required (g)
10	60	4712.39	0.48	2.26
	80	6283.19		3.01
	100	7853.98		3.77
16	60	12,063.72		5.79
	80	16,084.95		7.72
	100	20,106.19		9.65

3.4 Evaluation of the material physical properties

Generally, both kaolin clay and PET plastics must be tested under the Atterberg limit, PSD, relative density, and pycnometer tests (see Fig. 4a). The plastic and liquid limit of kaolin clay was studied, and the plasticity index value was calculated based on the numerical difference between the plastic and liquid limit to analyze the state of kaolin clay based on the standard, as shown in Table 1. The plasticity index is also known as plasticity consistency, in which the values can determine the state of fine-grained soil, varying between four states: solid, semi-solid, plastic, and liquid. Through the cone penetration test, the liquid limit can be assessed, while the plastic limit is determined by drying the wet soil.

The PSD for fine-grained soil (kaolin clay) that passes through a 63 µm sieve was assessed through a hydrometer test, while coarse-type material (PET plastic) was sieved at 6.30 mm, 5.00 mm, 3.35 mm, 1.18 mm, 0.6 mm, 0.3 mm, 0.15 mm, and 0.063 mm based on BS 1377: Part 2: 1990: 9. The results obtained are presented in a semi-logarithmic graph to determine the size trend of the material. This graph, based on the USCS (Unified Soil Classification System) and AASHTO (American Association of State Highway and Transportation Officials), is vital for soil classification.

The pycnometer test was executed based on the standard in Table 1, measuring the specific gravity of kaolin clay and PET plastic. The sample was poured into a small

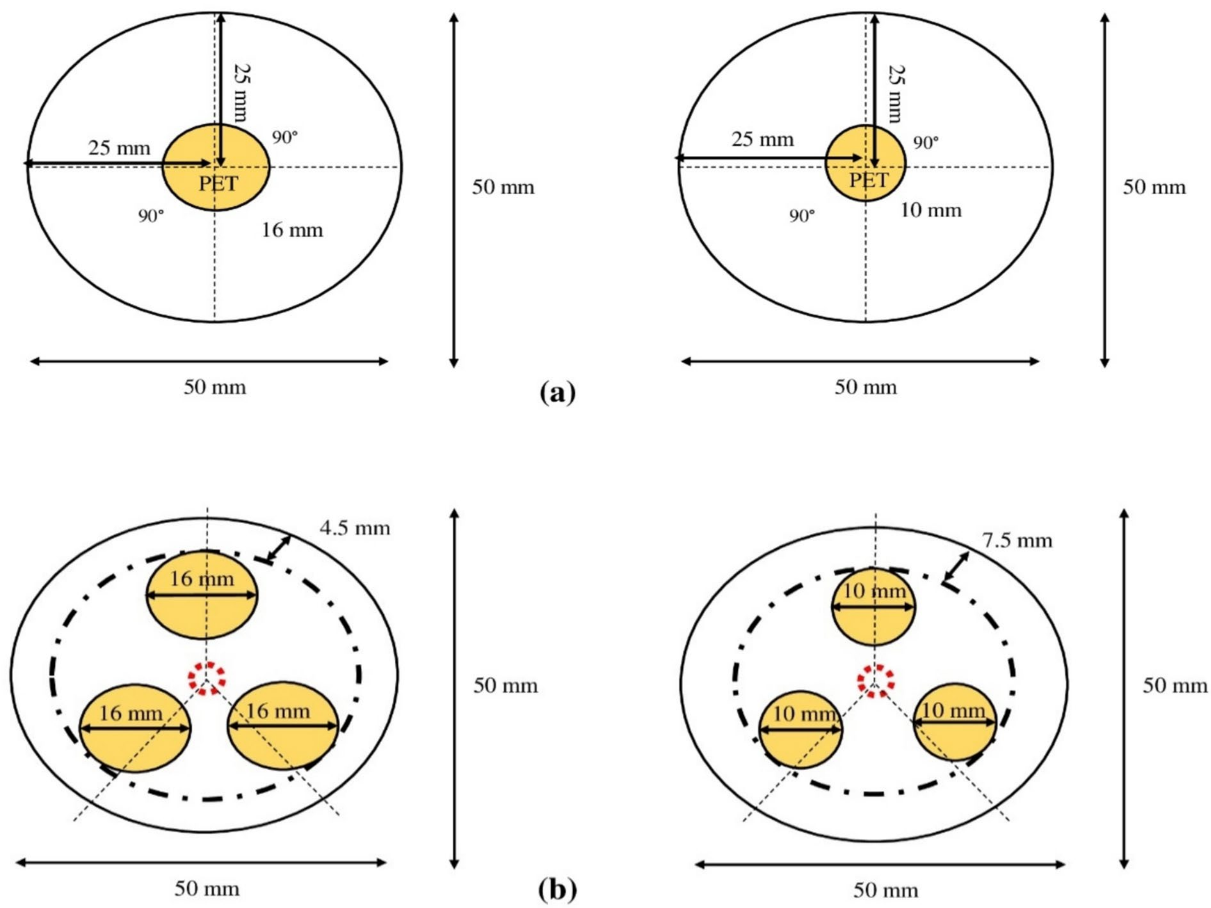


Fig. 3 Detailed arrangement of (**a**) the single PET column and (**b**) the group PET columns

pycnometer before filling up half the volume of the container, and leaving it inside the chamber for 1 day to eliminate the air inside the container. This was followed by measuring the weight of the pycnometer containing the sample. The value of specific gravity was computed using Eq. 1.

$$G_s = \frac{(W_2 - W_1)}{\left(W_4 - W_1\right) - (W_3 - W_2)} \tag{1}$$

where G_s is the specific gravity, w_1 is the mass of the pycnometer, w_2 is the mass of the pycnometer with the sample, w_3 is the mass of the pycnometer with the sample and water, and w_4 is the mass of the pycnometer with water.

The relative density was determined by measuring the maximum and minimum dry density of coarse material upon vibration in a vibrating table. The mold (with predetermined volume) was filled with material (such as PET plastic), measuring the weight and the height of the mold afterward. After vibration, the relative density of the PET plastic was computed based on the difference in height by applying Eq. 2.

$$D_r = \frac{\gamma_{max}(\gamma - \gamma_{min})}{\gamma\left(\gamma_{max} - \gamma_{min}\right)} \times 100\% \tag{2}$$

where D_r is the relative density (expressed in percentage), γ is the unit weight of the material, γ_{max} is the maximum unit weight of the material, and γ_{min} is the minimum unit weight of the material. Figure 4a shows the setup for the experiments to assess the physical properties of the materials.

3.5 Evaluation of the material mechanical properties

In this section, two major mechanical parameters—compaction and hydraulic conductivity—are examined (see Fig. 4b). Compaction properties indicate optimum moisture content (OMC) or maximum dry density (MDD) values, which can be ascertained through standard Proctor or compaction test by BS 1377; Part 4: 1990; 3.3. These two properties are related to each other by plotting a compaction curve, where the maximum point of the curve generates the values. The initial part of the test involves the compaction of three layers of kaolin clay using a 2.5 kg free-falling hammer, where each layer is hit by

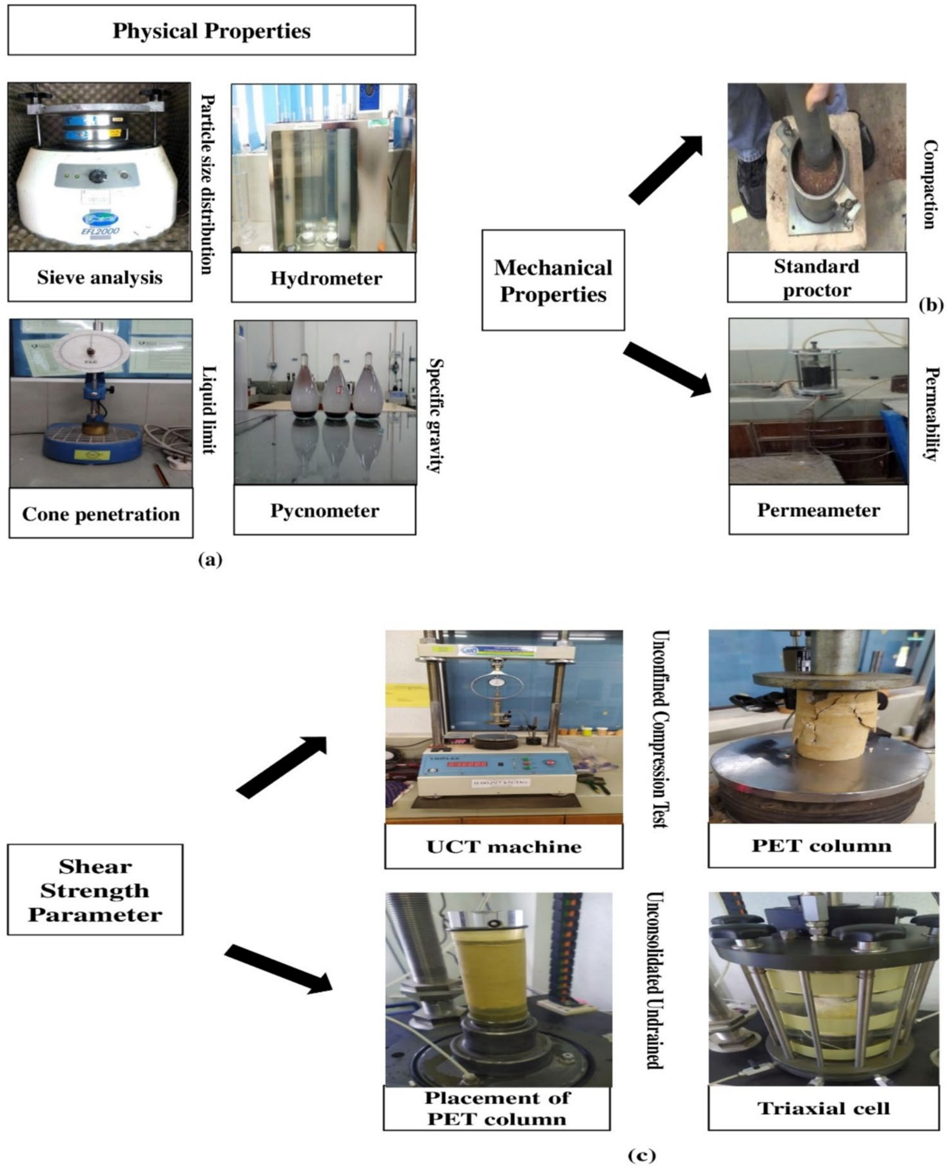


Fig. 4 Experimental procedures for evaluation of (**a**) physical properties, (**b**) mechanical properties, and (**c**) shear strength parameters

30 blows, and the measurement distance is about 30 cm above the layer from the tip of the hammer.

The coefficient of permeability, or hydraulic conductivity, of PET plastic was evaluated by employing the constant head test, as the PSD shows a coarse-aggregate type of material based on the standard in Table 1. The value of this specific parameter is acquired after a certain time by clustering the water data from the model test. The fine aggregate kaolin clay was inspected using the data from the falling head test, where a diameter of 82 mm was used as the parameter during the test.

3.6 Evaluation of the shear strength parameters for the single and group PET columns

To assess the shear strength parameters, the relevant geotechnical UCT and UU tests were executed, as shown in Fig. 4c. To ensure the uniformity and accuracy of the results, (1) the prepared PET columns were made identical by fixing the kaolin at a constant 280 g, (2) the density of PET plastic was kept at 0.480 g/cm^3, and (3) the density of kaolin clay used was 0.1540 g/cm^3.

The UCT was executed following ASTM D 2166 to obtain the shear strength value, where the sample was sheared at a constant rate of axial deformation, and it was terminated when column failure occurred, for instance, bulging of the column. Since the UCT machine exerts axial loading towards the upper part of the sample with zero effective confining pressure, the axial load and strain are recorded as displayed in the indicator. The PET columns tested under the UCT machine have A_{rr} values of 4.00%, 10.24%, 12.00%, and 30.72%, where these samples comprise different heights of installed PET columns of 60 mm, 80 mm, and 100 mm, while the A_{rr} is zero for the control sample (or no PET reinforcement). The current study categorizes the sample into 13 batches, where each batch has three samples with different PET column penetrating heights, making up the total 39 samples needed to perform this test. The primary objective of the UCT is to assess the shear strength parameters, where doubling the value of undrained shear strength gives the undrained compressive strength. Similarly, Eq. 3 shows that the soil cohesion is equivalent to dividing the undrained compressive strength by half.

$$S_u = \frac{q_u}{2} \text{or } c = \frac{q_u}{2} \tag{3}$$

where S_u is the undrained shear strength, c is the soil cohesion, and q_u is the undrained compressive strength.

The UU test, which is under the triaxial test series, functions by adjusting the effective confining pressure between 100 kPa, 200 kPa, and 400 kPa. To analyze the performance of PET columns under this test, the chamber fluid was filled and covered the sample, which was fixed inside the cell system. By setting the axial strain limit at 20%, the cell system terminates once the value has been reached. The chamber fluid inside the cell system was discharged, and the triaxial cell was dismantled and moved to a safe place. Then the machine was shut down, and the next sample was tested. The shear strength parameter of the PET columns was analyzed and computed following Eq. 4.

$$\tau_f = c + \sigma \tan\varphi \tag{4}$$

where τ_f is the shear strength, c is the soil cohesion, σ is the normal stress summation, and φ is the soil friction angle.

3.7 Statistical analysis

The statistical analysis was implemented using one-way analysis of variance (ANOVA) via Microsoft Excel. The analysis was performed to differentiate the engineering properties of unreinforced and reinforced specimens, which included physical and mechanical properties. In addition, Fisher's least significance difference (LSD) test was adopted after the ANOVA. This examination method was used as a post hoc analysis to identify which group of data means were significantly different from each other, at the level of $p < 0.05$. In addition, the correlation of the shear strength parameters between the physical factors of soil was developed with the assistance of Pearson's correlation analysis, measuring its strength and direction of relationship. Error bars were displayed to represent the variability of the data, expressing the significant difference in results between the unreinforced and reinforced specimens. The regression analysis to establish a relation between the shear strength parameters of soils with different dimensions of PET columns was achieved following Eq. 5.

$$y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \cdots + \beta_{p-1} x_{i,p-1} + \varepsilon \tag{5}$$

where y_1 and x_1 are the independent variables, β_0 is the intercept, β_1, β_2, …, β_{p-1} are the coefficients of regression for the explanatory variables, and ϵ is the error term.

4 Results and discussion

4.1 Physical properties of the materials

The PSD of both materials was analyzed by the hydrometer test and sieve analysis, as depicted in Fig. 5a and b, respectively. Figure 5a demonstrates the range of the particle diameter of kaolin clay, where it lies within 0.001–0.0625 mm, which classifies it as fine-grained soil. According to the value, it is classified to the category of A-4 in AASTHO, signifying that it is a low-plasticity silt soil. This result is identical to the classification of kaolin clay by Hasan and Yee (2024), which identified an inorganic clay with medium plasticity.

For coarse-type material, the plotted graph shows that the majority of the ground PET plastic lies within the range of 1–6 mm, and the majority (more than 50%) retained on a particular sieve size was on the 1.18 mm sieve. Based on the AASTHO guidelines, it is under the group A-1 and classified as A-1-a, or the PET plastic behaves like sand or gravel-type material. The C_c and C_u values obtained are 1.25 and 2.22, respectively, as corroborated by another study which obtained C_c and C_u values for PET of 1.2 and 2.4, respectively (Arulrajah et al. 2020), which categorized the PET in a similar soil classification. Furthermore, the distribution curve of PET plastic displays a similar trend of well-graded properties, which is identical to the study by Thorneycroft et al. (2018). The study results show that the majority of PET plastic was retained on a specific sieve, where the PET fragment used in the study was in the range of 0.5–4 mm. These results indicate that the PET obtained from Glowmore Express Sdn Bhd shows identical soil classification to that obtained following the standard tests, although the PET plastic can be generated and produced from different sources and prepared by other methods.

The following analysis concerns the Atterberg limit (see Fig. 6), which is only for fine-grained soil and kaolin clay, due to the standard requirement, and thus PET plastic was not included. The values obtained from the liquid limit (20 mm cone penetration test) and plastic limit are 35.00% and 29.00%, respectively. Figure 6a shows the relationship between the cone penetration distance and its moisture content, while Fig. 6b depicts the USCS chart or the plasticity

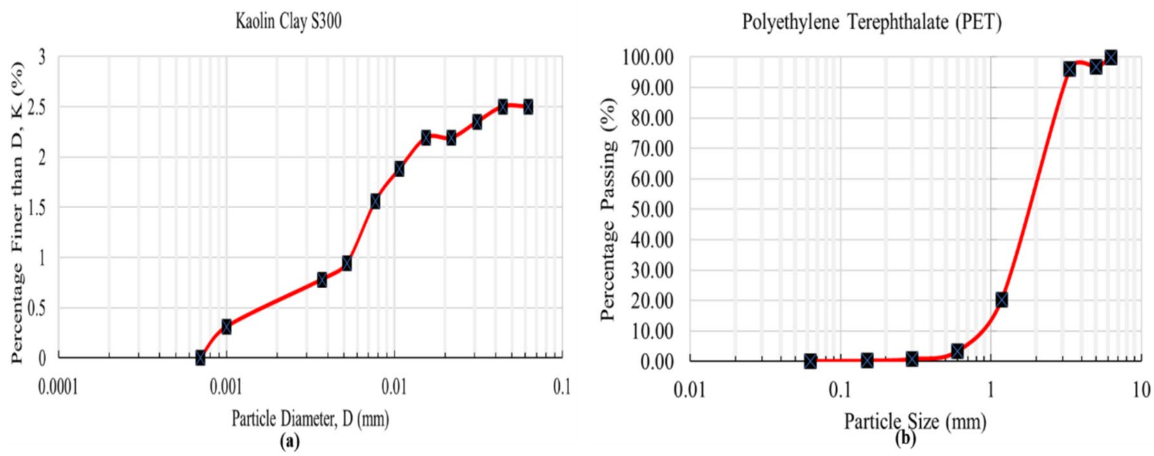


Fig. 5 The particle size distribution of (**a**) kaolin clay S300 and (**b**) PET plastic

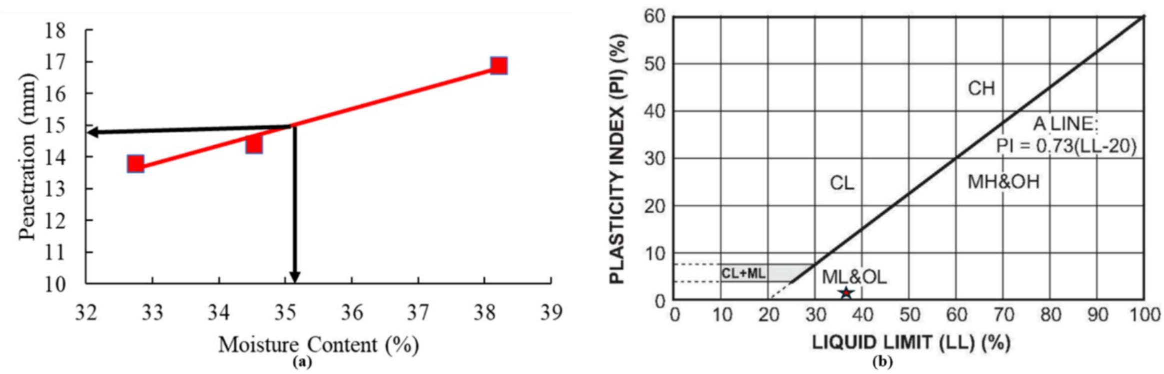


Fig. 6 Atterberg limit: (**a**) 20 mm cone penetration, (**b**) USCS chart for soil classification

chart for the classification of kaolin. Based on the USCS, the combination of the data gives the value of ML (red star), which is below the "A" line. ML means the kaolin clay is low-plasticity silt, similar to the result from a previous study (Syamsul et al. 2023).

Another physical property is the relative density, and the test was only for PET plastic due to its coarse behavior. By measuring the difference in elevation before and after vibration, minimum and maximum dry density values of 0.430 g/cm^3 and 0.530 g/cm^3, respectively, were obtained for the PET plastic. In addition, the in situ density or the density of PET plastic was acquired by employing the raining method, where the PET density values from different sets of data were averaged, obtaining a value of 0.48 g/cm^3 or 56.59%. Nonetheless, it is significant to note that the voids that exist between the PET particles can function as vertical drains, easing the water accumulation issue by dissipating the excessive pore water pressure.

The specific gravity values for kaolin clay and PET plastic are 2.62 and 1.40, respectively, as obtained via the small pycnometer test. The result for kaolin clay is similar to that reported by Bin Hasan et al. (2011), who obtained a value of 2.65, which shows a difference of 0.03. However, Syamsul et al. (2023) and Bozyigit et al. (2021) reported the same result as the current study, 2.62. For the PET plastic used in the study, which was in the form of sand from the recycling center, the specific gravity may vary slightly due to the impurity content in the material. Bozyigit et al. (2021) obtained a value of 1.38 by using PET plastic average thickness of 0.05 mm, while Arulrajah et al. (2020) obtained 1.37. As reported by Jaafar et al. (2018), the increase in carbon volume percentage in the tested material can cause a decrease in specific gravity, as the higher carbon volume makes the specimen lighter, reducing the iron oxide content in the material. The specific gravity of the PET indicates the porosity of the material. Kim et al. (2005) reported that low specific gravity of a material shows that it has a higher percentage of pores and a popcorn-like texture of particles within the specimen. The value indicates that the higher amounts of porous particles cause a reduction in the specific gravity of PET plastic, proving it is an inversely proportional trend for this factor.

4.2 Mechanical properties of the materials

This section discusses the compaction properties of kaolin clay, which include the OMM and MDD values, as illustrated in Fig. 7. Referring to the compaction curve, the values for OMM and MDD are 20.0% and 1.54 Mg/m^3, respectively. The previous study from Bin Hasan et al. (2015) obtained an OMM value of 19.50% and MDD of 1.53 Mg/m^3, which are slightly different from the current study. The current OMM and MDD results are also similar to the values of 18.40% and 1.58 Mg/m^3, respectively, reported by Syamsul et al. (2023). Compaction affects both parameters, as it will alter the air void content inside the material. In addition, the presence of foreign material or impurities and the shape of the soil inside the kaolin clay can result in fluctuating values.

The coefficient of hydraulic conductivity for both materials was acquired through the falling head and constant head tests, with values of 4.197×10^{-8} m/s and 2.503×10^{-4} m/s, respectively. Based on the values obtained, the kaolin clay is categorized as less permeable soil, while PET plastic is a permeable material, where the value of PET plastics is almost twice that of kaolin clay. Problematic soil which exhibits weak engineering properties is typically fine-grained soil (kaolin and silt) due to the impermeability characteristic that often leads to a lower coefficient of permeability. PET plastic, which behaves like sand or gravel, shows better flexibility, ranging from weak to strong, as expressed in terms of its permeability, signifying that it is capable of acting as additional drainage to relieve the water accumulation issue. Bozyigit et al. (2021) concluded that PET plastic, which acts as reinforcement, forces clay to show ductile behavior, thus enhancing the mechanical behavior of clay.

4.3 Effect of PET column installation on shear strength

This section discusses the performance of the control sample (no PET reinforcement), single, and group PET columns, which enhance the resilience of kaolin clay towards imposed axial loading by improving its shear strength, as depicted in Fig. 8a. The values were obtained by averaging three identical specimens for control, single, and group specimens. The control sample functioned as the calculation reference, with a value of 11.71 kPa (see Fig. 8b), and the shear strength improvement rates were computed using this value. For a single PET column, the average shear strength value varied from 15.87 kPa to 15.12 kPa, then dropped to 14.93 kPa with column height of 60 mm, 80 mm, and 100 mm. In contrast to group PET columns, the average shear strength value does not show a similar trend to the single group: an increasing trend was recorded when the column height was increased from 60 to 100 mm, with values of 14.17 kPa to 18.14 kPa, and then a further increase to 18.33 kPa. The values are further translated into shear strength improvement rates of 21.00% to 54.91%, and then to 56.53%. Among the single category, the PET column with 16 mm diameter and 100 mm height or fully penetrated 16 mm PET column produced the largest shear strength improvement (values in green), while the lowest value was also recorded in this category when the PET column height was 60 mm. Previous studies that utilized bottom ash as reinforcement material proved that the fully penetrated single column produces the largest improvement value for the kaolin clay (Hasan et al. 2021; Jun Shen et al. 2025). To further classify and understand the details, a PET column with 16 mm diameter and 100 mm height generates the largest enhancement of kaolin clay among the single PET column category.

Furthermore, the group PET columns were constructed with a triangular configuration, as depicted in

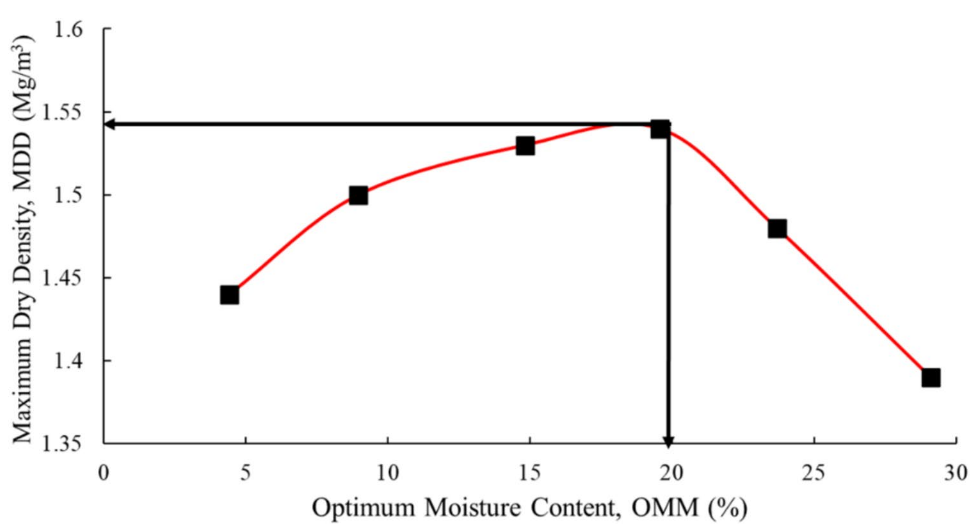
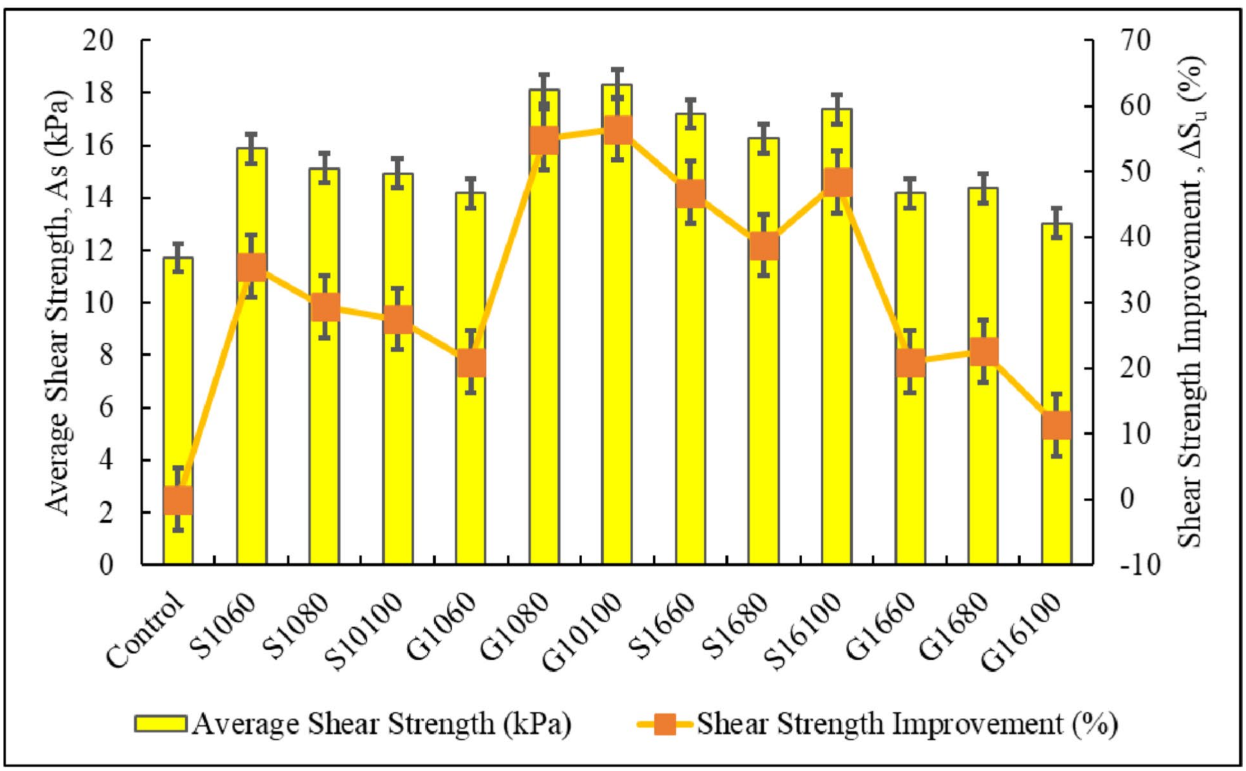


Fig. 7 Evaluation of OMM and MDD values of the kaolin clay

PET column category	Column diameter (mm)	Column height (mm)	Unconfined compression stress, q_u (kPa)	Shear strength, S_u (kPa)	Shear strength improvement, ΔS_u (kPa)
Single (1 PET column)	10	60	31.75	15.87	35.52
		80	30.24	15.12	29.37
		100	29.86	14.93	27.49
	16	60	28.35	14.17	21.00
		80	36.28	18.14	54.91
		100	36.66	18.33	56.53
Group (3 PET columns)	10	60	34.39	17.19	46.79
		80	32.50	16.25	38.77
		100	34.77	17.38	48.42
	16	60	28.35	14.17	21.00
		80	28.72	14.36	22.63
		100	26.08	13.04	11.35

(a)



(b)

Fig. 8 Results of the UCT. (**a**) Shear strength improvement of kaolin clay after the installation of single or group PET columns. Green values = the highest recorded improvement values; red values = the lowest recorded improvement values. (**b**) Comparison between the average shear strength (A_s) and shear strength improvement (ΔS_u)

Fig. 3. Referring to Fig. 8, the average shear strength values recorded for the 10 mm group PET columns were 17.19 kPa, 16.25 kPa, and 17.38 kPa for column height of 60 mm, 80 mm, and 100 mm, translating to shear strength improvement of 46.79%, 38.77%, and 48.42%, respectively. Similarly, the 16 mm group PET column improved up to 14.17 kPa, 14.36 kPa, and 13.04 kPa for height of 60 mm, 80 mm, and 100 mm, representing improvement rates of 21.00 kPa, 22.63 kPa, and 11.35 kPa, respectively. A comparison of this category reveals that the lowest shear strength improvement (values in red) occurred when a 16 mm column with 100 mm height was employed for all the samples tested in this category. Conversely, a PET column with 10 mm diameter and 60 mm height produced the highest improvement rate. Analyzing the parameter values using the single and group PET columns, the most optimum column height is 80 mm, where both categories have moderately reinforced the kaolin clay. In addition, Fig. 8 shows that the shear strength improvement rate is inconsistent, fluctuating between 60 and 100 mm column height, which has recorded either the lowest or the highest improvement rate among all the column designs. The study suggests that the shear strength of kaolin clay has been strengthened through the installation of single and group PET columns. The fluctuation of the improvement rate can be explained by the proportion of the PET content in contrast to the undrained shear strength, beyond which a certain amount will cause a reduction in strength (Bozyigit et al. 2021). As noted by Meenakshi and Mohini (2020), the value of the soil shear strength fluctuates because the material shape of PET reinforcement may hinder the reaction between the soil particles, which is coherent with the current results.

4.4 Effect of the area replacement ratio (A_{rr}) on the shear strength of kaolin clay after reinforcement with PET columns

Apart from the analysis of shear strength parameters after the installation of single and group PET columns, the column itself affected the performance. The current subsection focuses on how the area replacement ratio (A_{rr}) influences the overall function. A clear presentation of the relationship between the A_{rr} and the column design is illustrated in Fig. 9, where the column designs have A_{rr} values of 4.00%, 10.24%, 12.00%, and 30.72%, resulting in a fluctuating shear strength improvement value from 11.71 kPa to 18.33 kPa, and showing a numerical difference of 6.62 kPa by altering the design of the PET column. Analyzing this factor, the tested samples have been split into four groups, where the first group ($A_s = 15.13$ kPa) includes S1060, S1080, and S10100, and has an A_{rr} value of 4.00% showing a maximum shear strength improvement of 35.32%, which is much lower as compared to the second group ($A_s = 16.88$ kPa), which is for S1660, S1680, and S16100, having an A_{rr} value of 10.24% and recording a maximum improvement rate of 56.53%, an increase of 21.21% compared to the $A_s = 15.13$ kPa group.

The remaining groups are for the group PET columns, where the third group ($A_s = 16.94$ kPa) has an A_{rr} value of 12.00% and includes the G1060, G1080, and G10100 samples; this group produces maximum shear strength improvement of 48.42%, as demonstrated in Fig. 9, which is almost double the maximum improvement rate of the fourth group ($A_s = 13.86$ kPa), which has an A_{rr} value of 30.72%, consists of G1660, G1680, and G10100 samples, and resulted in only a 22.63% shear strength improvement. Based on Fig. 9 and the four groups, the largest shear strength improvement was produced from the second group, or a single PET column

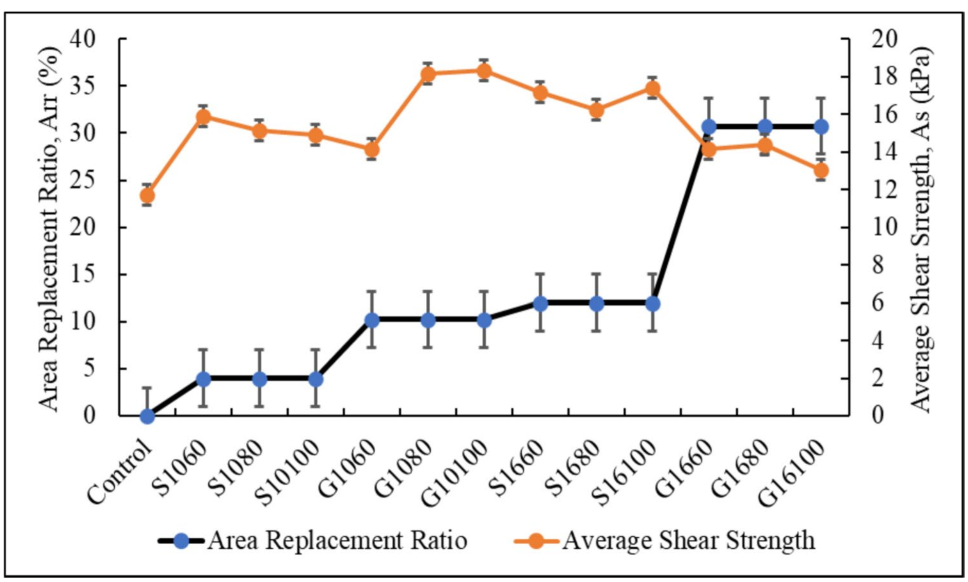


Fig. 9 The relationship between the area replacement ratio (A_{rr}) and the average shear strength (A_s) for the single and group PET columns

with an A_{rr} value of 10.24%. However, a single PET column arrangement ($A_s = 16.88$ kPa) produced a better shear strength improvement rate as compared to a triangular group arrangement of PET columns ($A_s = 16.94$ kPa), with a difference of 0.06 kPa or 0.36%. The utilization of a foreign material-made column, which serves as the reinforcement with the correspondence factor of A_{rr}, can rectify the poor properties of kaolin clay, which is supported by previous research (Najjar 2013; Rezaei-Hosseinabadi et al. 2022), where the use of a granular column promotes the soil bearing capacity, but it will obtain a different average shear strength value when the A_{rr} value is altered. The results also prove that the least improvement occurred in the fourth group, where a larger A_{rr} value disturbs the soil's original state by drilling out a large portion of the soil, therefore resulting in the shear strength reduction.

The same concept of shear strength reduction was endorsed by Hasan and Yee (2024) and Zaini and Hasan (2024), who concluded that a smaller diameter of a reinforced column causes higher confining stress in the column, producing higher stiffness of the column. A smaller-diameter column can gather all the inserted materials closely, filling up the empty air voids that exist between the materials, particularly the reinforcement material, which has a lower value of relative density (Jun Shen et al. 2025). Conversely, when the diameter increases, the confining pressure drops, resulting in a lower value of column stiffness. Referring to the A_{rr} values, the shear strength improvement increases as the A_{rr} value increases up to 12.00%, followed by a decrease in shear strength when the A_{rr} is further increased to 30.72%. When the axial loading is applied to the sample, the loading will initially spread evenly to the upper part of the column and will subsequently cause the failure of the column. The larger diameter of the column, which results in a larger value of A_{rr}, will cause the looser PET material inside the pre-drilled hole to withstand less force. Based on the existing data, this study proves that the removal and disturbance of soil significantly influence the enhancement of the kaolin clay shear strength.

4.5 Effect of the height penetrating ratio (Hpr) on the shear strength of kaolin clay after reinforcement with PET columns

The other column factor, height penetrating ratio (H_{pr}), which can affect the performance of the shear strength parameter, was inspected as shown in Fig. 10. The *y*-axis represents the A_s value of the single and group PET columns, whereas the *x*-axis represents the H_{pr} value. By using the control sample value as a base reference, the single PET column reinforcement resulted in significant improvement from 11.71 kPa to 14.17 kPa, then 15.87 kPa at $H_{pr} = 0.6$, and ranged from 11.71 kPa to 15.12 kPa, then 18.14 kPa at $H_{pr} = 0.8$. At $H_{pr} = 1.0$, it ranged from 11.71 kPa to 14.93 kPa, then 18.33 kPa. For the group PET columns, a similar trend was observed at $H_{pr} = 0.6$, where the shear strength value increased from 11.71 kPa to 14.17 kPa, then

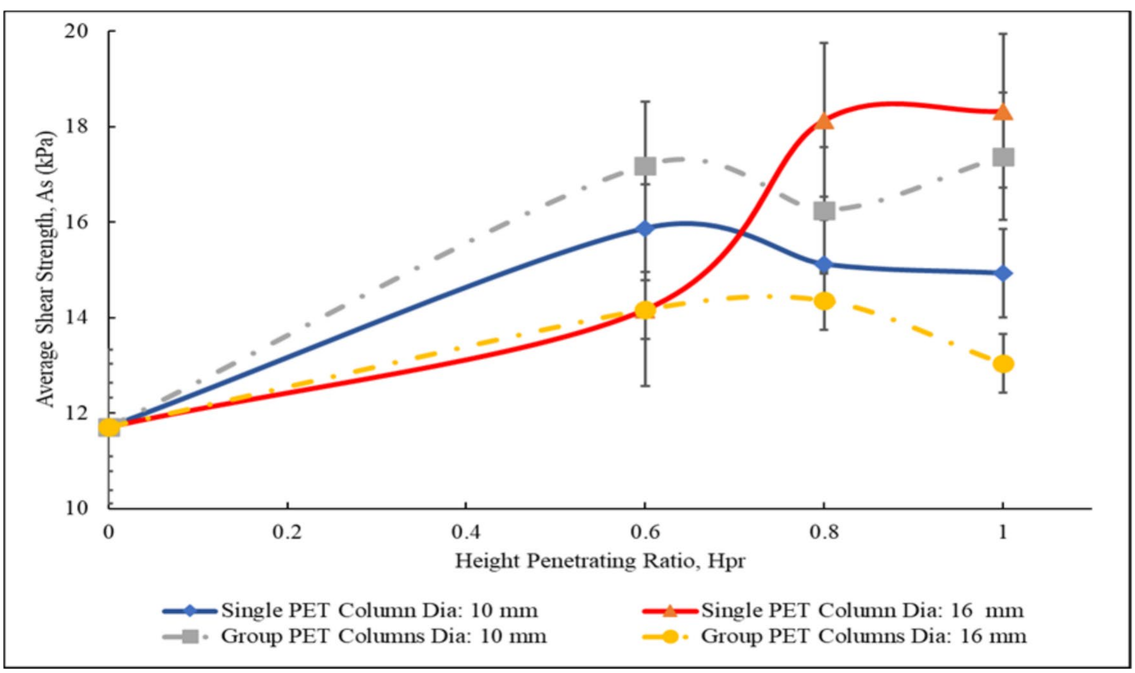


Fig. 10 The relationship between the average shear strength value (A_s) and the height penetrating ratio (H_{pr}) for the single and group PET columns

17.19 kPa. It ranged from 11.71 kPa to 14.36 kPa, then 16.25 kPa at $H_{pr} = 0.8$, and at $H_{pr} = 1.0$, the value increased from 11.71 kPa to 13.04 kPa, then 17.38 kPa. Based on Fig. 10, for single and group PET columns, the critical value of H_{pr} in this study that produced the highest shear strength improvement is 1.0. Below the critical value, the value of the recorded shear strength fluctuates within the boundary of the lowest to the moderate range, as the applied axial loading may not distribute the load completely to the entire length of the PET column. This result is supported by previous researchers: Hasan et al. (2021) reported maximum shear strength improvement when an H_{pr} value of 1.0 PP column was employed in the study, and the critical column length of the column was about 7.14 times, which was correctly predicted by Bin Hasan et al. (2015), who reported that the range should be within 5–8 times to obtain the maximum rate. The other influencing factors include the column diameter, placement position of the column, and the interaction between the soil and the PET plastic, which play an important role in improving the soil stiffness (Syamsul et al. 2023). Based on the critical H_{pr} result, a fully penetrated column will not lose its function in transmitting the applied axial loading to the bottom of the underlying clay, whereas the employment of a partially penetrated column will expose the unreinforced soil on the bottom of the sample to the high risk of column failure.

As indicated in Fig. 10, a general trend can be observed where the increase in H_{pr} leads to an increase in shear strength; however, the H_{pr} of the single and group PET columns should not be applied directly as the major factor in influencing the improvement rate, since it does not solely rely on this parameter. There was a certain amount of soil being replaced with PET plastic, which was inserted beneath the kaolin clay, resting on the ambient soil which helped in increasing the strength. The data obtained from the single and PET columns in terms of the H_{pr} value can only be classified as substantial. An optimum diameter of a granular column mobilizes a higher stiffness that leads to higher strength and shows better performance as compared to a larger granular column diameter (Rezaei-Hosseinabadi et al. 2022).

4.6 Effect of the column height-to-column diameter ratio (Hdr) on the shear strength of kaolin clay after reinforcement with PET columns

The effect of column height-to-column diameter ratio on the kaolin shear strength was assessed and plotted in Fig. 11, thus demonstrating the average shear strength of kaolin clay after being reinforced with single and PET group columns, and the average shear strength against the column height-to-column diameter ratio (H_{dr}). A comparison of the data from the control sample (see Fig. 11) indicates that the highest shear strength improvement was obtained with a critical column length of 1.0 for all sample categories. At $H_{dr} = 6.25$, the single PET columns had an average shear strength of

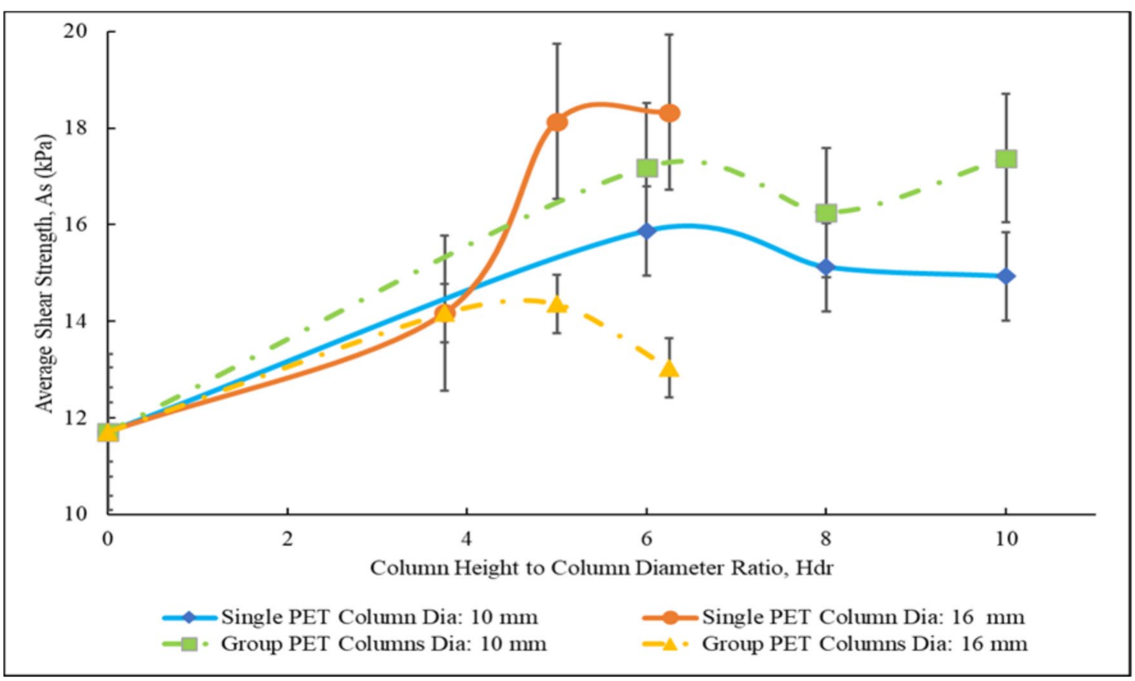


Fig. 11 The relationship between the average shear strength value (A_s) and the column height-to-column diameter ratio (H_{dr}) for the single and group PET columns

18.33 kPa, and the group PET columns had an average shear strength value of 17.38 kPa. Furthermore, the highest average shear strength of 18.33 kPa after the installation of the PET column was obtained with the S16100 design at $H_{dr} = 6.25$, and the lowest average shear strength (13.04 kPa) was observed with the G16100 design at $H_{dr} = 6.25$. The results indicate that the shear strength of kaolin clay using single or group PET columns was effectively enhanced, as expressed in terms of average shear strength. Exceptions included G16100 ($H_{dr} = 10$), G1660 and S1660 ($H_{dr} = 3.75$), and G1680 ($H_{dr} = 5$) with average shear strengths below 15 kPa, at 13.04 kPa, 14.17 kPa and 14.36 kPa, respectively. Based on the above analysis, the change in column height exerts a substantial influence on shear strength, with the column diameter fixed at 16 mm. Further, the H_{dr} does not increase simultaneously with average shear strength, and the alteration of the column diameter and height can cause the value to increase or decrease. As observed from Fig. 11, the peak average shear strength was obtained with $H_{dr} = 6.25$, diameter of 16 mm, and height of 100 mm for a single PET column. The same parameters but for the group PET columns resulted in the lowest average shear strength. A further increase or decrease in H_{dr} resulted in different values.

The results also suggest that the positive or negative peak value occurs at the critical column length, which was 1.0 for the current research. Similar conclusions were made by Hoque et al. (2023) and Shen et al. (2023), who proved that different replacement materials in granular column applications obtained the highest shear strength improvement rate when the critical column length was 1.0. Shen et al. (2024) reported that the granular column diameter influences the degree of improvement, where it changes the value of H_{dr}, regardless of single or group PET columns. In addition, the alteration of the H_{dr} value causes the force distribution area that is measured from the edge of the column to the outer diameter to either increase or decrease by the radius of the sample. As compared to both the largest and lowest average shear strength value, due to the larger portion of soil that had been drilled out, the S16100 design had greater stiffness after being replaced with PET plastic, which was sufficient to overcome the degree of soil disturbance. Thus, the excavation of soil loosened the soil particles, disturbed the original condition of the soil, and influenced the performance of shear strength enhancement.

4.7 The effect of the volume replacement ratio (Vrr) on the shear strength of kaolin clay after reinforcement with PET columns

The relationship between the V_{rr} value and the average shear strength of kaolin clay after reinforcement with single and group PET columns was assessed and plotted in Fig. 12, demonstrating a significant increase in the strength of kaolin clay relative to the control sample, ranging from 11.71 kPa to 18.33 kPa regardless of the value of V_{rr}. As shown in Fig. 12, the highest value of average shear strength was recorded at $V_{rr} = 30.72$, where it does not show the peak value of average shear strength, recorded at only 13.04 kPa.

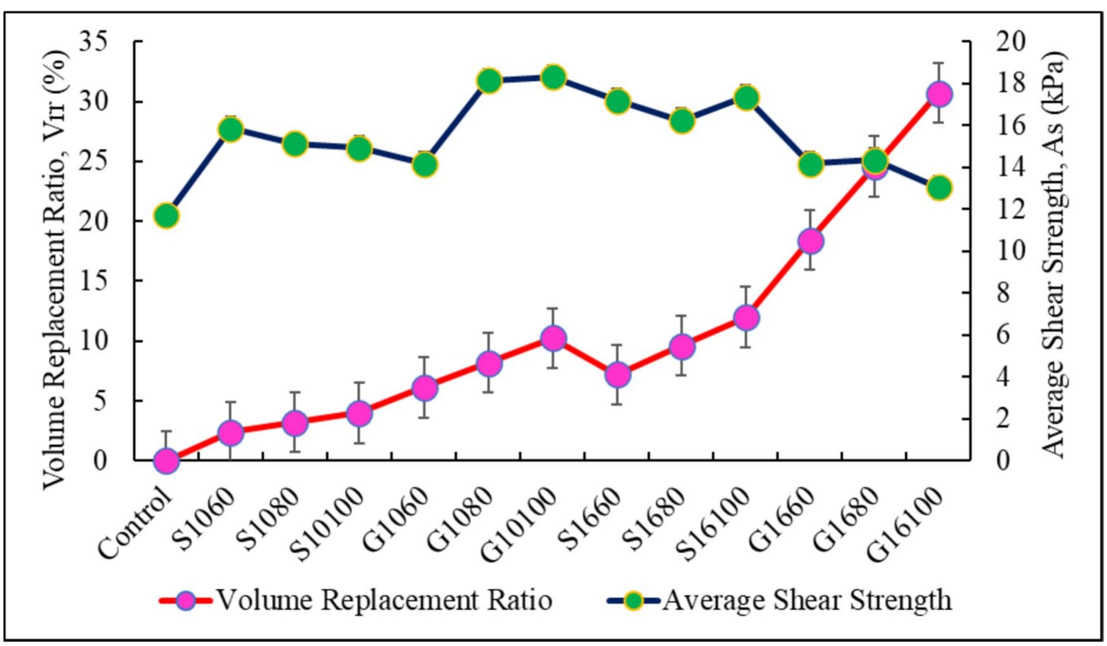


Fig. 12 The relationship between the average shear strength value (A_s) and the volume replacement ratio (V_{rr}) for the single and group PET columns

Based on this observation, the greatest value of shear strength improvement occurred when a single PET column with a 10 mm diameter was installed beneath the kaolin clay, with a critical column height of 1.0. By researching the data obtained for only a single PET column with a V_{rr} value, an inconsistent trend is observed when the V_{rr} value ranges between 2.4 and 6.14, but the overall trend shows an increase as the V_{rr} value increases. Thus, the increase in the V_{rr} value increases the average shear strength value. Group PET columns display an inversely proportional trend as the V_{rr} value increased from $V_{rr}=7.2$ to 30.72, for which the average shear strength decreased from 17.19 kPa to 13.04 kPa, which is an approximately 24.14% reduction. This phenomenon can be expressed in terms of its stiffness, where the larger soil disturbance reduces the density of soil particles, thus decreasing the initial stored shear strength. Syamsul et al. (2023) emphasized the above phenomena as the decrease in the stress–stress relationship that exists between the soil and the foreign material.

Similar to the previous study, a single granular column produced the largest shear strength improvement (Hasan and Yee 2024; Hoque et al. 2023), where the employment of a single PET column has a smaller confining area that creates a higher confining pressure within that particular column, and the stiffness of PET is fully projected by compaction. Coherent to that, bonding between soil particles and foreign materials becomes stronger. In addition, the shear strength improvement of group PET columns yielded a smaller improvement result as compared to the single PET column, which was due to the total area of replacement of group PET columns being twice as large as the single PET column area using the same value of H_{pr}. When the axial loading was applied directly to the surface of the sample, the group PET columns containing a larger volume of PET had less efficiency in distributing the load evenly to the ground, as the remaining width was smaller between the PET columns, thus making them ineffective in load transmission and deteriorating the column bulging condition. The remaining kaolin in the PET column was densified upon compression, expanding the soil particles, which resulted in the narrowing of the soil shear stress. Hoque et al. (2023) reported that the particle density of soil as well as its intergranular contact forces determine the rate of change of volume with its friction. Up to a maximum limit of exerted force, the soil particles will become completely loosened, which results in substantially lower shear strength.

4.8 Analysis of the cohesion and soil friction angle of kaolin clay after reinforcement with PET columns

The Unconsolidated undrained (UU) test was conducted to evaluate the cohesion and soil friction angle of kaolin clay reinforced with single and group PET columns. This test was conducted at confining pressures of 100 kPa, 200 kPa, and 400 kPa for the same column design. Table 3 presents the relationship between the A_{rr}, H_{pr}, H_{dr}, V_{rr}, cohesion, and soil friction angle. As predicted, the reinforcement of either single or group PET columns improved the cohesion and soil friction angle as compared to the unreinforced sample. A slight improvement in the soil friction angle was observed between the unreinforced sample and reinforced sample; however, in terms of cohesion, the improvement rate was larger than the soil friction angle improvement rate.

With regard to the cohesion of kaolin clay, the recorded value was 42.2 kPa, and for the single PET columns with a 10 mm diameter, values were 47.5 kPa, 51.4 kPa, and 47.8 kPa for S1060, S1080, and S10100, respectively. The single PET columns with a 16 mm column diameter (S1660, S1680, and S16100) had cohesion values of 47.0 kPa, 46.0 kPa, and 49.6 kPa, respectively. The group PET columns with a 10 mm column diameter (G1060, G1080, and G10100) produced cohesion values of 49.1 kPa, 54.5 kPa, and 46.3 kPa, respectively, and the 16 mm column diameter (G1660, G1680, and G16100) showed values of 47.1 kPa, 57.3 kPa and 44.4 kPa, respectively. The highest cohesion value was found for the G1680 design, with a value of 57.3 kPa, while the lowest value recorded was 44.4 kPa for the G16100 design. These results suggest that the optimum length for obtaining the highest value of cohesion is 0.8, which is similar to previous analysis of UCT, where the authors noted that the critical length was within 0.8–1.0. Table 3 indicates that the improvement in cohesion improved the soil friction angle of the kaolin clay reinforced with either single or group PET columns. The improvement in cohesion was expressed in the independent value and unit, which shows a disparity between the unreinforced sample and the reinforced sample. As investigated by Ferreira et al. (2021), the authors proved that the inclusion of PET fiber increased the cohesion of sand with a maximum percentage of 161%, where the PET fiber caused the soil particles to hold together in a better position. When the cohesion value increases, higher bonding forces between the soil particles and the foreign material exist (Hasan and Yee 2024). Furthermore, Meenakshi and Mohini (2020) reported that the addition of PET increases the soil cohesion value up to an optimum value, and shows no increase beyond this amount. The authors also deduced that the use of similar PET particle sizes produces a better improvement, which may relieve the hindrance between the soil particles. The study proved that the use of PET columns increased the cohesion from 42.2 kPa to a maximum value of 57.3 kPa, or an improvement percentage of 35.78%.

The soil friction angle (φ) influences the cohesion value (refer to Table 3). The unreinforced sample (control) displayed a soil friction angle of 30.0°. The soil friction angles

Table 3 Data obtained from the UU test for the kaolin clay after reinforcement with single and group PET columns

Sample	Cell pressure (kPa)	Column diameter (mm)	Column height (mm)	A_{rr}	H_{pr}	H_{dr}	V_{rr}	Cohesion (c) (kPa)	φ (°)
Control	100	0	0	0	0	0	0	42.2	30.0
	200								
	400								
S1060	100	10	60	4	0.6	6	2.4	47.5	34.0
	200								
	400								
S1080	100	10	80	4	0.8	8	3.2	51.4	31.0
	200								
	400								
S10100	100	10	100	4	1.0	10	4	47.8	31.5
	200								
	400								
S1660	100	16	60	10.24	0.6	3.75	6.14	47.0	31.8
	200								
	400								
S1680	100	16	80	10.24	0.8	5.00	8.19	46.0	32.8
	200								
	400								
S16100	100	16	100	10.24	1.0	6.25	10.24	49.6	33.0
	200								
	400								
G1060	100	10	60	12	0.6	6	7.2	49.1	31.4
	200								
	400								
G1080	100	10	80	12	0.8	8	9.6	54.5	31.8
	200								
	400								
G10100	100	10	100	12	1.0	10	12	46.3	31.2
	200								
	400								
G1660	100	16	60	30.72	0.6	3.75	18.43	47.1	31.5
	200								
	400								
G1680	100	16	80	30.72	0.8	5.00	24.58	57.3	32.9
	200								
	400								
G16100	100	16	100	30.72	1.0	6.25	30.72	44.4	33.2
	200								
	400								

for single PET columns of 10 mm diameter were 34.0°, 31.0°, and 31.5° for column height of 60 mm, 80 mm, and 100 mm, respectively. Columns in the same category but with a diameter of 16 mm and height of 60 mm, 80 mm, and 100 mm had values of 31.8°, 32.8°, and 33.0°, respectively. Similarly, group PET columns with a 10 mm diameter and height of 60 mm, 80 mm, and 100 mm showed soil friction angles of 31.4°, 31.8°, and 31.2°, respectively. In addition, the soil cohesion values were 31.5°, 32.9°, and 33.2° for the G1660, G1680, and G16100 designs, respectively. The largest soil friction angle of 34.0° was obtained with the S1060 design, which produced a cohesion value of 47.5 kPa, while the lowest soil friction angle recorded was 31.0° for the S1080 design, which had a cohesion value of 51.4 kPa. A general trend was observed, where the soil friction angle and cohesion are directly proportional to each other up to a certain value depending on the model test, as supported by Malafatti-Picca et al. (2023). The cohesion and soil friction angle are defined from a Mohr circle by the relationship between shear stress and normal stress; a tangent line is intersected approaching the maximum point of the individual Mohr circle that is generated from each value of confining pressure. A larger Mohr circle will produce a larger cohesion and soil friction angle. Zaini and Hasan (2024) emphasized that the change in shear stress or normal stress will have a significant effect on the soil friction angle, and the arrangement of the PET columns results in different cohesion value improvements (Maltseva et al. 2023).

4.9 Analysis of the stress–strain behavior of reinforced kaolin clay at different effective confining pressures

This subsection further discusses the data analysis obtained from the UU test, and the stress–strain behavior of reinforced kaolin clay at effective confining pressures of 100 kPa, 200 kPa, and 400 kPa, as demonstrated in Fig. 13a–c. The figure shows that all the tested column designs comprising single and PET columns performed better as compared to the control sample. The increase in shear stress corresponds to the increase in confining pressure, where the parameter of axial strain is not segregable. As analyzed from the 100 kPa of confining pressure for the single PET column, the peak shear stress occurred at an H_{pr} value equal to 1.0 for the S16100 design, where this value is the optimum column length to maximize the efficiency of the built-in PET column, while the least deviator stress recorded was for the S10100 design with the same value of $H_{pr} = 1.0$. Conversely, at the confining pressure of 200 kPa, the lowest deviator stress occurred at $H_{pr} = 0.6$ for the S1060 design; however, the peak value recorded was for the S1660 design, possibly due to the effective association of PET plastic in the kaolin clay in this design. Jun Shen et al. (2024) noted that beyond the critical column length of the specific granular column, the shear strength improvement of soil begins to drop or shows no significant increase despite the change in column stiffness and materials. Syamsul et al. (2023) reported that the length of the column should be based on a consideration of all the materials, and shorter columns such as those with $H_{pr} = 0.6$ cause the stress to be concentrated only on the bottom part of the column.

According to the results from the 400 kPa confining pressure, a single PET column displayed a similar trend, where $H_{pr} = 0.6$ for the S1660 sample obtained the lowest deviator stress pressure, while $H_{pr} = 1.0$ for the S16100 sample recorded the highest deviator stress. The results suggest that the PET column with a diameter of 16 mm diameter achieved a greater improvement than that with 10 mm due to the larger amount of coarse material replacement while assisting in distributing the load across the entire column. A previous study from Shen et al. (2024) reported that the use of a single granular column significantly improved the raw kaolin clay shear strength. This phenomenon implies that the column performance is affected by the column design, for instance, substituent material and penetration height.

The relationship between deviator stress and axial strain for group PET columns is presented in Fig. 13a–c (ii). For the confining pressure of 100 kPa, the largest and smallest deviator stress values recorded occurred for the G16100 and G1680 designs with 16 mm column diameter, with the numerical difference of 42.65 kPa and 6.01 kPa, respectively. For the remaining two confining pressures of 200 kPa and 400 kPa, the maximum deviator stress after reinforcement of group PET columns occurred with the same column design with a diameter of 16 mm and height of 100 mm, with improvement values of 45.67% and 75.18%, respectively. The longest penetrating depth or critical column length concept was supported by Najjar (2013). The least improvement in deviator stress was shown by the G10100 and G1080 group PET columns with a diameter of 10 mm but different heights with confining pressures of 200 kPa and 400 kPa, respectively. At the largest applied pressure of 400 kPa, the PET columns with 80 mm height or longer with the corresponding diameter of 10 mm may deform faster than any design due to the transmission of loading stopping in the middle, causing the column failure at the remaining unreinforced part of the column. Overall, the group PET column performed in the extreme range of improvement at $H_{pr} = 0.8$ and 10. Considering the factor of A_{rr}, the increase in A_{rr} proves that the deviator stress will increase for single and group PET columns. Coherent to that, the single PET column with a diameter of 16 mm and 100 mm height ($A_{rr} = 10.24$) resulted in a higher percentage of improvement, 50.31%, and the group PET column with $H_{pr} = 1.0$ and 16 mm diameter ($A_{rr} = 30.72$) produced the largest deviator stress, or 75.18% improvement, among all the tested samples. The larger value of A_{rr} implies that the soil is heavily disturbed upon drilling; however, the proper analysis of the material and the means of transferring the material can compromise the reduction in shear strength due to the soil disturbance. The larger A_{rr} value can produce a greater shear strength improvement, as also reported by Shen et al. (2023).

For $H_{pr} = 0.6$ or the partially penetrated column in this study, the results obtained from both single and group PET columns did not show a huge fluctuation for the effective confining pressures of 100 kPa, 200 kPa, and 400 kPa. The above results suggest that the applied pressure which converts into axial loading has been well distributed except for the S1060 and S1660 designs. At 60 mm penetrating height, which is 60% of the column height, the forces that are transmitted to the PET columns can separately expand in all directions before reaching both ends of the sample,

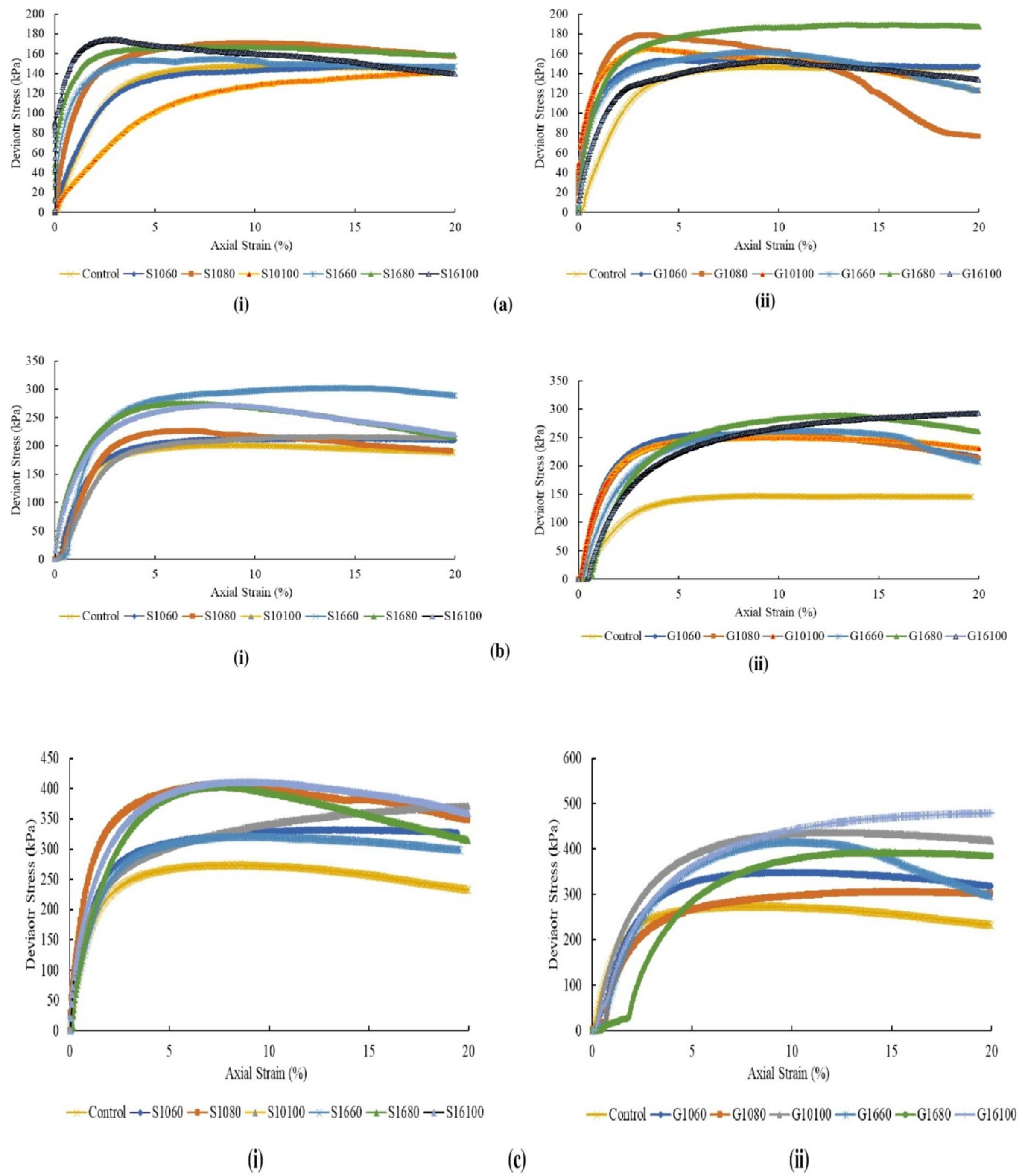


Fig. 13 The results obtained from the unconsolidated undrained test for the single and group PET columns at confining pressure of (**a**) 100 kPa, (**b**) 200 kPa, and (**c**) 400 kPa. (**i**) Single PET column. (**ii**) Group PET column. S, single: G, group

where the remaining unreinforced parts have almost the same distances. Therefore, the current study suggests that the design of a 60 mm column behaves moderately under confining pressure from 100 to 400 kPa. As reported by Bin Hasan et al. (2014), the length-to-diameter ratio to obtain the maximum efficiency improvement in shear strength parameters must not range between 4 and 8, where Rezaei-Hosseinabadi et al. (2022) supported the proposed value by emphasizing that the overvalue of critical column length is appropriate for overcoming the settlement issue.

4.9.1 Statistical analysis and determination of the optimum regression model for shear strength improvement prediction through the numerous regression analyses

This subsection presents statistical analysis including the utilization of error bars (see Figs. 8, 9, 10, 11, and 12), one-way analysis of variance (ANOVA), Fisher's least significance difference (LSD), Pearson's correlation analysis, and regression analysis. The error bars displayed in these figures are the graphical representation of the variability in shear strength parameters, revealing the standard error within and between data groups. The error bars were interpreted at a confidence level of 95%, coherent with the potential errors obtained during the UCT and UU test measurements. This approach is coherent with the research by Syamsul et al. (2023). With respect to the error bars, the non-overlapping bars between the shear strength parameters indicate that the data are significantly different, while overlapping bars indicate no significant difference. Referring to Fig. 8b, the difference in the A_s values of the reinforced kaolin clay between the single and group PET columns demonstrates a nonsignificant difference due to the overlapping of error bars. Similarly, the unreinforced and reinforced samples from both the single and group PET columns suggest a statistical difference in values, evidenced by the non-overlapping bars as shown in Fig. 8b. Hence, it can be concluded that the fabrication of single and group PET columns of varying dimensions and configurations exert different effects on the shear strength of kaolin clay. In addition, the area replacement ratio (A_{rr}) indicates a nonsignificant difference regarding the average shear strength value with regard to the type of reinforced sample for single and group PET columns, with a confidence level of $p < 0.05$. However, the A_{rr} factor yields a significant difference in the role of reinforcing the kaolin clay relative to the control sample.

The following discussion is focused on the H_{pr} factor, as depicted in Fig. 10. At a value of $p < 0.05$, the data provide a thorough interpretation regarding the H_{pr} factor and the influence of the installation of single PET and group PET columns with diameters of 10 mm and 16 mm on the enhancement of shear strength. The data are significantly different from the control sample, as the error bars are not overlapped. In contrast, the overlapping bars of the H_{pr} value indicate the lack of a significant difference corresponding to the single and group PET columns with 10 mm and 16 mm diameters. Figure 10 demonstrates a significant difference in the dataset when comparing the group PET column value generated from the 16 mm column diameter. The relation of H_{dr} is expressed in the error bars as displayed in Fig. 11 at a confidence level of 95%. There is no significant difference between the H_{dr} and the reinforced single and group PET columns for 10 mm and 16 mm column diameters as compared to the control sample. The error bars shown above differ from the others, as indicated by their greater length. This is attributed to the extensive uncertainty and variability in the value of A_s. In addition, there are no significant differences between the reinforced single and group PET columns (10-mm and 16-mm column diameters), as shown by the overlapped error bars. The graph presented in Fig. 12 proves that the V_{rr} and the increase in the A_s value of kaolin clay are statistically nonsignificant; however, there are significant differences in regard to the reinforced kaolin samples and the control sample at the a 95% confidence level. The significant difference in the dataset is observed for the group PET columns with 16 mm diameter, as indicated by the shorter length of error bars.

The statistical analysis proceeded to the one-way ANOVA, where the eight parameters included the number of columns, column diameter, column height, A_{rr}, H_{pr}, H_{dr}, V_{rr}, and confining pressure. The results indicated that these parameters have a significantly different relationship with each other, with a p value less than 0.05. The parameters were subsequently investigated via the LSD approach, verifying which parameter offered the difference between the group means. The LSD analysis focused on 28 groups of data means; 15 groups were found to accept the null hypothesis, and 13 groups were detected to reject the null hypothesis. The acceptance of the null hypothesis signified that the value of the absolute mean difference was greater than the LSD value. Ikumapayi et al. (2024) reported that the utilization of the LSD approach after ANOVA analysis is a reliable means of verifying the significant difference in data means. Therefore, the LSD results are tabulated in Table 4, summarizing the data at the LSD value of 20.48. Referring to this value, Table 4 presents the significant difference between these eight parameters, where the number of columns and column height recorded a mean difference of 72.00, the number of columns and confining pressure at a mean difference of 231.48, the column diameter and column height at a mean difference of 61.84, the column diameter and confining pressure at a mean difference of 221.33, the column height and A_{rr} at a mean difference of 60.70, the column height and H_{pr} at a mean difference of 73.10, the column height and H_{dr} at a mean difference of 67.8461, the column height and V_{rr} at a mean difference of 63.33, the column height and confining pressure at a mean difference of 159.48, the A_{rr} and confining pressure at a mean difference of 220.18, the H_{pr} and confining pressure at a mean difference of 232.59, the H_{dr} and confining pressure at a mean difference of 227.33, and the V_{rr} and confining pressure at a mean difference of 222.81.

$\bar{x}_1$, number of columns; $\bar{x}_2$, column diameter; $\bar{x}_3$, column height; $\bar{x}_4$, area replacement ratio (A_{rr}); $\bar{x}_5$, height penetration ratio (H_{pr}); $\bar{x}_6$, column height to column diameter ratio (H_{dr}); $\bar{x}_7$, volume replacement ratio (V_{rr}); $\bar{x}_8$ confining pressure.

Table 4 LSD analysis of the observed parameters with respect to shear strength improvement

Mean	Absolute mean difference		Remark
	Mean difference	Value	
$\bar{x}_1$	$\bar{x}_1$-$\bar{x}_3$	72	Confidence level of 95%, two-tailed test; LSD value = 20.48
	$\bar{x}_1$-$\bar{x}_8$	231.48	
$\bar{x}_2$	$\bar{x}_2$-$\bar{x}_3$	61.84	
	$\bar{x}_2$-$\bar{x}_8$	221.33	
$\bar{x}_3$	$\bar{x}_3$-$\bar{x}_4$	60.70	
	$\bar{x}_3$-$\bar{x}_5$	73.10	
	$\bar{x}_3$-$\bar{x}_6$	67.84	
	$\bar{x}_3$-$\bar{x}_7$	63.33	
	$\bar{x}_3$-$\bar{x}_8$	159.48	
$\bar{x}_4$	$\bar{x}_4$-$\bar{x}_8$	220.18	
$\bar{x}_5$	$\bar{x}_5$-$\bar{x}_8$	232.59	
$\bar{x}_6$	$\bar{x}_6$-$\bar{x}_8$	227.33	
$\bar{x}_7$	$\bar{x}_7$-$\bar{x}_8$	222.81	

The results generated from Pearson's correlation analysis are summarized in Table 5. This examination method measures and correlates the relationship between the observed parameters, with the Pearson's correlation value *r*. Ikhwan et al. (2024) established a relationship between the correlation value and classification of correlation, where a value of 0–0.4 is considered a weak correlation, 0.4–0.6 is categorized as a moderate correlation, 0.6–1.0 is classified as a strong correlation, and a negative value suggests that an inverse proportional trend exists between these variables. Referring to the table, the correlations of the number of columns to A_{rr} and V_{rr} are strong, yielding correlation values of 0.75 and 0.72, respectively. However, within the same parameter, number of columns demonstrates an extremely weak correlation to confining pressure, and column diameter, column height, H_{pr}, and H_{dr} display a weak to moderate correlation. In addition, the correlation of column height to H_{pr} and H_{dr} is extremely strong, with recorded values of 1.00 and 0.82, respectively. The parameters A_{rr} and V_{rr} show a weak to moderate correlation to the column height parameter according to its *r* value. Furthermore, the A_{rr} and V_{rr} demonstrate a strong correlation relationship, observed from the *r* value of 0.94. There is a well-established relationship between H_{pr} and H_{dr}, with an *r* value of 0.82. In contrast, negative correlations exist between column diameter and confining pressure, A_{rr} and H_{dr}, and H_{dr} and confining pressure. This indicates an inverse relationship regardless of the *r* magnitude reported. Similarly, seven out of eight parameters (number of columns, column diameter, column height, A_{rr}, H_{pr}, H_{dr}, and V_{rr}) generate no correlation with confining pressure, as the recorded *r* values are nonsignificant and approaching zero.

The following regression analysis investigated and establishes a comprehensive mathematical equation and determines the optimum regression model based on the eight studied parameters with respect to the shear strength of kaolin. The prediction model is formulated to correlate the relationship of the magnitude of shear strength, and an optimum regression model from Table 6 is chosen, which yielded the optimum values of regression analysis, *F*-sig, R^2 value, and adjusted R^2 value. The current research examined a total of 83 sets of data combinations, and 27 sets of data are included referring to the R^2 value and adjusted R^2 value, which are greater than 0.9. The remaining data combinations presented a weak correlation between the variables, with the range of R^2 value and adjusted R^2 value lower than 0.9,

Table 5 Pearson's correlation analysis results for the eight parameters in terms of shear strength improvement

Parameter	X	Y	Z	A_{rr}	H_{pr}	H_{dr}	V_{rr}	A
X	1.00							
Y	0.37	1.00						
Z	0.39	0.61	1.00					
A_{rr}	0.75	0.65	0.29	1.00				
H_{pr}	0.39	0.61	1.00	0.29	1.00			
H_{dr}	0.32	0.15	0.82	−0.07	0.82	1.00		
V_{rr}	0.72	0.62	0.43	0.94	0.43	0.04	1.00	
A	3.72×10^{-17}	-2.1×10^{-17}	1×10^{-17}	1.81×10^{-17}	0.00	-3.42×10^{-17}	0.00	1.00

Table 6 The establishment of the optimum regression model of shear strength parameters following the regression analysis

Regression equation	F-sig	R^2	Adj R^2
$C_u = 0.6415x_2 + 1.1169x_6$	1.24×10^{-22}	0.9377	0.9090
$C_u = 0.1462x_3 + 0.015x_8$	2.63×10^{-22}	0.9351	0.9063
$C_u = 14.6270x_5 + 0.015x_8$	2.63×10^{-22}	0.9351	0.9063
$C_u = 4.0681x_1 + 1.2336x_2 - 0.5974x_4$	5.55×10^{-23}	0.9497	0.9191
$C_u = -0.056x_1 + 0.6466x_2 + 1.1240x_6$	2.31×10^{-21}	0.9377	0.9065
$C_u = 3.3691x_1 + 1.1704x_2 - 0.5664x_7$	3.61×10^{-21}	0.9361	0.9048
$C_u = 1.0285x_2 - 0.1469x_4 + 2.165\ x_6$	5.44×10^{-22}	0.9427	0.9117
$C_u = 0.6537x_2 + 0.1240x_4 - 0.2565x_7$	3.01×10^{-21}	0.9368	0.9055
$C_u = 0.3031x_2 + 0.1033x_4 + 0.013x_8$	1.08×10^{-21}	0.9404	0.9093
$C_u = 0.2049x_3 + 0.7033x_4 - 0.9527x_7$	1.43×10^{-21}	0.9394	0.9083
$C_u = 0.1494x_3 - 0.020x_4 + 0.015x_8$	4.60×10^{-21}	0.9352	0.9039
$C_u = 0.7033x_4 + 20.4995x_5 - 0.9527x_7$	1.43×10^{-21}	0.9394	0.9083
$C_u = -0.020x_4 + 14.9460x_5 + 0.0155x_8$	4.60×10^{-21}	0.9352	0.9039
$C_u = 13.0735x_5 + 0.1912x_6 + 0.0154x_8$	4.41×10^{-21}	0.9354	0.9040
$C_u = 3.5226x_1 + 1.0526x_2 + 0.0309x_3 - 0.5279x_4$	5.97×10^{-22}	0.9509	0.9181
$C_u = -0.2466x_1 + 1.0645x_2 - 0.1522x_3 + 2.2351x_6$	7.70×10^{-21}	0.9429	0.9094
$C_u = 2.4084x_1 + 0.70195x_2 + 0.0897x_3 - 0.4744x_7$	4.81×10^{-22}	0.9515	0.9188
$C_u = 0.2268x_1 + 0.2890x_2 + 0.1004x_3 + 0.0137x_8$	1.52×10^{-20}	0.9406	0.9069
$C_u = 1.1555x_2 - 0.1315x_3 - 0.1109x_4 + 1.9667x_6$	3.47×10^{-21}	0.9455	0.9123
$C_u = 0.3424x_2 + 0.1626x_3 + 0.4722x_4 - 0.7528x_7$	8.70×10^{-21}	0.9425	0.9090
$C_u = 0.5635x_2 + 0.090x_3 - 0.1548x_4 + 0.0134x_8$	2.79×10^{-21}	0.9462	0.9130
$C_u = 0.7033x_4 + 23.2456x_5 - 0.2801x_6 - 0.9856x_7$	1.87×10^{-20}	0.9398	0.9061
$C_u = -0.0058x_4 + 13.3541x_5 + 0.1678x_6 + 0.0154x_8$	6.28×10^{-20}	0.9354	0.9013
$C_u = 18.9273x_5 - 0.2807x_6 - 0.1418x_7 + 0.0154x_8$	2.74×10^{-20}	0.9385	0.9046
$C_u = 2.8801x_1 + 1.1185x_2 - 0.0232x_3 - 0.1126x_4 + 0.5577x_6$	6.91×10^{-21}	0.9514	0.9163
$C_u = 2.9405x_1 + 0.8595x_2 + 0.0640x_3 - 0.2230x_4 - 0.2882x_7$	5.52×10^{-21}	0.9521	0.9170
$C_u = 3.0667x_1 + 0.9015x_2 + 0.0246x_3 - 0.4697x_4 + 0.0110x_8$	1.83×10^{-22}	0.9610	0.9270
$C_u = 0.5687x_4 + 19.8201x_5 - 0.2802x_6 - 0.8242x_7 + 0.0122x_8$	4.78×10^{-21}	0.9525	0.9175

indicating a nonsignificant influence on the shear strength parameters of kaolin.

Referring to Table 6, the F-sig value for all sets of data rejected the null hypothesis, by following the benchmark of confidence level of $p < 0.05$. The rejection proves that the regression equations in Table 6 are formulated in a strong relation, and the model is significant. The R^2 value indicates that more than 93.00% of the shear strength variables utilize the model, as tabulated in Table 6. However, the adjusted R^2 value causes a reduction in R^2 value due to the elimination of new variables that are exerting a nonsignificant influence. Thus, considering the parameters from the technique of regression analysis, the optimum regression model that is appropriate to represent the shear strength parameters in the current study is presented in Eq. 6.

$$C_u = 3.0667x_1 + 0.9015x_2 + 0.0246x_3 - 0.4697x_4 + 0.011x_8 \tag{6}$$

where C_u is the undrained shear strength, x_1 is the number of columns, x_2 is the column diameter, x_3 is the column height, x_4 is the area replacement ratio (A_{rr}), and x_8 is the confining pressure. It can be concluded from Eq. 6 that the undrained shear strength of kaolin is strongly affected by the number of columns constructed beneath the soil, the column diameter, the column height, the A_{rr} value, and the imposed confining pressure from the triaxial cell. This equation has an adjusted R^2 value of 0.9270, indicating that 92.70% of the data can be deduced from this specific model.

5 Conclusion

This study investigated the effect of installing single and group PET columns beneath kaolin soil, acting as a reinforcement to modify the shear strength parameters. According to the results obtained from all the relevant geotechnical tests, the following conclusions can be drawn:

1) Kaolin clay soil type S300 is classified as ML, referring to the plasticity chart, and is given the A-4 value from the AASTHO soil classification standard. In addition, the liquid limit and plastic limit values are 35.00%

and 29.00%, respectively, which produce a plasticity index of 6.00% with a specific gravity of 2.60. These data verify that kaolin soil is a low-plasticity soil, containing silt or inorganic silt with slight plasticity. Via the identical AASTHO method, the PET plastic yields the value of A-1-a, proving this material behaves like coarse material. It also shows that PET is like a well-graded sand with a specific gravity value of 1.40. The standard Proctor test yields OMM and MDD values of 2.000% and 1.54 Mg/m^3, respectively. The permeability coefficients for kaolin clay S300 and PET plastic are 4.197×10^{-8} m/s and 2.503×10^{-4} m/s, respectively. The addition of PET plastic can resolve the water accumulation issue by providing additional drainage due to the extreme value of the hydraulic conductivity coefficient of kaolin soil.

2) The construction of PET columns in terms of single and group categories effectively enhanced the shear strength of kaolin clay. The alteration of A_{rr}, H_{pr}, H_{dr}, and V_{rr} values exerts a significant influence on the shear strength improvement, with the range of value from the minimum of 11.35% up to 56.53%, referring to the shear strength magnitude of the control sample. For both single and group PET column categories, the highest ΔS_u values of 56.53% and 48.42%, respectively, occurred with a 16 mm column diameter and 10 mm column diameter at $H_{pr} = 1.0$, and the smallest ΔS_u values of 27.49% and 11.35%, respectively, recorded the identical H_{pr} value of 1.0 with the column diameter of 10 mm and 16 mm, respectively. Coherently, a further reduction of the H_{pr} value to 0.8 and 0.6 leads to the fluctuation of ΔS_u, recorded with either an increase or decrease in the A_s value. Thus, the 100 mm of penetrating height is verified as the critical column height in this study. Furthermore, the application of the UU technique that applies different confining pressures plays an important role in determining the friction angle, φ, cohesion, and c value of the control and reinforced samples. Further compression and squeezing of kaolin soil occurs in the triaxial soil, causing the sample to be more cohesive between the fabricated PET columns. The results generated from the UU test have validated the modification of the stone column technique with the PET column installed in single and group categories to amend the φ and c values. Referencing from the control sample values of 42.2 kPa and 30.0°, the maximum increase in cohesion is 15.1 kPa when the group PET column with 16 mm diameter is assessed, and a friction angle of 34.0° is recorded from the single PET column of 10 mm diameter.

3) The error bars confirm the significance of the observed parameters in this study between the control sample, single PET column, and the group PET columns. The distinct dimension and arrangement of the samples exert a crucial influence on the A_s value and the $\Delta S_{u.}$ at the confidence level of 95.00%. Apart from that, the execution of one-way analysis of variance (ANOVA) has ascertained a significant difference between the eight observed parameters, with the rejection of the null hypothesis at $p < 0.05$. Similarly, the subsequent verification approach, Fisher's least significance difference (LSD), is implemented to identify which group of parameters have contributed to the significant difference from each other. As shown in Table 4 LSD analysis of the observed parameters with respect to shear strength improvement there are 28 groups of data analyzed at the LSD of 20.48. Fifteen groups of data accept the null hypothesis (LSD > absolute mean difference), and 13 groups of data reject it with the LSD value smaller than the absolute mean difference. Moreover, Pearson's correlation analysis is conducted accordingly with the eight observed parameters, and at least one of the independent parameters is certified to have a strong correlation ($r > 0.06$) to another parameter. Last but not least, the regression analysis is carried out to establish the regression model, in which 27 sets of data are tabulated with the R^2 value and adjusted R^2 greater than 0.9. The optimum regression model is chosen and shown in Eq. 6, with 92.70% of data elaborated from this specific model. Hence, it is concluded that the revision of the functions in Eq. 6, including the number of columns, column diameter, column height, A_{rr} value, and confining pressure, modifies the shear strength of kaolin soil.

Based on the summary of findings, the authors therefore conclude that the application of PET plastic in fabricating PET columns in the stone column technique rectifies the poor engineering properties of kaolin clay soil. These discoveries can be applied to actual construction in the field by geotechnical engineers, referring to the respective multipliers and ratios, which include the column ratios, grain size distribution of soil and PET, and the boundary limit of the site, to execute the modified sustainable stone column technique accordingly. In addition, the method of single and group PET columns is to be implemented depending on the type of soils, complexity of construction, and foundation system, as more detailed data from the soil investigation report are required to execute this approach. Similarly, a revised version of PET reinforcement may be done based on the construction projects, in which a mega-project such as infrastructure construction should fabricate a longer length of PET columns. Coherently, a periodic checking using geotechnical approaches such as the electro-resistivity method can be deployed to examine the performance of PET columns beneath the soft clay soil, although the PET material is chemically inert. In addition, a cost–benefit analysis is suggested to be implemented, combining the price of materials in the subsequent research to deduce the possible cost savings through the proposal. The research proposes the construction of a fully penetrating column ($H_{pr} = 1.0$), in which the 16 mm column diameter should be applied in designing the single PET column, while the 10 mm column diameter is suggested for the group PET columns for the related parties in treating the problematic clay soil in the construction industry. According to this discovery, the authors also suggest carrying out the consolidated undrained (CU) test in the future for the clarification of results via the consolidating undrained parameters, which are the volume change and compressibility of soil under identical confining pressure. The above findings have proven that the shear strength of kaolin can be reinforced up to 56.53%.

Author contributions All authors contributed to the study conception and design. Ng Jun Shen: Conceptualization, Methodology, Investigation, Data acquisition, Formal analysis, Writing – original draft preparation, Writing – review and editing. Muzamir Hasan: Funding acquisition, validation, supervision, investigation, project administration. All authors read and approved the final manuscript.

Funding The work was supported by Universiti Malaysia Pahang Al-Sultan Abdullah (UMPSA) and Hokoku Engineering Co. Ltd. (Japan) for assisting and providing financial support through UMPSA International Matching Grant RDU252702 and Grant UIC251503. The cooperation given by all parties involved in this research is greatly acknowledged.

Data Availability The data that support the findings of this study are not shared openly and are available from the corresponding author upon reasonable request.

Declarations

Competing Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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