Journal of Sustainable Construction Materials and Technologies

Volume 10 | Issue 2 Article 2

2025

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Recommended Citation

Shen, Ng Jun and Hasan, Muzamir (2025) "Sustainable Modification of Stone Column Technique with Polyethylene Terephthalate (PET) Plastic for Strengthening the Expansive Clay," *Journal of Sustainable Construction Materials and Technologies*: Vol. 10: Iss. 2, Article 2.
https://doi.org/10.29187/2458-973X.1186
Available at: https://commons.yildiz.edu.tr/jscmt/vol10/iss2/2

JOURNAL OF SUSTAINABLE CONSTRUCTION MATERIALS AND TECHNOLOGIES 2025;10:156–168

RESEARCH ARTICLE

Sustainable Modification of Stone Column Technique with Polyethylene Terephthalate (PET) Plastic for Strengthening the Expansive Clay

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ABSTRACT

This research investigated the modification of stone column application by the association of PET plastic as a coarse aggregate material for sustainable material replacement. Clay soil improvement with a granular material fabricated column substantially affected its soil-bearing capacity. Subsequently, it avoided severe problems such as soil settlement and structural instability. Previous studies have mentioned the function and alteration of stone columns using materials like bottom ash and fly ash. Still, no attention has been paid to the utilization of PET plastic for this area. This study examined the feasibility and reliability of materials, PET plastic, and kaolin clay S300 before examining geotechnical properties through their physical and mechanical characteristics. The fundamental geotechnical tests verified that kaolin clay was a problematic soil, and PET plastic was a substitute for coarse aggregate. Via the Unconfined Compression Test (UCT) approach, the highest improvement magnitude of soil recorded was at 17.38kPa or 48.42%, referring to the unreinforced kaolin specimen, which occurred at the GC10100 specimen. Coherently, it was suggested that the critical column penetrating ratio was 1.0. The research proposed that using PET plastic could act as a reinforcing component to rectify the engineering characteristics of kaolin.

Keywords: Expansive clay, Foundation, PET plastic, Ground improvement, Shear strength

1. Introduction

Soft clay is commonly defined as problematic soil, with a series of issues occurring when this type of soil is used for construction purposes, such as concrete mixtures and foundation building. It is a complicated process for construction activities to be implemented over the soft clay soils in geotechnics, particularly when designing infrastructures, EL Gendy et al. [1]. According to Foda et al. [2], clayey deposits are mainly found in coastal areas, which combine a certain amount of silt and silty sand. Shen et al. [3] reported that kaolin clay soil is available in powder form, and it is an extremely fine-grained mineral, appearing in white or nearly white color. The soil particles in a measurement are lower than 0.002 mm, and the spacing between the particles is minimal. Therefore, they exhibit cohesive properties, which are defined as cohesive soil [4]. Due to its sticky properties, clayey soil is sensitive to the variation of water, where the changes in the degree of moisture content can easily turn the soil into mud. This property leads to a higher compressibility issue, and the water retained within the soil is ready to be expelled from the soil particles when a force is applied to it. The less permeable characteristic of clay restricts water flow to discharge out, which maintains a higher water ratio within the particles than its total volume. Hasan et al. [5] stated that the massive alteration of soil volume leads to uneven

Received 26 November 2024; revised 30 March 2025; accepted 11 April 2025.
Available online 30 June 2025

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https://doi.org/10.29187/2458-973X.1186

soil settlement, inducing serious structural stability issues in the foundation system. Similarly, the higher compressibility of clay soil signifies the soil's lower bearing capacity, which cannot cater to the dead and live loads imposed by the structure and occupant [6]. Previous research by Phanikumar and Ramanjaneya [7] discovered the failure of the structure constructed on the soft clay bed, leading to the cracking of the structure due to the soil settling after the loads were applied. Yoobanpot et al. [8] reported that raw clay soil possesses a very high content of natural water and a very low undrained shear strength value (in kPa), posing a higher risk to utilize directly for construction applications.

Furthermore, Dhianty and Mochtar [9] discovered that the classification of sand with silty or clayey properties exhibits undrained shear strength between 0 and 50kPa, and the hardness is labeled as soft to medium. Jun Shen et al. [10] found that clay soils tend to deviate significantly, and shape deformation occurs instantly due to the weak absorption of loads by the soil itself. However, Suwito et al. [11] reported that areas with periodic rainfall will further deteriorate the engineering properties of clay, imposing more structural issues on the foundation system due to the constant increment of water content in the clay soil. Referring to the reviews and research data provided, unstable soils like kaolin clay are rectified with their engineering behaviors to enhance the shear strength parameters of the soil. Several techniques have been proposed to improve the soft soil, including soil stabilization and ground improvement [12, 13]. These methods enhance shear strength parameters, specifically for cohesive and fine-grained soils.

As proposed by the United Nations about the concept of sustainable development goals (SDGs), the idea and concept of sustainability have been encouraged and prioritized for application, including in the construction industry. Li et al. [14] summarized the importance of SDGs in response to the ESG (Environment, Social, and Governance) concept in response to the growing sustainability issues worldwide. Hence, the recent research on soil stabilization and ground improvement techniques has encompassed the concept of sustainable development to ensure the long-term advancement of society. Soil stabilization deals with the stabilizing function of soil with the addition of foreign materials, and curing of soil within a certain days is required before proceeding to materials investigation. Coherent with that, reinforcing the soil is not limited to clayey soil but also the black cotton soil by associating with the glass powder and plastic blends [15]. The soil-kilned and processed glass wastes were deployed within the same approach to stabilize the expansive clay soil [16]. Zaini & Hasan [17] substituted silica fume and lime for clay soil stabilization; however, the approach requires specific curing days to achieve the research's objectives. Haidder et al. [13] adopted shredded PET plastic to determine soil improvement efficiency. Apart from that, this technique is not limited to constructing foundation systems. Kumar et al. [18] utilized plastic waste to raise the strength of subgrade in the application of transportation engineering. In this research, the authors employed the stone column method, a popular ground improvement technique. It regards the inclusion of granular fabricated columns, which will be built beneath the soft clay soil, mainly the unreinforced section. With the consideration of sustainable materials, Syamsul et al. [19] applied the bottom ash to build the granular column, and Jun Shen et al. [10] used the fabricated crushed brick column as a replacement material in a partially or fully saturated bed that established a reinforced ground to strengthen the soil bearing capacity. Installing the granular column can accelerate the soil consolidation, acting as a human intervention activity [20]. Besides, the authors emphasized that using a certain amount of fiber induces a substantial effect by disturbing the soil grain interaction between the clay and additives, yielding a positive outcome. The above findings are supported by Dey & Debnath [21], where the granular column influences the consolidation of the surrounding clay. However, this effect is reduced as the distance increases. Aslani et al. [22] reported that the speed-up of the soil consolidation process is due to the provision of additional drainage by reinforcement material. Thus, referring to the soil consolidation parameters, the additional drainage reduces the soil compression index, making it less compressible upon receiving external forces.

In contrast, the annexation of coarse-type material generates positive results in expelling confined water stuck within the clay particles, compared to only pure clayey soil, which permits the higher compressibility property.

By doing so, Haddad and Shahverdi [23] reported that water pressure relief in clayey soil slashes down the bearing pressure settlement in response to installing floating and non-floating granular columns. The authors deduced that the design of granular columns unleashes an influential relationship between the shear strength improvement and the soil type. Hoque et al. [24] conducted a study regarding the effect of Area Replacement Ratio (ARR), Column Penetration Ratio (CPR), Column Height to Column Diameter Ratio (HDR), and Volume Replacement Ratio (VRR) of the fabricated column. They concluded that these ratios modify the improvement of shear strength.

(a) (b)

Fig. 1. Location of purchased materials (a) Kaolin (M) Sdn. Bhd. (b) Glowmore Express Sdn. Bhd.

Furthermore, Zaini and Hasan [25] mentioned the alteration of shear strength parameters regarding these ratios: deviatoric stress, axial strain, shear strength value, and shear strength improvement rate. However, the design of a granular column considers the scale size in either the laboratory or on-site, the column's boundary, and the column's category, which can be single or group. The application of single bottom ash column deployed by Shen et al. [3], crushed brick fabricated columns (consisting of 3 columns) applied by Jun Shen et al. [10], and both single and group bottom ash columns utilized by Syamsul et al. [19], and all the researchers yielded positive soil's improvement. Thus, using waste materials like bottom ash and plastic has been proven as a sustainable approach to enhance the engineering properties of kaolin clay soil through the ground improvement technique.

Polyethylene Terephthalate or PET is a chemical name given for this specific plastic, with the code 1 to signify the category of plastic. This plastic has a very long polymer chain, which classifies it under the generic group of polyesters [26], which can be formed through the transesterification of dimethyl terephthalate [27]. The authors mentioned that the polymerization reaction process solidifies the formation of PET plastic and has been proven to possess distinguished properties such as high-pressure resistance and mechanical strength. Due to its properties, PET plastic has been utilized in many areas, such as asphalt mix in modifying the pavement [28], acting as an antifreeze component [29], and improving soil strength [13].

Consequently, the current study deployed the stone column technique. It modified the existing approach by replacing conventional coarse aggregate, like sand, with PET plastic to rectify the engineering behaviors of kaolin soil within the laboratory scale. However, none of the previous studies have discovered the relationship between the fabricated group PET columns and the shear strength improvement of kaolin clay S300, which also considers the column ratios. This study expects the association of kaolin clay S300 and PET plastic materials to enhance the soil's fundamental geotechnical properties and the shear strength parameters. Thus, it centralizes the construction of PET columns on the soft kaolin clay with respective designs, which were then investigated using the UCT machine. In addition, this proposal was crucial in highlighting the integration of PET columns in increasing soil-bearing capacity. Coherently, both materials' physical and mechanical properties were explored by conducting the relevant tests, which played crucial roles in the design of group PET columns. Therefore, the objectives of this study were (1) to identify the kaolin clay soil and PET plastic in terms of physical and mechanical properties, and (2) to examine the shear strength parameters of unreinforced and reinforced kaolin clay soil with distinct PET column designs.

2. Setup of experiment

The first part of this chapter reviewed the materials utilized in the research, which were kaolin clay S300 and PET plastic. The following section discusses the procedures and standards deployed to implement all the necessary investigative tests.

2.1. Research materials

The primary material of this study was kaolin clay S300, which acts as the clayey soil component that meets all the requirements of being a fine-grained aggregate. Kaolin clay S300 material was purchased from Kaolin (M) Sdn. Bhd is a company in Puchong, Selangor, Malaysia, as shown in Fig. 1(a). This material was selected because of the convenience of kaolin clay S300's solubility in water, which can form

Table 1. The physical properties of kaolin clay S300 [19,34].

No.	Parameter	Value
1	Natural water content (%)	1.58
2	Specific gravity	2.63
3	Atterberg limit;	
	Liquid limit, LL (%)	38
	Plastic limit, PL (%)	32
	Plastic index, PI (%)	6
4	Soil content;	
	Sand (%)	0
	Silt (%)	47
	Clay (%)	53

Table 2. Mechanical properties of kaolin clay S300.

Parameter	Researcher data		
	[10]	[19]	[5]
MDR (Mg/m^3)	1.59	1.58	1.60
OMO (%)	20.50	18.40	19.00
Permeability coefficient (m/s)	6.05×10^{-12}	2.57×10^{-8}	2.27×10^{-12}

Table 3. The significant mineralogy content of kaolin clay S300 [17].

Chemical composition	Value (%)
SiO_2	66.11
CaO	0.08
Al_2O_3	20.15
K_2O	2.85
MgO	1.23
Fe_2O_3	0.73
Total	91.15

into a slurry product easily when contacted with a mild amount of water [11]. Regarding its chemical formula, kaolin clay, which has kaolinitic minerals, has the general formula of Al2Si2O5(OH)4, which makes it possess the hydrophilic characteristic. The name is aluminium silicate hydroxide based on its formula, which consists of aluminium, silicon, oxygen, and hydroxide components. As mentioned by Syamsul et al. [19] and Hasan et al. [30], this material is convenient for producing a homogeneous soft clay specimen, which is significant for ensuring the accuracy and consistency of material content during the data acquisition process. Table 1 summarizes the physical engineering properties of kaolin clay S300 based on the relevant geotechnical parameters such as soil categorization and natural moisture content. Referring to Table 2, the mechanical properties of kaolin clay S300 were deduced based on the previous data, mainly the maximum dry density (MDR), optimum moisture content (OMC), and permeability coefficient. Table 3 summarizes the significant chemical composition of kaolin clay S300.

The second material was regarding the reinforcing component, PET plastic. This plastic was purchased from the ground floor of Glowmore Express (M) Sdn. Bhd is a recycling company located in Pelabuhan Klang, Selangor, Malaysia, as depicted in Fig. 1(a) and (b). There were several reasons for choosing PET plastic: (1) sustainable material as it was from the disposal of PET plastic, mainly ground from unwanted PET bottle and containers, thus reducing the volume of disposal in the landfills area (2) cost-effective (3) durable as it was proven to utilize in many civil engineering fields to act as a coarse-grained material replacement alternative, for instance, soil enhancement and pavement subgrade application [31, 32]. Zair et al. [33] reported that PET plastic has a breaking strength of 50 MPa, a tensile strength of about 1700MPa, and a water absorption rate of 0.5% (measured after 24 hours), which these characteristics and the mentioned reasons by the authors made it to be the selected substituting materials in this research.

2.2. Research approaches

Referring to the study objectives stated in the previous chapter, the research materials, kaolin clay S300 and PET plastic, must be ascertained with relevant geotechnical tests as the primary phase in this investigation. Coherently, the phase was classified into two sections, kaolin clay examination and PET plastic examination, as stated in Table 4, with the corresponding American Society for Testing and Materials (ASTM) and British Standards (BS) guidelines. The tests included for kaolin clay S300 were hydrometer, Atterberg limit, falling head, and standard proctor. The replacement material encompasses sieve analysis, relative density, and constant head. However, a small pycnometer test was deployed for both materials to yield a specific gravity result. Similarly, the Unconfined Compression Test (UCT) was implemented to assess the shear strength parameters of pure kaolin clay or unreinforced specimens. PET columns reinforced with kaolin clay or denoted as reinforced specimens with the standard of ASTM D 2155.

The first test began with the deployment of a hydrometer test, aiming to obtain the data on particle size distribution (PSI), as shown in Fig. 2(a). The kaolin powder from the grade S300 was air-dried and passed through the 0.063 mm sieve, which met the requirement for fine particles. The Wet sieving method was chosen from the standard operating procedures instead of the dry sieving method due to the tendency of kaolin clay particles to clump together. Stoke's law was applied to the hydrometer application, in which a hydrometer bulb was used to fill the solution. Hence,

Table 4. Relevant testing for kaolin clay S300, PET plastic, and reinforced kaolin.

Research material	Investigation approach	Standard
Kaolin clay S300	Hydrometer	BS 1377: Part 2: 1990: 8.3
	Atterberg limits;	
	Liquid limit	BS 1377: Part 2: 1990: 4.3
	Plastic limit	BS 1377: Part 2: 1990: 5.3
	Pycnometer	BS 1377: Part 2: 1990: 8.3
	Standard proctor	BS 1377: Part 2: 1990: 3.3
	Falling head	ASTM D 2434
PET plastic	Sieve analysis	BS 1377: Part 2: 1990: 9.6
	Relative density	BS 1377: Part 2: 1990: 4
	Pycnometer	BS 1377: Part 2: 1990: 8.3
	Constant head	ASTM D 2434
Reinforced kaolin	Unconfined Compression Test (UCT)	ASTM D 2166

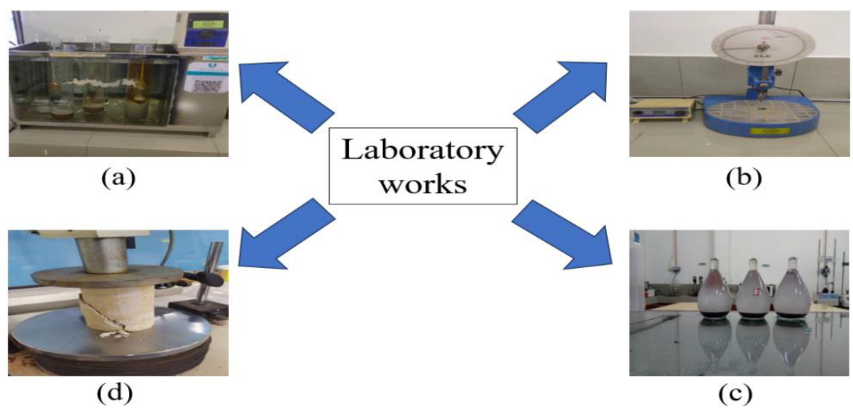


Fig. 2. The implementation of laboratory works (a) Hydrometer apparatus, (b) cone penetrometer, (c) small pycnometer bottles, (d) unconfined compression machine.

the description of drag force in the hydrometer of fluid provided the understanding of the behavior of kaolin clay particles. For the dry sieving method, sieve analysis was applied to a coarse-grained material, PET plastic. The selected sieve sizes were 4.75 mm, 2.36 mm, 1.18 mm, 0.3 mm, and 0.063 mm. The PET plastic was poured in descending order of sieve sizes, from sieve 4.75 mm to sieve 0.06 mm, covered with a lid at the top and a pan at the bottom. The following investigation was the Atterberg limit test, which comprised the Liquid Limit (LL) and Plastic Limit (PL) tests. The LL test was executed through the semi-automated cone penetrometer by recording the dial reading to the nearest 0.1 mm, as demonstrated in Fig. 2(b). In contrast, the PL test was implemented by molding kaolin slurry into a spherical shape and measuring the loss in moisture content after drying the kaolin in the oven overnight.

Subsequently, Fig. 2(c) depicts the small pycnometer test to ascertain the specific gravity of kaolin clay and PET plastic. The pycnometer bottles were filled with dry soil and water, and 20 g of oven-dried samples were prepared. After filling it with water and covering it with a stopper, the pycnometer bottle was placed in vacuum desiccators for 24 hours to stabilize the water vapor. This step was repeated, and the necessary data were utilized to compute the specific gravity of each material. Data accuracy was ensured by ensuring that the obtained specific gravity did not alter by more than 0.03 Mg/m3.

The standard proctor analysis was implemented to determine the maximum dry density (MDR) and optimum moisture content (OMC) of kaolin clay, and the values were to be used to design the PET-reinforced kaolin clay specimen. The test procedure was varied according to the different added water volumes, resulting in distinct dry density and dry unit weight data. Around 3 to 4 kg of oven-dried kaolin soil was used for mixing purposes, and the compaction work was done by dropping a 2.5 kg hammer from a distance of 250 mm above the soil. The entire procedure was repeated 6 times, where every repetition increased 5% of moisture content. The subsequent examination was the hydraulic conductivity of kaolin clay and PET plastic, in which the falling head and constant head tests were conducted, respectively. Both tests followed the same standard, ASTM D 2434, where the water flow rate through the

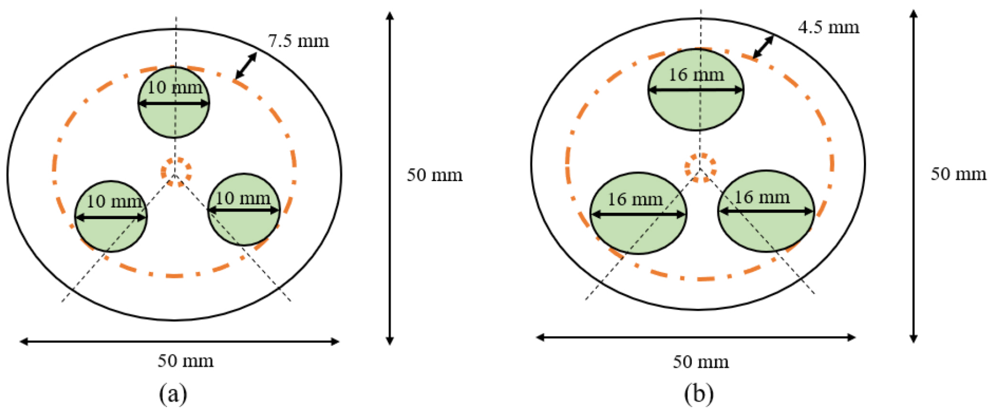


Fig. 3. The group PET column design (a) 10 mm diameter, (b) 16 mm diameter.

Table 5. The design of the PET column corresponds to its density.

Column diameter (mm)	Column length (mm)	Column volume (mm^3)	Density of PET (Mg/m^3)	Mass of PET required (g)
10	60	4712	0.47	2.21
	80	6283		2.95
	100	7853		3.69
16	60	12063		5.66
	80	16084		7.55
	100	20106		9.44

soil was obtained, which was crucial for computing the permeability coefficient.

Before accessing the shear strength parameters of soil, the unreinforced and reinforced specimens were prepared based on the MDR and OMO values generated from the proctor curve. The current research utilized 330g of air-dried kaolin powder to prepare the specimen with a customized mold, 100 mm height, and 50 mm diameter. Afterward, the 10 mm and 16 mm diameter holes were drilled using the respective sizes of drilling bits on the unreinforced kaolin specimen. Reinforcement was achieved by installing the group PET columns based on the design depicted in Fig. 3, as referred to in Tables 4 and 5, where 60 mm, 80 mm, and 100 mm height columns were constructed, respectively. During this stage, the poured-in PET plastic was hit by the backside of the drilling bits, creating a vacuum area within the PET column. The PET columns reinforced the kaolin specimen, which was then extruded out with the assistance of an extruder. In Table 5, each group's PET column design was expressed in the column design section; for instance, GC1060 denoted group PET columns with 10 mm diameter and 60 mm height.

The investigation of shear strength parameters was obtained through conducting UCT, where the placement of unreinforced and reinforced specimens in the center of the UCT machine is shown in Fig. 2(d). The calibration works were done before the experiment started, and the time interval of 20 seconds, load dial reading, and specimen deformation were recorded. The test was terminated when the load dial presented a decreasing or constant load with increasing strain.

Table 6. The group PET column design with the respective ratios.

Column design	CPR	HDR	VRR (%)
Control	–	–	–
GC1060	0.6	6	2.40
GC1080	0.8	8	3.20
GC10100	1.0	10	4.00
GC1660	0.6	3.75	6.14
GC1680	0.8	5	8.19
GC16100	1.0	6.25	10.24

3. Results and discussion

This chapter separated the analysis of results into three parts, where the first part reviewed the geotechnical characteristics obtained from the tests conducted, as stated in Table 3. The following part discusses the shear strength parameters generated from the implementation of UCT, such as the shear strength value and its improvement rate based on the unreinforced specimen. The third part analyzed the column ratios, including the ARR, HDR, and VRR, regarding the shear improvement rate using the correlation technique. The regression coefficient, R2, measured the correlation accuracy.

Table 7. Kaolin clay S300 engineering characteristics.

Research material	Parameter	Value
Kaolin clay S300	AASHTO	A-4
	USCS chart	ML
	Liquid limit (LL)	37.48%
	Plastic limit (PL)	31.58%
	Plasticity index (PI)	5.90%
	Maximum dry density (MDR)	1.55 Mg/m^3
	Optimum Moisture Content (OMO)	19.10%
	Specific gravity	2.59
	Permeability coefficient	4.097×10^{-8} m/s

3.1. Geotechnical characteristics of kaolin clay S300 and PET plastic

As follows the ASTM and BS guidelines, all the proposed tests, as stated in Table 3, were successfully implemented, and the properties of kaolin clay were summarized in Table 7.

From Table 7, the soil categorization standard, AASHTO, had classified the kaolin clay S300 for A-4, showing that this material was a silty-clay mineral with more than 35% of soil passing through the 0.075 mm sieve. The measurement was assisted by the value of LL, PL, and PI values yielded from the Atterberg limit test, which deduced the ML value based on the USCS plasticity chart. It demonstrated that the kaolin clay S300 was inorganic silt and possessed the characteristics of very fine sands with slight plasticity. The above results were supported by Zaini and Hasan [25], in which the authors obtained the identical AASHTO classification, A-4. The hydrometer test concluded the PSI of kaolin clay S300. It determined this soil as a poorly graded sand, in which the detected majority of soil particles ranged from 0.005 mm to 0.008 mm, as depicted in Fig. 4(a).

In contrast, the proctor curve generated a slight difference in the values of MDR and OMO, with 1.55 Mg/m3 and 19.10%, respectively, as shown in Fig. 5. Hasan et al. [5] presented the MDR value as 1.60 Mg/m3 and 19.00% for the OMO value. However, Hoque et al. [24] reported a bigger gap in value for these two parameters, with 1.65 Mg/m3 for MDR and 18.20% for OMO value. The subtle differences in these values were attributed to the compaction effort and the compacting device's weight, producing varying results.

The small pycnometer test yielded a specific gravity value of 2.59. The value proved that kaolin clay S300 was denser than water, with a mass-of-unit volume ratio of 2.59 times that of water. Suwito et al. [11] and [35] reported the same type of kaolin possessed values of 2.63 and 2.62, which made the difference between 0.03 and 0.04. The slight data variation can be classified as water evaporation when the specimen was placed inside the vacuum desiccator. Furthermore, the execution of the permeability investigation step obtained the coefficient of hydraulic conductivity of kaolin clay S300, with the value of 4.097 × 10–8 m/s. It signified that this material was less permeable soil, where the value was less than the 1 × 104 m/s limit.

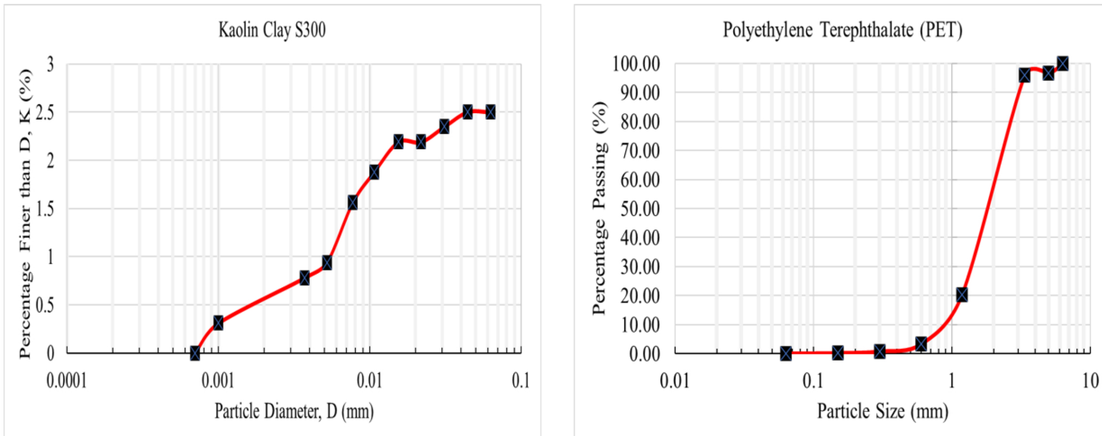
Similarly, the geotechnical properties of PET plastic were tabulated in Table 8, referencing respective standards as stated in Table 4.

Due to its natural behavior, the PET plastic underwent the dry sieving process, with most of the particles retained on the 1.18 mm sieve size, as depicted in Fig. 4(b). Hence, this particle size of PET plastic was selected as the reinforcing substituent for PET column fabrication. Like every type of soil, the PET plastic was examined under the AASHTO soil classification system and obtained the value of A-1-a. This categorization indicated that PET plastic was a granular material, with less than 35% of the material passing through the No. 200 sieve. PET was also depicted as behaving like stone fragments, minerals, gravel, and sand, which had a good to excellent rating as a subgrade. The above data were supported by Haider et al. [13], in which the shredded PET material was a supporting element for the long-term durability and stability of the soil stabilization process. Similarly, Arulajah et al. [36] obtained the identical result with the current findings, verified by its uniformity and curvature coefficient.

The relative density test generated PET plastic's maximum and minimum dry density, 0.530 Mg/m3 and 0.430 Mg/m3, respectively. By determining its in-situ density, 0.48 Mg/m3, the computed relative density was approximately 56.59%. This value signified that PET plastic has a medium range of compactness when considered as cohesionless soil. This was reflected in the generation of the permeability coefficient, which was obtained at 2.603 × 10–4 m/s. Therefore, it was a coarse-grained aggregate as it could solve the issue of kaolinitic clay, for example, providing additional drainage to discharge the excessive water, enhancing the soil's resistivity towards the axial load, and reducing the soil's settlement rate.

3.2. Examination of unreinforced and reinforced kaolin clay S300 with PET columns

The determination of unreinforced and reinforced kaolin was executed via the implementation of UCT, in which the shear strength parameters were obtained, including the shear strength value and shear strength improvement. The data were tabulated in



(a) (b)

Fig. 4. The particle size distribution (PSI) of research materials: (a) Hydrometer test for kaolin clay S300, (b) sieve analysis for PET plastic.

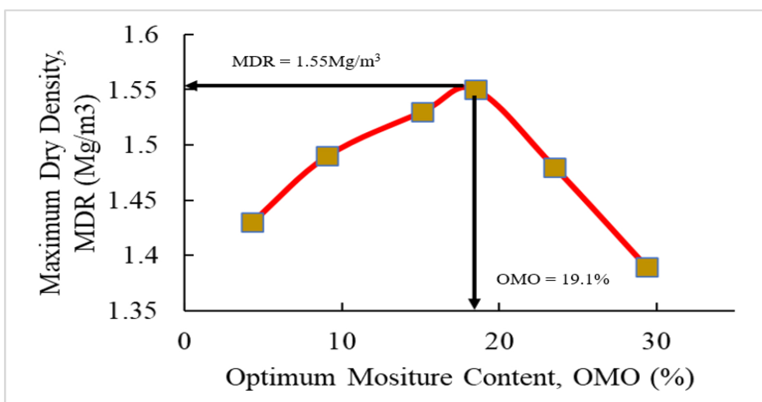


Fig. 5. The proctor curve of kaolin clay S300.

Table 8. PET plastic engineering characteristics.

Research material	Parameter	Value
PET plastic	AASHTO	A-1-a
	Maximum dry density	0.530 Mg/m^3
	Minimum dry density	0.430 Mg/m^3
	Relative density	56.59%
	Specific gravity	1.39
	Permeability coefficient	2.603×10^{-4} m/s

Table 9, corresponding to the respective column ratios, ARR, HDR, and VRR.

Table 9 recorded the highest values at the GC10100 design, with the SH and ΔSH values of 17.38 kPa and 48.23%, respectively. In contrast, the lowest values were yielded at the GC16100 design, with only 13.04 kPa or 11.35% improvement. From the GC16100 design, the specimen had improved by 1.33kPa, much lower than the GC10100 design, which showed an improvement of 5.67kPa. In general, the SH value showed an inconsistent trend of improvement, which translated to the trend of ΔSH.

By looking into the column ratio of CPR, the critical value of CPR occurred at the G10100 design, signifying that the 1.0 CPR ratio generated the optimum result. Coherently, the GC16100 design produced the least ΔSH; therefore, the authors concluded that the diameter of PET columns influenced the SH value. Based on the stated ratio value of HDR in Table 9, the range of HDR from 6–10 improved from 38% to 48%. However, Hasan et al. [5] reported that the optimum range of HDR is within the value of 4 to 7. This was due to the different diameters of fabricated columns constructed beneath the kaolin clay. The VRR ratio also presented an inversely proportional trend to the SH and ΔSH values. The current results were supported by Najjar [37], where the soil disturbance level increases as the replacement ratio increases.

Regarding the same number of fabricated granular columns in ground improvement, Jun Shen et al. [10] obtained the CPR value at 1.0, HDR value of 3.75–6.25, and VRR of 6.14–10.24%. However, a single granular column utilization yielded a different column ratio, in which the ideal ratios of CPR, HDR, and

Table 9. The results of shear strength parameters in accordance with the column ratios.

Column design	CPR	HDR	VRR (%)	Shear strength, SH (kPa)	Shear strength improvement, ΔSH (%)
Control	–	–	–	11.71	–
GC1060	0.6	6	2.40	17.91	46.79
GC1080	0.8	8	3.20	16.25	38.77
GC10100	1.0	10	4.00	17.38	48.42
GC1660	0.6	3.75	6.14	14.17	21.00
GC1680	0.8	5	8.19	14.36	22.63
GC16100	1.0	6.25	10.24	13.04	11.35

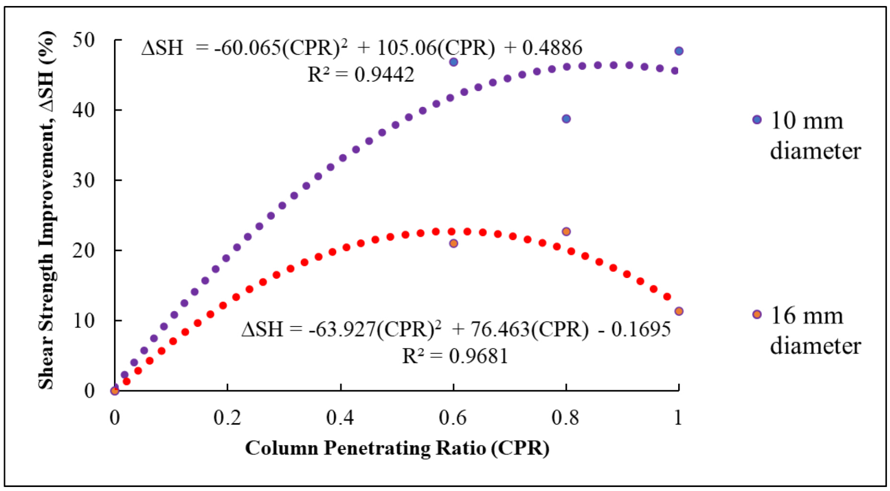


Fig. 6. Correlation of column penetrating ratio (CPR) to the shear strength improvement (ΔSH).

VRR are 0.8, 4.28–7.14%, and 4.70–7.84%, respectively [38]. The replaced material, column designs, and preparation methods influenced the divergence of these ratios. Moreover, particle size selection has also substantially influenced the shear strength reinforcement, which is monitored by the ratio of column diameter to particle size. Hasan et al. [38] emphasized that the ratio significantly influences the reinforced specimen contacts with varying compression areas during the shearing process. Therefore, the specimen receives different axial loads aligned with the diameter values. As stated by Najjar et al. [39], the drilling effect produces a notable soil disturbance level, which reduces the initial shear strength of the soil.

Analyzing the morphological characteristics of PET plastic demonstrates a smooth, asymmetric, and spherical shape. The asymmetric characteristic signifies that the PET structures have no interconnection with each other and a variation of molecular arrangement [40]. However, the smooth PET structure, proper selection of PET particle size in 1.18 mm, and appropriate arrangement of PET columns allow the movement of pore water to discharge effectively via the provision of an additional drainage path. Although specific water molecules adhered to the surroundings of the specimen due to the lower PET surface energy, the proper design of PET columns was still able to offset the moderate adhesion property of PET plastic.

3.3. Correlation of column ratios to the shear strength and shear strength improvement value

This sub-chapter deployed the correlation technique to correlate the respective column ratios, CRP, HDR, and VRR, into a single graph, with a simplified power one function and regression coefficient to streamline the engineering parameters' complexity.

3.3.1. Correlation of column penetrating ratio to the shear strength improvement

Fig. 6 demonstrates the graph of the correlation of column penetrating ratio (CPR) to the shear strength improvement (ΔSH). With the assistance of data from Table 9, it was noticed that the critical CPR value fell to 1.0, where 10 mm diameter group PET columns yielded the peak value. In comparison, 16 mm diameter group PET columns produced the lowest value. As the diameter of columns was increased from 10 mm to 16 mm, the area of soil disturbance increased drastically, given the same length of columns. Thus,

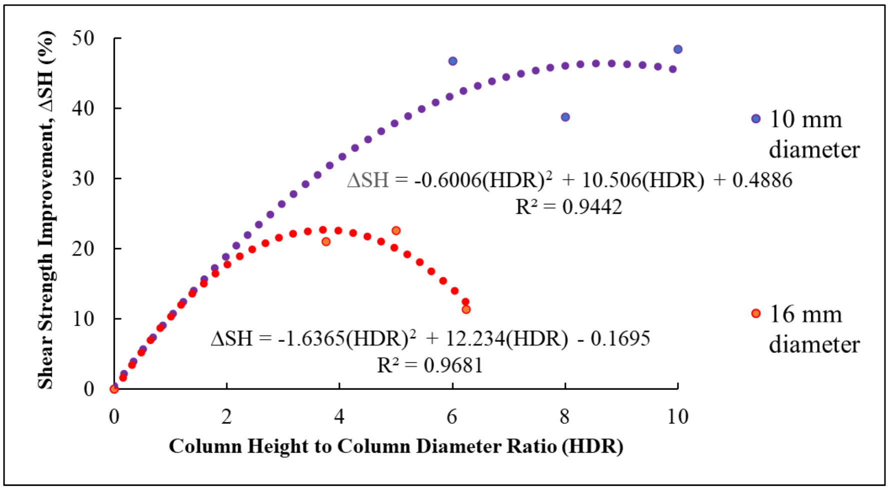


Fig. 7. Correlation of column height to column diameter ratio (HDR) to the shear strength improvement (ΔSH).

the shear strength of the surrounding unreinforced area was reduced, although the reinforcement works were carried out afterward. The installation of group PET columns that provided a certain degree of stiffness did not compromise the soil's disturbance level, which caused the drop in shear strength. Coherent with that, the axial load applied to the top part of the reinforced PET 16 mm group columns specimen with 1.0 CPR had not transferred the loading effectively to the bottom part of the specimen, which resulted in the early failure of the specimen, such as column bulging. Similarly, the 10 mm diameter group PET columns transferred the loads efficiently, which, in turn, absorbed a certain magnitude of forces from the compacted kaolin due to the minimum level of disturbance during the PET columns installation process. Previous analyses that utilized group crushed brick columns reported the same data, in which 1.0 CPR was the critical ratio [10]. The authors mentioned that load transference was effectively carried out when the pressure was spread across the specimen, which prolonged the failure of the specimen under the shearing process. Eq. (1) displayed the engineering function of group PET columns for 10 mm diameter with the R2 = 0.9442, and Eq. (2) showed the function of the 16 mm group PET column with the R2 = 0.9681.

$$\Delta SH = -60.065(CPR)^2 + 105.06\,(CPR) + 0.4886 \quad (1)$$

$$\Delta SH = -63.927(CPR)^2 + 76.463\,(CPR) - 0.1695 \quad (2)$$

3.3.2. Correlation of column height to column diameter ratio to the shear strength improvement

The correlation graph of HDR to ΔSH was depicted in Fig. 7. The optimum value of the HDR ratio was 10, which produced the SH value of 17.38 kPa that yielded 48.42% of the ΔSH value. Coherently, previous studies that utilized the group fabricated columns had reported that the optimum range of HDR was within 6 to 10 times, as reported by Hasan et al. [41]. However, the HDR ratio from 3.75 to 6.25 only generated the ΔSH from around 11% to 22%, which showed a difference in ΔSH of approximately 20%. Jun Shen et al. [10] reported the lowest value of ΔSH production when a ratio of 3.25HDR was applied. The authors summarized that the drop in ΔSH was due to the insufficient granular material supply concerning the column height, with its diameter for fabricating the reinforcement column. It led to the expansion of the column when the UCT machine examined it. The regression value, R2 = 0.9442, was displayed in Eq. (3) for 10 mm group PET columns, and R2 = 0.9681 was shown in Eq. (4) for 16 mm group PET columns.

$$\Delta SH = -0.6006(HDR)^2 + 10.506\,(HDR) + 0.4886 \quad (3)$$

$$\Delta SH = -1.6365(HDR)^2 + 12.234\,(HDR) - 0.1695 \quad (4)$$

3.3.3. Correlation of volume replacement ratio to the shear strength improvement

The correlation graph of VRR to ΔSH was demonstrated in Fig. 8. The lowest value of the kaolin clay improvement rate occurred when VRR = 10.24%, and

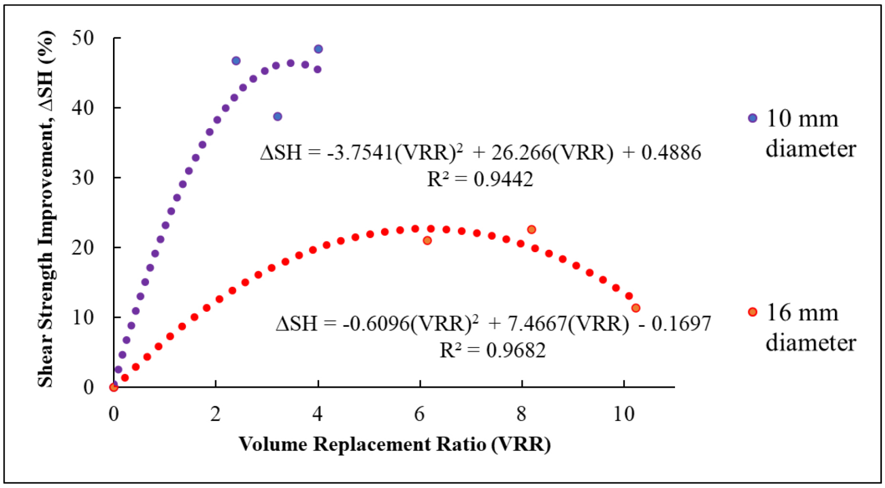


Fig. 8. Correlation of volume replacement ratio (VRR) to the shear strength improvement (ΔSH).

the highest value was noticed when a 4.00% VRR ratio was applied to the fabrication of group PET columns. Najjar et al. [42] discovered that the replication of homogeneous stone columns on a very soft to soft clay specimen was a challenging process due to the natural behavior of the soil. Although Table 9 displayed a certain degree of alteration of SH and ΔSH by the VRR ratio, it was deduced that the increase in the VRR ratio led to the reduction of the SH and ΔSH values. The initial state of kaolin clay S300 turned from undisturbed to disturbed conditions, in which the SH value was certainly lowered as the soil particles tended to lose their charge. Thus, a certain level of dispersion of soil particles occurred when drilling bits were utilized to drill the pre-mixed kaolin powder. The correlation functions for the 10 mm and 16 mm diameter of group PET columns were shown in Eqs. (5) and (6), with the regression coefficients R2 = 0.9442 and R2 = 0.9682, respectively.

$$\Delta SH = -3.7541(VRR)^2 + 26.266\,(VRR) + 0.4886 \quad (5)$$

$$\Delta SH = -0.6096(VRR)^2 + 7.4667\,(VRR) - 0.1697 \quad (6)$$

4. Conclusions

The current study utilized PET plastic as a replacement material for coarse aggregate, which yielded a positive result by modifying the stone column method's existing ground improvement technique. The geotechnical properties of research materials, kaolin clay S300 and PET plastic, were examined following the appropriate tests with standards. Via the UCT, the shear strength parameters of unreinforced and reinforced kaolin clay S300 were obtained, and the degree of improvement was measured. Hence, several conclusions and recommendations can be deduced based on this study.

i) Kaolin clay S300 was investigated as a soft clay soil that was identical to the previous studies. The AASHTO and USCS plasticity charts were utilized to categorize this soil, which was silty soil with high plasticity. These results were similar. Besides, implementing the proctor test generated the value of MDR and OMO, with 1.55 mg/m^3 and 19.1%, respectively. Regarding the coefficient of permeability, it was checked to be a less permeable soil, with a value of less than 1 × 10ˆ (–4 m/s). Thus, it was a highly compressible soil.
ii) Using the same geotechnical test and standards, the PET plastic was verified to behave like a coarse-grained material based on the dry sieve analysis. With the same soil classification standard, AASHTO classified PET as sand or gravel-type material. Furthermore, the relative density test measured the maximum and minimum dry densities, resulting in a relative density index of 56.59%. Similarly, the PET plastic was tested for its specific gravity, with a value of 1.39. The execution of the constant head test determined the hydraulic conductivity of PET plastic, which was 2.603 × 10^{-4} m/s. The overall assessment referred to PET plastic as a potentially sustainable conventional coarse aggregate substitution material.
iii) Deploying PET columns enhanced the kaolin soil efficiently, yielding an improvement rate from 11.35% to 48.42%. Furthermore, the

establishment of regression equations confirmed a strong correlation between the shear strength parameters, as observed by the R2 value higher than 0.9. This situation can be explained by providing additional drainage for discharging pore water and enhancing soil stiffness. The column ratios exerted a substantial influence, with the optimum CPR value lying at 1.0, the HDR value in the range of 6–10, and the VRR value lying at 2.4–4.0%.

iv) Periodic checking of the installed PET column beneath the soft clay soil is necessary to ensure the structure's performance in enhancing the shear strength improvement rate.

v) Similar research can be repeated using different particle sizes of PET and the mixture of PET with other coarse materials like bottom ash to examine the potential combination to improve the optimum shear strength.

vi) The existing data can be used to compare with the data produced from the construction site. The PET columns were produced homogeneously during the experimental works, while the stone columns' dimensions at the construction site might have a larger measurement deviation.

Acknowledgement

The authors would like to express their gratitude to Universiti Malaysia Pahang Al-Sultan Abdullah (UMPSA) and the Ministry of Higher Education Malaysia for assisting and providing financial support through the UMPSA Research Grant. RDU223309, and MYBRAIN 2.0 Scholarship. The cooperation given by all parties involved in this research is greatly acknowledged.

Conflict of interest

The authors declare that they have no conflict of interest.

Data availability statement

The authors confirm that the data supporting this study's findings are available within the article. Raw data supporting this study's findings are available from the corresponding author upon reasonable request.

Author's contributions

None.

Ethics

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

Use of Ai for writing assistance

Not declared.

Peer-review

Externally peer-reviewed.

References

1. El Gendy M, Mohamady A, Nabil T, Shams M. Effect of the Presence of Soft Clay on the Structural Design of Highway Sections. *Port-Said Engineering Research Journal*. 2019;23(2):26–33. doi:10.21608/pserj.2019.49559.
2. Foda T, Abdelkader A, Ibrahim HM. A Review of Soil Stabilization Using Stone Columns Technique. 2023.
3. Shen NJ, Hasan M, Amina N, Hashim A. The Influence of Bottom Ash Column in the Geotechnical Properties Enhancement of Soft Clay Soil. 5(5):1–13.
4. Safi W, Singh S. Efficient & effective improvement and stabilization of clay soil with waste materials. *Mater Today Proc*. 2021;51:947–55. doi:10.1016/j.matpr.2021.06.333.
5. Hasan M, et al. Sustainable ground improvement method using encapsulated polypropylene (PP) column reinforcement. *IOP Conf Ser Earth Environ Sci*. 2021;930(1). doi:10.1088/1755-1315/930/1/012016.
6. Hasan M, Jusoh WNW, Chee WS, Hyodo M. The undrained shear strength of soft clay reinforced with group encapsulated lime bottom ash columns. *International Journal of GEOMATE*. 2018;14(46):46–50. doi:10.21660/2018.46.45208.
7. Phanikumar BR, Raju ER. Compaction and strength characteristics of an expansive clay stabilised with lime sludge and cement. *Soils and Foundations*. 2020;60(1):129–38. doi:10.1016/j.sandf.2020.01.007.
8. Yoobanpot N, Jamsawang P, Horpibulsuk S. Strength behavior and microstructural characteristics of soft clay stabilized with cement kiln dust and fly ash residue. *Appl Clay Sci*. 2017;141:146–56. doi:10.1016/j.clay.2017.02.028.
9. Dhianty E, Mochtar IB. Method of removing secondary compression on clay using preloading. *MATEC Web of Conferences*. 2018;195:1–10. doi:10.1051/matecconf/201819503006.
10. Jun Shen N, Hasan M, Yong Ler L. Influence of Crushed Brick Columns on Geotechnical Properties of Expansive Soil. *J Teknol*. 2024;86(4). doi:10.11113/jurnalteknologi.v86.21191.
11. Suwito AR, et al. Basic Geotechnical Characteristic of Soft Clay Stabilised with Cockle Shell Ash and Silica Fume. 2024;4:255–60. doi:10.15282/construction.v4i2.11110.

12. Ray P, Roy S. An Analytical Review on Comparative Analysis of Ground Improvement Using Various Admixtures. *Journal of Mines, Metals and Fuels*. 2024:1939–53. doi:10.18311/jmmf/2023/35343.
13. Haider AB, Iravanian A, Selman MH, Ekinci A. Using Waste PET Shreds for Soil Stabilization: Efficiency and Durability Assessment. *International Journal of Geosynthetics and Ground Engineering*. 2023;9(4). doi:10.1007/s40891-023-00473-8.
14. Li TT, Wang K, Sueyoshi T, Wang DD. ESG: Research progress and future prospects. *Sustainability (Switzerland)*. 2021;13(21). doi:10.3390/su132111663.
15. Tsegaye Woldesenbet T. Strength Improvement of Black Cotton Soil Using Plastic Bottles and Crushed Glass Wastes. *Journal of Engineering (United Kingdom)*. 2023;2023. doi:10.1155/2023/1583443.
16. Tsegaye Woldesenbet T. Experimental Study on Stabilized Expansive Soil by Blending Parts of the Soil Kilned and Powdered Glass Wastes. *Advances in Civil Engineering*. 2022;2022. doi:10.1155/2022/9645589.
17. Zaini MSI, Hasan M. Effect of Optimum Utilization of Silica Fume and Lime On the Stabilization of Problematic Soils. *International Journal of Integrated Engineering*. 2023;15(1):352–66. doi:10.30880/ijie.2023.15.01.032.
18. Kumar M, Azhar M, Mondal S, Singh RP. Stabilization of expansive soil subgrade by waste plastic. *Arabian Journal of Geosciences*. 2022;15(10). doi:10.1007/s12517-022-10112-7.
19. Syamsul M, Zaini I, Hasan M, Nursyafiqah W, Wan B. Utilization of bottom ash waste as a granular column to enhance the lateral load capacity of soft kaolin clay soil. *Environmental Science and Pollution Research*. 2023. doi:10.1007/s11356-023-25966-x.
20. Correia NS, Rocha SA, Lodi PC, McCartney JS. Shear strength behavior of clayey soil reinforced with polypropylene fibers under drained and undrained conditions. *Geotextiles and Geomembranes*. 2021;49(5):1419–26. doi:10.1016/j.geotexmem.2021.05.005.
21. Dey AK, Debnath P. Empirical approach for bearing capacity prediction of geogrid-reinforced sand over vertically encased stone columns floating in soft clay using support vector regression. *Neural Comput Appl*. 2020;32(10):6055–74. doi:10.1007/s00521-019-04092-1.
22. Aslani M, Nazariafshar J, Ganjian N. Experimental Study on Shear Strength of Cohesive Soils Reinforced with Stone Columns. *Geotechnical and Geological Engineering*. 2019;37(3):2165–88. doi:10.1007/s10706-018-0752-z.
23. Haddad A, Shahverdi M. Evaluation of Recycled Materials as Aggregate of End Bearing and Floating Stone Columns: A Comparative Study. *Journal of Rehabilitation in Civil Engineering*. 2021;9(3):61–74. doi:10.22075/jrce.2021.21286.1443.
24. Hoque MI, Hasan M, Mim NJ. Shear Strength of Soft Clay Reinforced With Single Encased Stone Dust Columns. *J Teknol*. 2023;85(5):27–34. doi:10.11113/jurnalteknologi.v85.19879.
25. Zaini MSI, Hasan M. Shear Strength of Soft Soil Reinforced with Singular Bottom Ash Column. *Construction*. 2024;4(1):82–90. doi:10.15282/construction.v4i1.10448.
26. dos Ferreira SJW, Senez PC, Casagrande MDT. Pet fiber reinforced sand performance under triaxial and plate load tests. *Case Studies in Construction Materials*. 2021;15. doi:10.1016/j.cscm.2021.e00741.
27. Soong YHV, Sobkowicz MJ, Xie D. Recent Advances in Biological Recycling of Polyethylene Terephthalate (PET) Plastic Wastes. *MDPI*. 2022. doi:10.3390/bioengineering9030098.
28. Choudhary R, Kumar A, Murkute K. Properties of waste polyethylene terephthalate (PET) modified asphalt mixes: Dependence on PET size, PET content, and mixing process. *Periodica Polytechnica Civil Engineering*. 2018;62(3):1–9. doi:10.3311/PPci.10797.
29. Gao Z, Ma B, Chen S, Tian J, Zhao C. Converting waste PET plastics into automobile fuels and antifreeze components. *Nat Commun*. 2022;13(1). doi:10.1038/s41467-022-31078-w.
30. Shen NJ, Hasan M, Anuar NN. Construction of coconut shell column for the enhancement of expansive soil. *Magazine of Civil Engineering*. 2024;(8):17. doi:10.34910/MCE.132.4.
31. Zhu J, Saberian M, Li J, Maqsood T, Yang W. Performance of clay soil reinforced with PET plastic waste subjected to freeze-thaw cycles for pavement subgrade application. *Cold Reg Sci Technol*. 2023;214. doi:10.1016/j.coldregions.2023.103957.
32. Alvarez A, Sosa J, Duran G, Pacheco L. Improved mechanical properties of a high plasticity clay soil by adding recycled PET. *IOP Conf Ser Mater Sci Eng*. 2020;758(1). doi:10.1088/1757-899X/758/1/012075.
33. Ben Zair MM, Jakarni FM, Muniandy R, Hassim S. A brief review: Application of recycled polyethylene terephthalate in asphalt pavement reinforcement. *MDPI*. 2021. doi:10.3390/su13031303.
34. Damoerin D, Prakoso WA, Utami Y. Improving shear strength of clay by using cement column reinforcement under consolidated undrained test. *International Journal of Technology*. 2015;6(4):709–17. doi:10.14716/ijtech.v6i4.1206.
35. Hasan M, Pangee N, Husaini NA. Strength of Soft Clay Reinforced with Square and Triangular Pattern Encapsulated Bottom Ash Columns. Second International Conference on Science, Engineering & Environment. (November), 2016. p. 21–23, [Online]. Available: internal-pdf://214.47.198.8/Strength Of Soft Clay Reinforced With square a.pdf.
36. Arulrajah A, Perera S, Wong YC, Horpibulsuk S, Maghool F. Stiffness and flexural strength evaluation of cement stabilized PET blends with demolition wastes. *Constr Build Mater*. 2020;239:117819. doi:10.1016/j.conbuildmat.2019.117819.
37. Najjar SS. A State-of-the-Art Review of Stone/Sand-Column Reinforced Clay Systems. *Geotechnical and Geological Engineering*. 2013;31(2):355–86. doi:10.1007/s10706-012-9603-5.
38. Hasan NM, Yee M. Stabilization of Soft Clay Soil by the Reinforcement of Single Bottom Ash Silica Fume (BASF) Column. *Journal of Rehabilitation in Civil Engineering*. 2024;12(3):117–31. doi:10.22075/jrce.2024.32181.1925.
39. Najjar SS, Sadek S, Zakharia M, Khalaf S. Effect of Sand Column Inclusions on the Drained Response of Soft Clays. 2012:4079–88. doi:10.1061/9780784412121.419.
40. Kusumocahyo SP, Ambani SK, Marceline S. Improved permeate flux and rejection of ultrafiltration membranes prepared from polyethylene terephthalate (PET) bottle waste. *Sustainable Environment Research*. 2021;31(1). doi:10.1186/s42834-021-00091-x.
41. Bin Hasan M, Marto AB, Hyodo M, Bin Makhtar AM. The strength of soft clay reinforced with singular and group bottom ash columns. *Electronic Journal of Geotechnical Engineering*. 2011;16:1215–27.
42. Najjar SS, Sadek S, Maakaroun T. Effect of Sand Columns on the Undrained Load Response of Soft Clays. *Journal of Geotechnical and Geoenvironmental Engineering*. 2010;136(9):1263–77. doi:10.1061/(asce)gt.1943-5606.0000328.