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RESEARCH ARTICLE

Greening groundworks: Stabilizing soft soil with acrylonitrile butadiene styrene-infused stone columns

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Abstract - The growing demand for sustainable approaches in geotechnical engineering has led to the exploration of novel materials. Incorporating waste materials such as Acrylonitrile Butadiene Styrene plastic into ground improvement applications offers a cost-effective and environmentally friendly solution. This investigation began with an assessment of the fundamental geotechnical properties of the materials, both physical and mechanical followed by an evaluation of shear strength parameters. The analysis includes particle size distribution, specific gravity, compaction, permeability, and shear strength enhancement. This study employs the vibro-replacement technique to fabricate reinforced columns at laboratory scale. It introduces a new technology aimed at addressing issues commonly associated with clayey soils, such as excessive settlement. The influence of column dimensions is examined through various ratios, including the Column Penetration Ratio, Column Penetration to Diameter Ratio, and Volume Substitution Ratio. Via the Unconfined Compression Test, the Acrylonitrile Butadiene Styrene column–reinforced kaolin soil recorded shear strength values ranging from 15.43 kPa to 22.56 kPa, compared to the raw shear strength value of 11.11 kPa. Across all designs, the reinforcement delayed column failure under constant axial deformation. Thus, it is deduced that the optimum column design occurred at an 8 mm diameter, with an improvement percentage of 103.06% at a critical column length of 50 mm. In conclusion, this study confirms the potential of this plastic as a viable material for improving the engineering properties of clayey soil, while also highlighting its environmental benefits.

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1. Introduction

Ground and soil improvement works are essential for construction activities, particularly in the development of large-scale infrastructure projects [1]. These projects often require extensive land use, necessitating construction on various soil types, including clayey, peat, and lateritic soils, which are typically unstable due to insufficient bearing capacity to support heavy loads. Soils with high kaolinitic mineral content are often classified as soft clay, exhibiting problematic geotechnical characteristics. According to Almeida et al. [2], kaolin soil consists of approximately 47% silt and 53% clay. Building on such soils can lead to serious issues, including soil dispersion, excessive settlement, and deformation [3]. To address these challenges, ground improvement techniques such as grouting and stone column installation have proven effective in enhancing soil behaviour [4] - [5]. These methods mitigate problematic soil conditions by reducing pore water pressure, increasing cohesion, filling voids, and densifying loose soils [6]. In line with this, numerous studies have validated the effectiveness of granular columns in both field applications and laboratory settings. Moreover, modifications to the granular column technique have gained popularity for incorporating sustainability principles, as highlighted by Li et al [7] in the context of environmental conservation. Considering the potential benefits of waste materials, including discarded plastics, industrial by-products, and other green alternatives, extensive analysis has been conducted on their application in stone column technology. The practicality, cost-effectiveness, and environmental advantages of these materials have been explored by substituting them for conventional coarse aggregates such as sand [8] - [9]. Based on these findings, researchers have made significant contributions to the geotechnical field, validating the potential of these materials to alter and enhance soil geotechnical properties.

Previous studies using plastic materials as replacement materials, such as Polyethylene Terephthalate (PET), Polypropylene (PP), and Acrylonitrile Butadiene Styrene (ABS), have verified their effectiveness in various engineering applications, including ground improvement, cement binder preparation, and the manufacturing industry. Shen and Hassan [9] successfully dissipated excessive pore water pressure in clayey soil via PET substitution, Chindasiriphan et al. [10] enhanced the mechanical performance of mortar by replacing an optimum percentage of PP fibre, and Syahrani et al. [11] fabricated sustainable paving blocks derived from the disposal of ABS material. Among these materials, ABS has attracted growing interest in its engineering characteristics, particularly within the construction industry [12]. ABS is a thermoplastic formed by polymerising styrene and acrylonitrile in the presence of butadiene [13]. It exhibits excellent mechanical properties, notably in impact resistance and chemical inertness. Consequently, ABS has been widely used as a green alternative for enhancing engineering materials, and literature data have proven its effectiveness as a reinforcing agent. Al-Ttayiy et al. [14] verified the effectiveness of ABS plastic in paving mixtures, reporting improvements in rutting susceptibility, moisture reduction, and cracking resistance against abrasion. The results are supported by Olsen et al. [15] who examined the functionality of ABS in modifying material properties and deduced that increasing the ABS percentage

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leads to decreases in workability, compressive strength, and abrasion-wear resistance. The authors also noted that a strong correlation among these parameters was obtained via statistical analysis. Thus, an appropriate amount of ABS usage is necessary to avoid significant reductions in key engineering variables upon replacement. These data suggest that ABS is a suitable alternative to traditional coarse aggregates, aligning with sustainability principles and supporting the goals of sustainable development.

Consistent with the literature data, the introduction of ABS material substitution in soil strength rectification has led to the modification of soil stabilisation techniques, where this research aims to construct ABS columns beneath soft clay soil at specified dimensions. At the laboratory scale, the design of the ABS column is set at 50 mm in diameter and 100 mm in height. However, existing literature lacks a focused investigation into the integration of ABS material for fabricating ABS columns aimed at improving soil properties, and there is no specific focus on the regression analysis of ABS-reinforced kaolin soil with respect to reinforcement configurations. Thus, considering all the relevant literature, constraints, and expected outcomes of this research, several hypotheses have been proposed: (1) the introduction of ABS plastic can alter the geotechnical properties of kaolin soil in the form of columns of varying dimensions, and (2) the fabricated ABS column beneath the soil can delay column failure under the constant application of axial force. To verify these hypotheses, the objectives of this study are: (1) to determine the geotechnical properties of kaolin and ABS plastic, (2) to examine the shear strength parameters of unreinforced and reinforced kaolin with varying designs of ABS columns, and (3) to verify the reliability of shear strength parameters and reduce analytical complexity through correlation analysis.

2. Materials and Methods

Figure 1 presents the research materials used in this study, namely ABS plastic and kaolin soil grade S300. ABS plastic was selected based on three key factors: (1) its cost-effectiveness, (2) its sustainability, as it is derived from recycled plastic waste, and (3) its potential as a reinforcing component, an approach previously demonstrated by researchers such as Ferreira et al. [16] and Perera et al. [17] who utilised Polyethene Terephthalate plastic. As shown in Figure 1(a), the ABS plastic (see Figure 1(b)) was sourced from Toray Plastic (M) Sdn. Bhd., the largest ABS resin producer in Southeast Asia, located in Pulau Pinang, Malaysia. The selection of this material is attributed to several factors: (1) cost-effectiveness, with an average price of RM1.00/kg, (2) suitability for replacing coarse aggregate in terms of its grain size distribution, and (3) proven mechanical performance in various applications, as reported in the literature. The second material, kaolin soil, serves as a clayey component that meets the criteria for fine aggregates. It was obtained from Kaolin (M) Sdn. Bhd., a raw materials manufacturer based in Selangor, Malaysia. Chemically, kaolin has the formula $Al_2Si_2O_5(OH)_4$, which gives it hydrophilic properties [3]. This characteristic allows it to readily form slurry in water-rich environments, making it ideal for producing homogeneous samples and achieving high accuracy in shear strength measurements. The engineering properties of kaolin are summarised in Table 1.

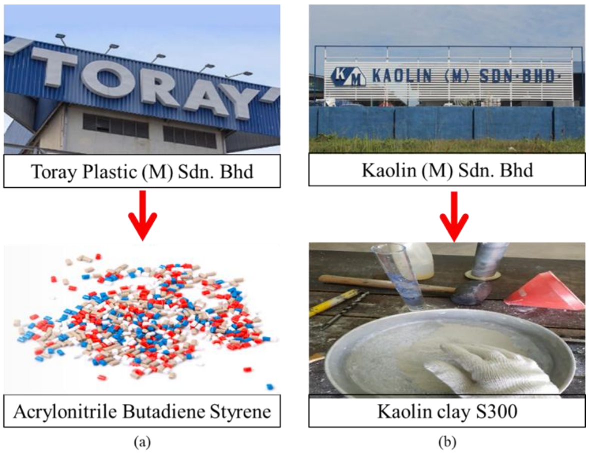

Figure 1. Research material details (a) ABS plastic (b) kaolin soil grade S300

Table 1. Physical behaviours of kaolin soil S300

No.	Parameter	Value
1	Colour	White
2	Natural moisture content (%)	1.59
3	Specific gravity	2.59
4	Atterberg limit	
	Liquid limit (%)	36
	Plastic limit (%)	26
	Plasticity index (%)	10
5	Particle size distribution	
	Silt (%)	46
	Clay (%)	54

2.1 Experimental Details

The execution of relevant geotechnical tests was aligned with the study's objectives and conducted in accordance with British Standards (BS) and the American Society for Testing and Materials (ASTM), as illustrated in Figure 2. The initial priority was to examine the physical and mechanical properties of kaolin and ABS plastic before investigating the shear strength parameters of both unreinforced and reinforced kaolin. The physical geotechnical approaches include the Atterberg limit test (using a cone penetrometer), small pycnometer analysis, sieve analysis, and hydrometer testing. The corresponding results are presented in Figure 2(a-d). Subsequent geotechnical testing involves permeability testing and standard compaction analysis, as shown in Figure 2(e-g). Collectively, these seven engineering methods establish the fundamental geotechnical properties of the research materials. The key variable, the shear strength parameter, was determined using the Unconfined Compressive Strength Test (UCT).

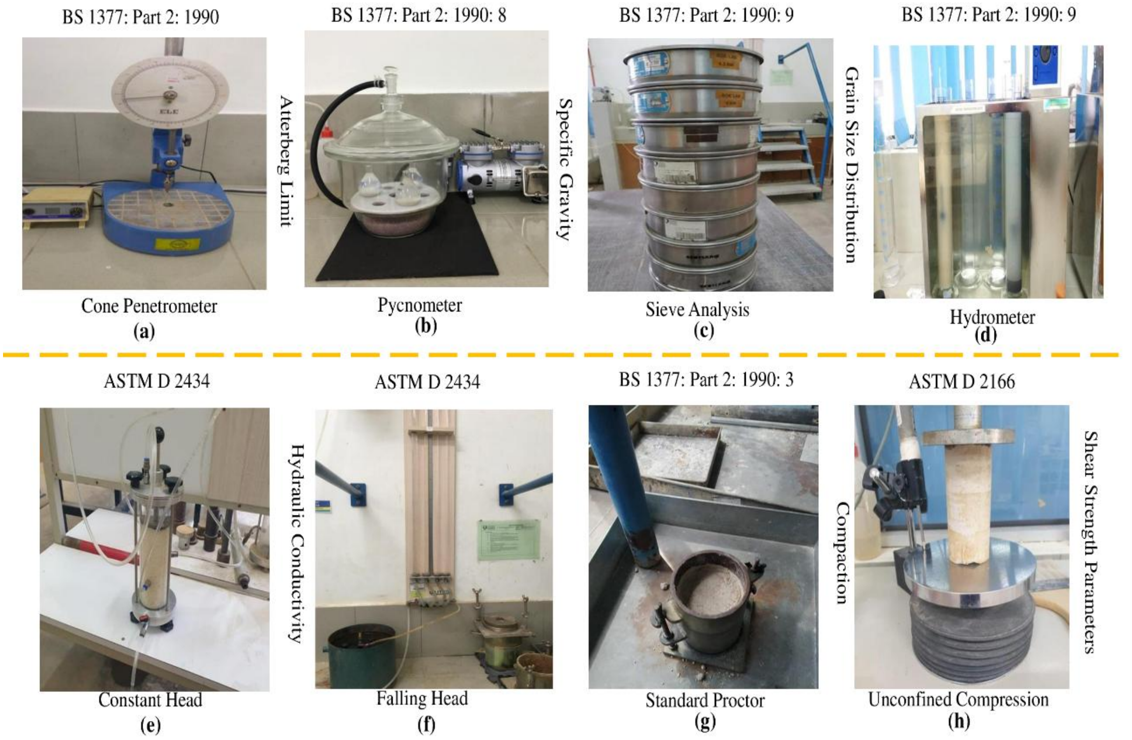

Figure 2. Geotechnical methods for material property evaluation: (a–d) physical tests (e–g) mechanical tests (h) shear strength test

2.2 Physical and Mechanical Behaviours

The dry sieve method was conducted for ABS plastic using a range of aperture sizes: 5.00 mm, 3.35 mm, 1.18 mm, 0.30 mm, 0.063 mm, and a pan. The weight of ABS retained on each sieve after mechanical shaking was recorded and used to calculate the percentage distribution. In contrast, the wet sieve technique was applied to the kaolin soil, which was air-dried and passed through a 63 µm sieve. The results were plotted on a semi-logarithmic scale to classify the kaolin soil. The variation in kaolin soil behaviour with respect to moisture content and plasticity was assessed using the Atterberg limits method. Soil boundaries is ranging from solid to semi-solid, plastic, and liquid states were determined through liquid limit and plastic limit tests, including cone penetrometer measurements. Additionally, the specific gravity of both materials was measured using small pycnometer bottles. The test was repeated until the difference between values was less than 0.03 to ensure accuracy. The maximum and minimum dry densities of ABS plastic were determined using the relative density method, based on height reduction following vibration. The dry density of ABS plastic was then calculated using Eq. 1.

$$DD_{ABS} = \frac{\gamma_{max}(\gamma - \gamma_{min})}{\gamma(\gamma_{max} - \gamma_{min})} \quad (1)$$

The maximum dry density (MaxDD) and optimum moisture content (OptMC) of kaolin soil were determined through a standard Proctor test. A total of six trials were conducted with varying water volumes, starting at 5% moisture content. The test was concluded at 30% moisture content, with the MaxDD showing no deviation greater than 0.03 Mg/m³. Subsequent mechanical analysis focused on determining the hydraulic conductivity coefficient. The permeability tests for both materials were conducted in accordance with ASTM D243, with hydraulic conductivity recorded at distinct hydraulic heads. Kaolin soil was tested using the falling head method and its corresponding equation, while ABS plastic was evaluated using the constant head method in accordance with Darcy's law. Permeability data were expressed in meters per second (m/s), and both tests employed head-loss techniques to measure flow conditions over time.

2.3 Unconfined Compression Behaviours

The specimen dimensions, strain rate, and loading conditions were designed in accordance with ASTM D2166 to ensure representative behaviour of cohesive soils. Kaolin soil was used to fabricate the unreinforced specimen, while the reinforced specimen was prepared by embedding an ABS column into the unreinforced sample to maintain homogeneity throughout the experiment. The specimens were subjected to axial deformation at a fixed rate without lateral confinement, positioned centrally within the shearing machine. Following the standard benchmark, the axial load was applied at a fixed rate of 0.5% per minute, with a calibration ring factor of 0.0167 kN/div. The crosshead movement for strain rate control was examined thoroughly to ensure a constant strain rate could be exerted. Instruments such as the deformation reader and proving ring dial gauge were calibrated to zero. The test was terminated upon observation of soil failure, such as column bulging or shear failure, or upon reaching a shear strain of 15%, whichever occurred first.

2.4 Conceptualisation of ABS Column Framework

The fabrication process of the ABS column begins with mixing kaolin soil to a moisture content of 20%, derived from the OptMC value. The kaolin is thoroughly mixed before being transferred to a customised mould measuring 50 mm in diameter and 100 mm in height. The kaolin is compacted in the mould with a hammer to ensure proper compaction before creating a cylindrical ABS column at the centre of the kaolin sample. Drilling bits of specific diameters (8 mm, 12 mm, and 20 mm) are used to drill a hole corresponding to the diameter of the ABS column, as displayed in Figure 3(c), and stated in Table 2. The ABS material is carefully transferred into the hole and compacted with the back of the drilling bits, as shown in Figure 3(a) and Figure *3*(b). Using a hydraulic jack, the sample is extruded and stored inside a plastic medium for 24 hours to allow soil stabilisation before testing.

Table 2. Structural details of the ABS column

Column diameter (mm)	Column Height (mm)	Column volume (mm^3)	CPR	PDR	VSR	ABS amount (g)	Density of ABS (g/cm^3)
Control			-	-	-	-	
8	50	3016	0.50	6.250	0.0128	3.14	1.04
	75	4021	0.75	9.375	0.0192	4.18	
	100	5027	1.00	12.500	0.0256	5.23	
12	50	6786	0.50	4.167	0.0288	7.06	
	75	9048	0.75	6.250	0.0432	9.41	
	100	11310	1.00	8.330	0.0576	11.76	
16	50	12064	0.50	3.125	0.0512	12.55	
	75	16085	0.75	4.687	0.0768	16.73	
	100	20106	1.00	6.250	0.1024	20.91	

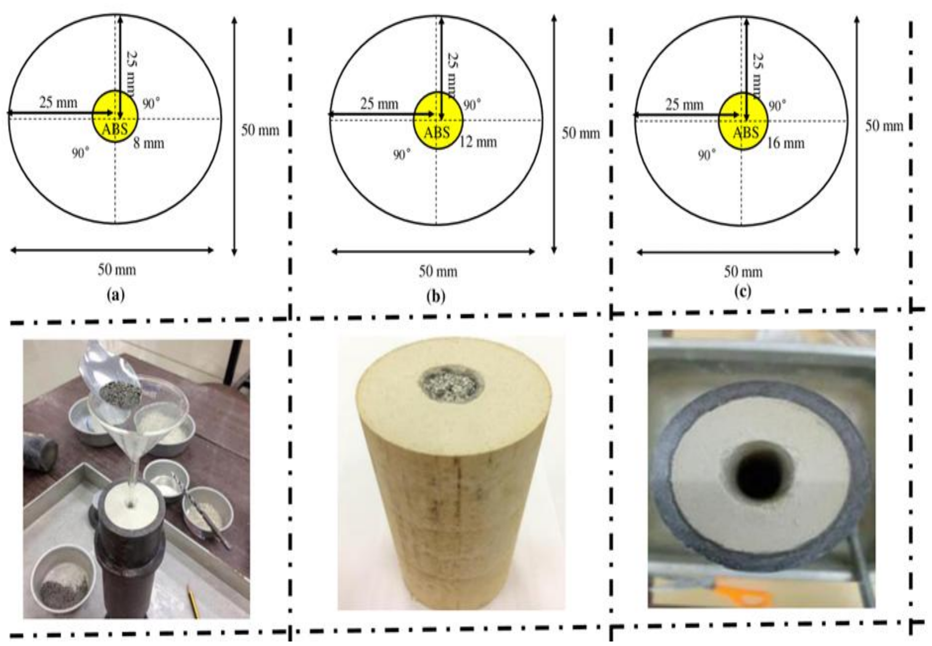

Figure 3. Structural layout of the ABS reinforcement (a) 8 mm diameter column; (b) 12 mm diameter column; (c) 16 mm diameter column

The concept of a stone column involves the penetration of granular materials into the soil, while soil stabilisation typically employs a mixing approach using stabilising agents or additives. This study incorporates both strategies and relates them to the D/d ratio, where *D* represents the column diameter and *d* denotes the diameter of the substituent material. Additionally, column ratios such as the Column Penetration Ratio (CPR), Penetration-to-Diameter Ratio (PRD), and Volume Substitution Ratio (VSR), as summarised in Table 2, play a significant role in granular column installation. These ratios are influenced by variations in column diameter and height, which reflect the properties of the substituent material, including dry density, angularity, and grain-size distribution (GSD). This approach was previously proposed by researchers such as Shen and Hassan [9] and Jamhuri et al. [18] for laboratory-scale investigations. Based on the dry sieving results, the *d* value for ABS plastic was selected as 1.18 mm, corresponding to the sieve size with the highest retained mass. The proposed D/d ratio is considered favourable, as it aligns with the prototype structure designed specifically for clayey soil applications. Drawing from multiple references, the D/d ratio was established within the range of 6.77 to 13.55 (see Figure 3(a-c)). The relative density of ABS plastic was then used to calculate the required quantity for column fabrication, based on the column design.

3. Results and Discussion

3.1 Materials Physical Properties

This section comprises six sections. Two sections focus on the physical and mechanical properties of the research materials, followed by an evaluation of ABS plastic and its contribution to enhancing the shear strength of kaolin soil through the fabrication of both unreinforced and reinforced specimens. Another section analyses the influence of column ratios, CPR, PDR, and VSR on the resulting shear strength values. These investigations are validated using regression analysis, including the development of a regression equation and assessment of the coefficient of determination (R^2). The particle size distribution of each material is illustrated in Figure 4. The ABS plastic exhibits a well-graded profile based on the gradation curve, with most particles retained at the 1.18 mm sieve size, as shown in Figure 4(a). Soil gradation was verified using the Coefficient of Uniformity (C_u) and Coefficient of Curvature (C_c), yielding values of 1.67 and 1.27, respectively [19]. According to the Unified Soil Classification System (USCS), ABS plastic is categorised as SW (well-graded sand). Furthermore, the maximum and minimum dry densities of ABS plastic were found to be 0.56 Mg/m³ and 1.09 Mg/m³, respectively. The in-situ dry density was measured at 1.03 Mg/m³, resulting in a computed relative density of 93.84%. This indicates that ABS plastic is a highly dense material with low compressibility. Similarly, the grain size distribution of kaolin soil is presented in Figure 4(b). The curve demonstrates well-graded characteristics, indicated by a smooth proportional relationship between particle size and cumulative percentage passing. Kaolin soil is identified as a clayey material with a significant silt fraction, as confirmed by both the American Association of State Highway and Transportation Officials (AASHTO) and USCS classifications, which designate it as ML and A-4, respectively (Figure *4*(d)). The ML classification confirms that kaolin is a silt-clay mineral, with at least 35% of its particles passing through the 0.075 mm sieve and a liquid limit below 50%. These findings align with those reported by Shen and Hassan [3] and Mohammed Ali[20], who concluded that kaolin is a problematic soft soil prone to particle dispersion.

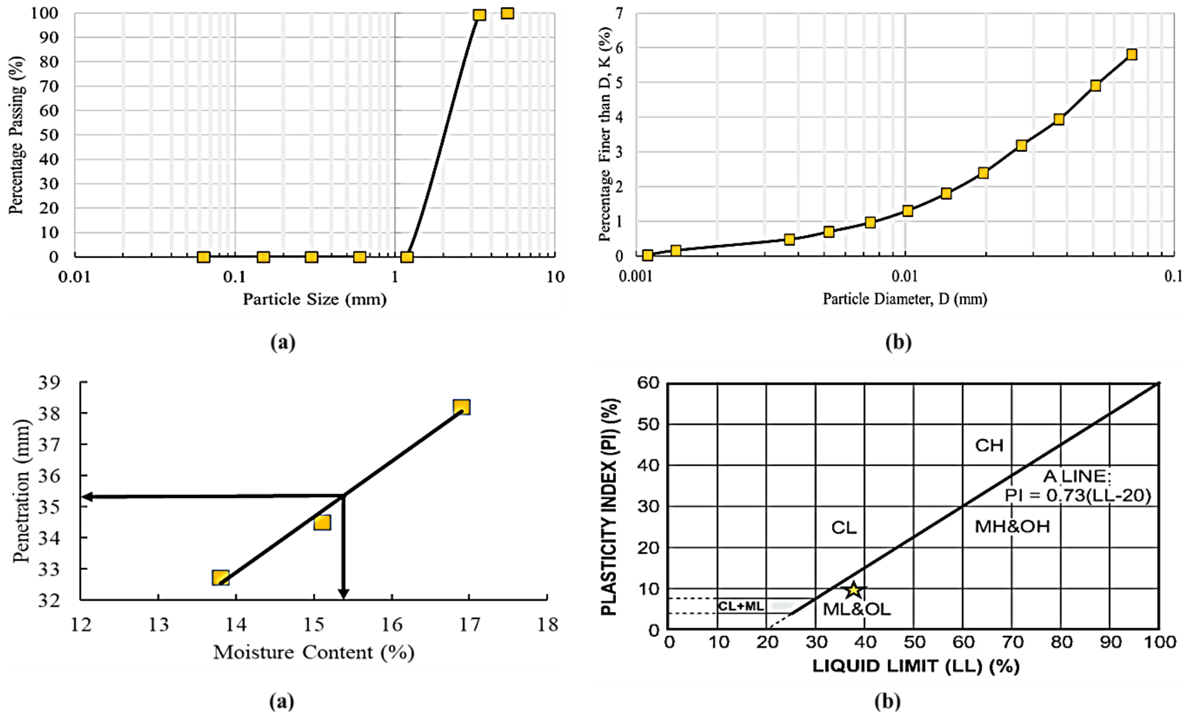

Figure 4. Physical properties of kaolin and ABS plastic (a) wet sieving; (b) dry sieving; (c) cone penetrometer (d) USCS chart

The transition between kaolin soil states was further analysed using liquid limit (LL) and plastic limit (PL) values, recorded at 36% and 26%, respectively (Figure 4(c)). The resulting plasticity index (PI) was calculated at 10%. These results are consistent with those reported by Hasan and Yee [21], with PI deviations not exceeding 1.00%. Specific gravity measurements using a small pycnometer yielded values of 1.07 for ABS plastic and 2.64 for kaolin. These results are in close agreement with data from Grigorescu et al. [22] and Shen and Hassan [3], who reported specific gravities of 1.05 and 2.62, respectively, showing a total variation of less than 2%. Both materials are denser than water, with kaolin being significantly heavier due to its complex mineral composition.

3.2 Mechanical Properties

The mechanical properties of ABS plastic and kaolin soil were evaluated using their hydraulic conductivity coefficients, which were 1.03×10^{-4} m/s and 4.81×10^{-12} m/s, respectively. ABS plastic was verified to discharge water rapidly due to its low water retention capacity, making it suitable for drainage applications. According to Khanh et al. [23], soils with a permeability coefficient below 1×10^{-4} m/s are classified as low-permeability soils, and vice versa. The extremely low permeability of kaolin is attributed to its tightly packed particles, high plasticity, and low porosity. This observation is supported by Jamhuri et al. [18], who reported permeability values similar to those observed in the current study. Additionally, Proctor compaction behaviour was analysed exclusively for kaolin soil. Through compaction testing, the MaxDD and OptMC were determined to be 1.55 Mg/m³ and 19.80%, respectively, as shown in Figure 5. The MaxDD value indicates that kaolin soil reaches its maximum compaction potential at 1.55 Mg/m³, and that further compaction beyond this point does not improve foundation stability. Conversely, the OptMC value is directly correlated with MaxDD, indicating that a moisture content of 19.80% provides optimal particle arrangement and compaction efficiency. According to experimental data from Yuan et al. [24], the MaxDD and OptMC were reported at 1.60 Mg/m³ and 19.00%, respectively. The authors attributed the variation in values to differences in compaction energy, equipment calibration, and inconsistencies in soil-water mixing. In short, Figure 5 summarises the mechanical performance of kaolin across incremental increases in water volume (6 increments of 5% each) and plays an important role in determining the actual water volume required for the preparation of kaolin samples. An overdose of the OptMC value negatively impacts mechanical performance because the kaolin cannot retain water molecules within the soil mass, thereby disrupting sample homogeneity.

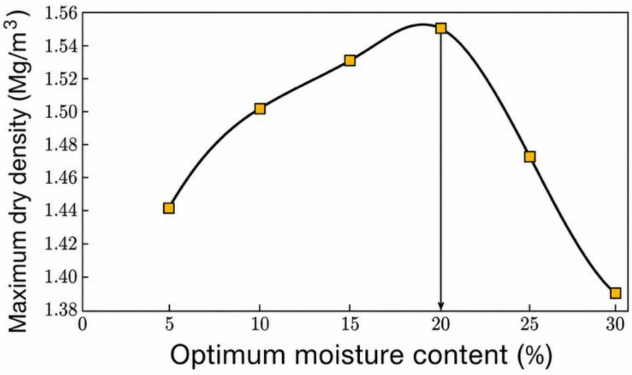

Figure 5. Proctor properties of kaolin soil

3.3 Shear Strength Properties

Table 3 presents the unconfined compressive behaviour of both unreinforced and reinforced specimens, evaluated using shear strength (SS) values and the corresponding improvement (ΔSS), with raw kaolin strength serving as the benchmark. Referring to Figure Figure *6*, the trend in ΔSS shows that an increase in either column diameter or height does not necessarily increase SS magnitude. This is attributed to the soil disturbance level associated with the surface area and volume of ABS. Based on the UCT data, the highest SS value is recorded for the S0850 specimen at 22.56 kPa, corresponding to a ΔSS of 103.06% relative to the raw shear strength of kaolin soil at 11.11 kPa. It signifies that at these specific dimensions; the axial load transfer is at its most efficient. Furthermore, the axial stress in the reinforced section is at an optimum, with the 50 mm ABS column distributing the pressure across the entire reinforced area. Within the same ABS column diameter, an increase in penetration height reduces the SS value, attributed to the loss of soil particles induced by vibration during ABS column construction. Correspondingly, the surrounding pressure exerted by the soil particles compacts the ABS plastic into a denser condition. A similar trend of shear strength progression is observed in other groups of ABS column diameters, where the soil disturbance level is directly proportional to the elongation of column length.

In contrast, the S1275 specimen exhibited the lowest SS value at 15.43 kPa, reflecting a 38.88% improvement in shear strength. Imam et al. [25] emphasised that the use of either partially or fully penetrating columns can significantly enhance soil strength. However, they noted that the effectiveness of these columns depends heavily on their dimensions and the type of reinforcing material used. The numerical difference in shear strength improvement between the two specimens was 7.13 kPa. This indicates that the S0850 specimen was more effective in delaying soil failure by distributing axial loads efficiently, while the S1275 specimen showed moderate performance under higher axial loads applied by the UCT machine. Najjar [26] highlighted that longer-penetrating columns do not necessarily yield proportional strength gains and may even cause greater soil disturbance. In summary, the improvement of raw kaolin shear strength is attributed to the installation of ABS columns with varying diameters and penetration heights beneath the soil. The ABS columns have effectively provided additional support to the kaolin soil against axial forces, increasing the interlocking forces between soil particles and reinforcing the stress–strain connection. All kaolin ABS-reinforced specimens recorded a significant enhancement in shear strength magnitude, ranging from 38.88% to 103.06%

Table 3. The shear strength parameters of unreinforced and reinforced kaolin

Specimen	Symbol abbreviation	Column diameter (mm)	Column height (mm)	Soil's shear strength, SS (kPa)	Shear strength improvement, ΔSS (%)
Unreinforced kaolin	Control	NA	NA	11.11	NA
Reinforced kaolin with ABS column	S0850	8	50	22.56	103.06
	S0875		75	19.32	73.90
	S08100		100	19.87	78.85
	S1250	12	50	16.51	48.60
	S1275		75	15.43	38.88
	S12100		100	16.32	46.89
	S1650	16	50	16.68	50.14
	S1675		75	16.10	44.91
	S16100		100	16.50	48.51

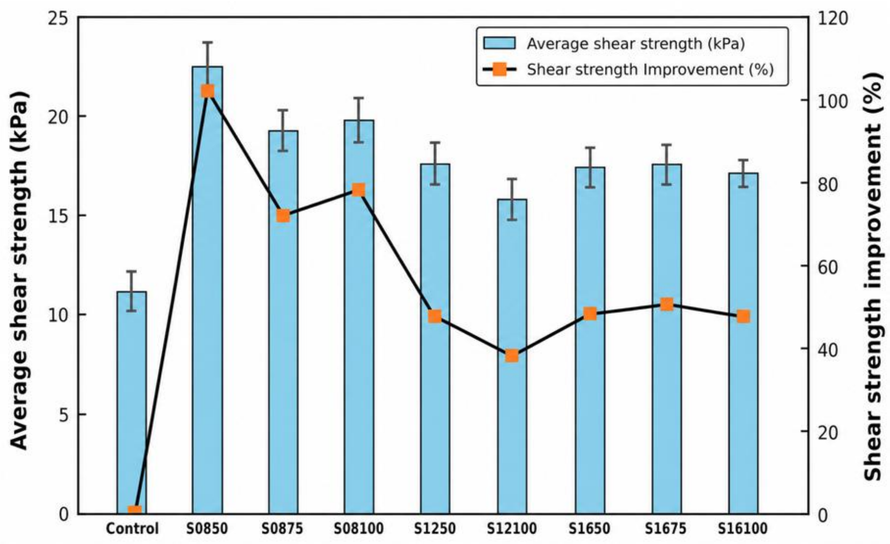

Figure 6. The relationship of average shear strength and its improvement data

3.4 Correlation of Shear Strength Improvement Against Column Penetrating Ratio

Referring to Figure 7, the relationship between ΔSS and CPR is modelled using a quadratic function, demonstrating a strong correlation between shear strength parameters. According to the graph, the highest ΔSS value, 103.06%, occurs at a CPR of 0.5. In contrast, the lowest ΔSS value, 38.88%, is observed at a CPR of 0.75. These findings suggest that the critical column length in this study is 0.5, where load distribution is most efficient through the soil matrix. This indicates that the lower half of the reinforced soil mass is effectively supported by the ABS material, and pressure transmission from the upper to lower section is delayed. As noted by Najjar et al. [27], the effectiveness of granular columns tends to decrease with increasing column length due to inefficiencies in the force transmission path. However, the current study also found that a CPR value of 1.0 across all ABS column diameters produced moderate ΔSS values ranging from 46.89% to 78.85%. Divya et al. [28] emphasised that soil disturbance during mixing and compaction can significantly affect the performance of granular columns, particularly with respect to column length. Previous studies on the use of PET columns to enhance the shear strength of kaolin reported a similar situation, in which the disturbance caused by drilling bits reduced the virgin shear strength of the kaolin soil [3]. The authors noted that the level of soil disruption should be mitigated by substituting granular material. Eq.s 2, 3, and 4 correlate ABS column diameters of 8 mm, 12 mm, and 16 mm with ΔSS values, yielding R^2 values of 0.8936, 0.9602, and 0.9143, respectively. Therefore, these correlation equations verify that ΔSS and CPR have a strong predictive relationship across the varying column diameters. Specifically, 89.36%, 96.02%, and 91.43% of the variability in ΔSS, the dependent variable, is explained by the CPR factor corresponding to ABS column diameters of 8 mm, 12 mm, and 16 mm, respectively.

$$\Delta SS = -206.6(CPR)^2 + 275.85(CPR) + 2.3975 \quad (2)$$

$$\Delta SS = -87.685(CPR)^2 + 133.03(CPR) + 0.7913 \quad (3)$$

$$\Delta SS = -78.586(CPR)^2 + 121.07(CPR) + 1.1022 \quad (4)$$

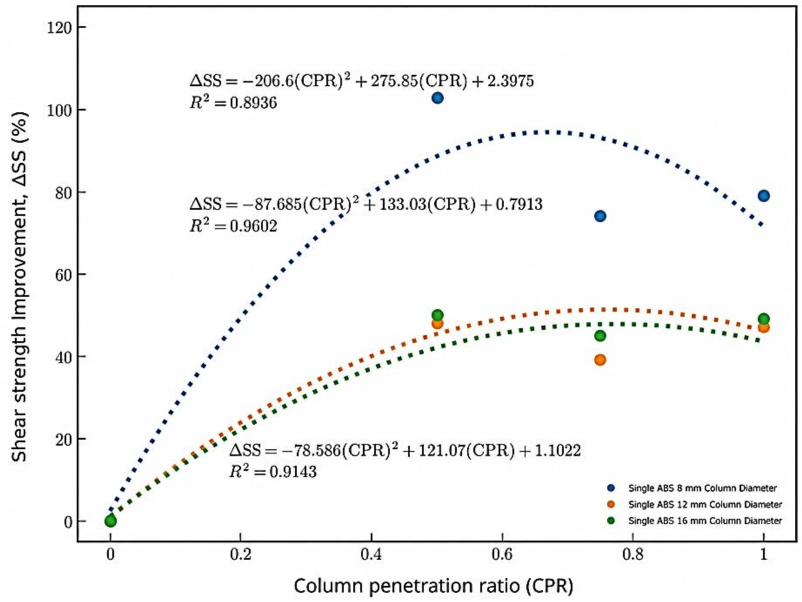

Figure 7. Correlation of shear strength improvement against column penetration ratio

3.5 Correlation Of Shear Strength Improvement Against Column Penetration To Column Diameter Ratio

The relationship between ΔSS and the PDR is modelled using a quadratic function and illustrated in Figure 8. Based on the findings, an increase in the PDR ratio does not consistently result in higher ΔSS values, instead showing a fluctuating trend influenced by column diameter and height. The lowest PDR value of 3.75, observed in specimen S1660, yielded a ΔSS of 50.14%. In contrast, the highest PDR value of 12.5 increased the shear strength from 11.11 kPa to 19.87 kPa, representing a 78.85% improvement. According to Hasan and Yee [21], the optimal PDR range lies between 4.28 and 7.14. However, Hoque et al. [29] reported a broader recommended range of 5 to 8. It is important to note that the PDR value is affected by the number of columns installed in the kaolin bed, as the neighbouring-column effect plays a significant role in the distribution of forces. Shen and Hassan [3] mentioned that the design of the PDR factor must consider the D/d ratio and the specimen's boundary limits, as an increase in PDR can cause unfavourable interactions within the soil matrix. This study identifies the ideal PDR range for single-column deployment as 7.5-12.5, achieving soil enhancement rates exceeding 70%. Eq.s 5, 6, and 7 represent the specific functions for ABS columns with diameters of 8 mm, 12 mm, and 16 mm, respectively, yielding R^2 values of 0.8936, 0.9602, and 0.9143. Based on the parameters, the quadratic functions for ABS columns with diameters of 8 mm, 12 mm, and 16 mm show a robust correlation between ΔSS and the PDR factor. Accordingly, 89.36%, 96.02%, and 91.43% of the variability in ΔSS can be explained by the PDR parameter, indicating a pronounced connection between column diameter and height under the influence of confining pressure. Moreover, the results provide insight that changes in column diameter significantly affect the variability of the CPR factor.

$$\Delta SS = -1.3222(PDR)^2 + 22.068(PDR) + 2.3975 \quad (5)$$

$$\Delta SS = -2.2446(PDR)^2 + 21.285(PDR) + 0.7912 \quad (6)$$

$$\Delta SS = -1.1325(PDR)^2 + 14.534(PDR) + 1.1003 \quad (7)$$

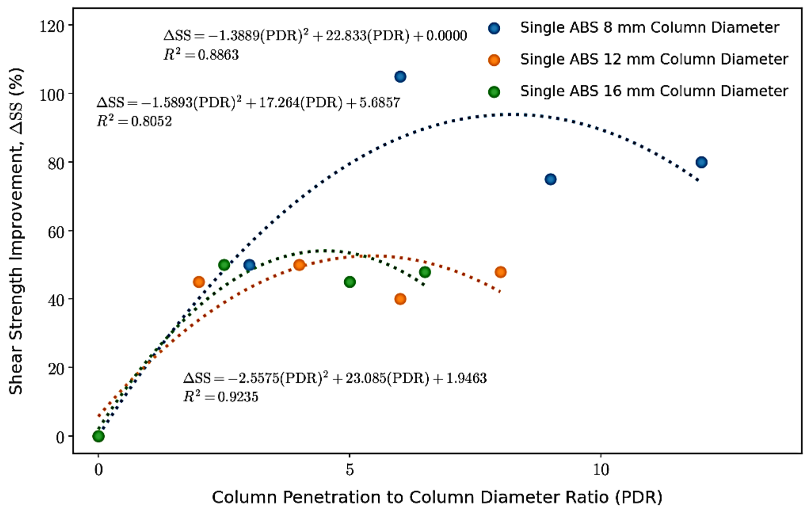

Figure 8. Correlation of shear strength improvement against column penetration to column diameter ratio

3.6 Correlation of Shear Strength Improvement Against Volume Substitute Ratio

Figure 9 illustrates the relationship between shear strength improvement and the VSR, expressed through quadratic functions. Based on the UCT results, the VSR is inversely proportional to both SS and ΔSS. As the VSR increases from 1.536 to 10.24, the SS value decreases from 22.56 kPa to 16.5 kPa. This corresponds to a reduction of 6.06 kPa, or a 26.86% decrease in ΔSS from the peak shear strength. Abdelhamid et al. [30] reported that the length of a granular column should not exceed four times its diameter, as longer columns do not yield significant shear strength improvements. The authors concluded that excessive column length leads to volume expansion, in which axial loads cause the upper section of the column to fail before the load reaches the bottom due to confined space limitations. Hasan and Yee [21] corroborated previously reported data, using bottom ash and silica fume with the same technique and observing that the enlargement of column volume caused the kaolin particles to become more cohesive with adjacent particles. This condition reduces the SS value if the stiffness of the replacement material is insufficient to compensate for the diminished soil strength. The current findings align with these observations, reinforcing the importance of column dimensions in controlling the VSR ratio. Eq.s 8, 9, and 10 correlate ABS columns of varying diameters with ΔSS, yielding R^2 values of 0.8936, 0.9143, and 0.9602, respectively. As in the previous analysis of the PDR and CPR factors, the R^2 values indicate a substantial correlation among the engineering variables. The variability results for 8 mm, 12 mm, and 16 mm ABS column diameters are 89.36%, 91.43%, and 96.02%, respectively, in explaining the ΔSS variability relative to the VSR factor. The manipulation of column diameter and height alters the VSR factor, as reflected in the computation of ABS reinforcement area and volume. Hence, it can be deduced that the VSR factor directly influences the CPR and PDR factors, consistent with the mathematical equation of a cylinder.

$$\Delta SS = -31.524(VSR)^2 + 107.76(VSR) + 2.3975 \quad (8)$$

$$\Delta SS = -2.3686(VSR)^2 + 21.019(VSR) + 1.1022 \quad (9)$$

$$\Delta SS = -0.8362(VSR)^2 + 12.992(VSR) + 0.7913 \quad (10)$$

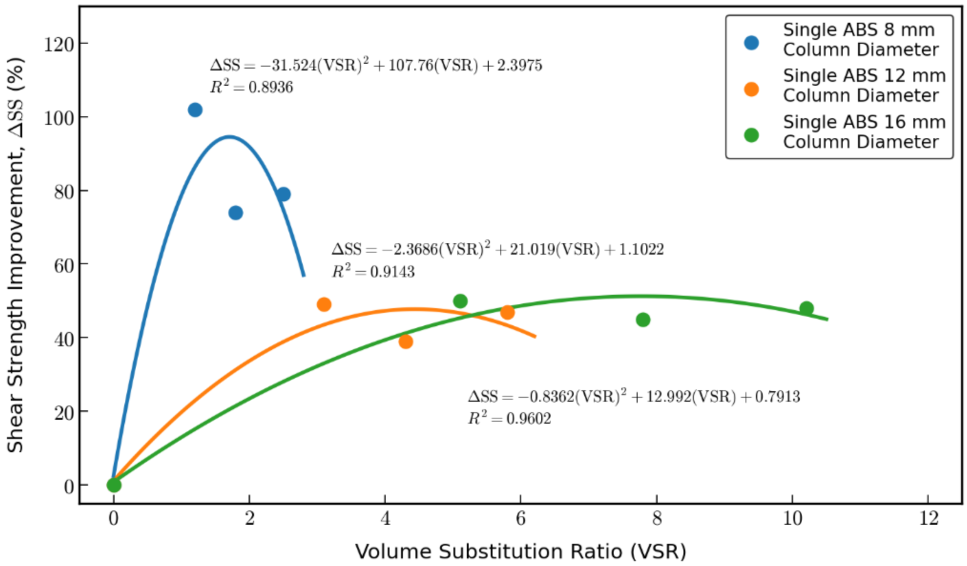

Figure 9. Correlation of shear strength improvement against volume substitute ratio

4. Conclusions

Based on the geotechnical analysis of the research materials, ABS plastic has proven to be a suitable alternative to conventional coarse aggregates. Accordingly, several conclusions, recommendations, and limitations can be drawn from this study, as outlined below:

1) Kaolin soil S300 is classified as a silty-clayey soil, designated as ML and A-4 according to the AASHTO soil classification and USCS chart. It is confirmed to be a dense material with a specific gravity of 2.64, indicating a complex mineral composition and a higher molecular mass. The Standard Proctor Test determined its MaxDD and OptMC to be 1.55 Mg/m³ and 19.80%, respectively. Additionally, its hydraulic conductivity was measured at 4.81×10^{-12} m/s, indicating high plasticity and limited water permeability due to tightly packed particles.
2) Using similar geotechnical methods, ABS plastic was validated as a well-graded (SW) coarse aggregate, with the majority retained on the 1.18 mm sieve. Its specific gravity is 1.07, slightly heavier than water, suggesting an amorphous molecular structure that enhances durability. The relative density of ABS plastic was calculated to be 93.84%, based on minimum, maximum, and in-situ dry densities of 0.56 Mg/m³, 1.09 Mg/m³, and 1.03 Mg/m³, respectively. These values confirm that ABS is a dense material with low compressibility and a permeability of 1.03×10^{-4} m/s.
3) The UCT results showed positive improvements in shear strength across all ABS column designs. Regression analysis simplified the interpretation of shear strength parameters, explaining over 80% of data variability. Improvements

ranged from 38.88% to 103.06%, with the highest ΔSS recorded for specimen S0850 and the lowest for S1275. The alteration of PRD value significantly influenced performance, as did the VSR value. Increased VSR led to greater soil disturbance, weakening particle interlocking. The study recommends a CPR value of 0.5, a PDR range of 6–12, and a VSR not exceeding 3% for optimal performance.

4) Based on the correlation analysis of the column ratios and shear strength parameters, they are highly correlated, as evidenced by the value of R^2. Most of the variability in the dependent variable can be explained by the specific quadratic equations, ranging from 89.36% to 96.02%.
5) The research can be conducted using advanced geotechnical approaches, particularly triaxial testing, to account for the effect of cell pressure.
6) Data obtained from the execution of UCT should be compared with actual field conditions and with the Soil Investigation report provided by the relevant authorities.
7) A larger boundary area should be examined to assess the neighbouring effects of ABS columns when additional reinforcements are constructed.
8) Minor variations in values are considered negligible in this study, and the influence of slight impurities in the soil mixture is disregarded.

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Declaration of Competing Interest
The author declares no conflicts of interest.

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Ng Jun Shen (Methodology, Investigation, Data acquisition, Formal analysis, Writing-original draft)
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Availability of Data and Materials
The data supporting this study's findings are available on request from the corresponding author.

Ethics Declarations
This study did not involve human participants or animals. Ethical approval was therefore not required.

Generative Artificial Intelligence Declarations
The authors claim that artificially intelligent-assisted technologies, such as generative AI, were not used to generate content, ideas, or theories. We have just utilised AI to enhance readability and refine the language. This was used with extreme human control and oversight. The authors take full responsibility for reviewing and approving the content.

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