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SHEAR STRENGTH OF SOFT CLAY REINFORCED WITH ACRYLONITRILE BUTADIENE STYRENE (ABS) COLUMN

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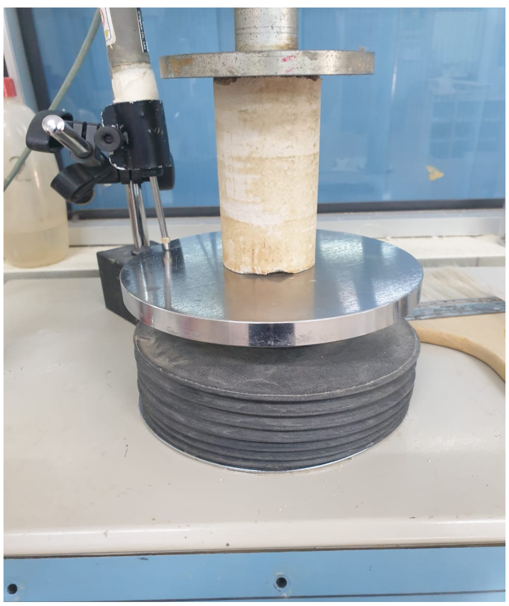
Graphical abstract



Abstract

The troublesome soil that many geotechnical engineers encounter in the sector is clay soil. It presents a major danger to the foundations of light structures. Granular columns have proved beneficial in resolving foundation stabilisation and settling issues, making soft clay more appropriate for foundation building. This study aims to determine whether adding acrylonitrile butadiene styrene (ABS) to kaolin clay increases its shear strength. The physical, mechanical, and morphological properties of the materials used in this research (i.e., kaolin and ABS) must first be identified. The soft clay kaolin was strengthened with ABS columns and tested using the unconfined compression test (UCT) and the unconsolidated undrained test (UUT). The diameter of the columns used in this study was 8, 12, and 16 mm, while the penetration depth ratio used was 0.5, 0.75, and 1.0. The highest improvement in shear strength occurred at a height penetration ratio of 0.5 with values of 102.94%, 48.56%, and 50.02%. The UCT results demonstrated a decrease in the volume of the replacement ratio, followed by an increase in the height of the column. The UUT was conducted to evaluate the soft clay's shear strength when reinforced with an ABS column. The cell pressure used was 50, 100, and 200 kPa with the same column diameter specification as the UCT. The friction angle, υ, increased significantly from 8.92% to 18.21%. Furthermore, there was an improvement in cohesiveness, c, which increased from 4.54% to 45.45%. The results show that installing ABS columns improves the strength and compressibility of clay samples.

Keywords: Ground improvement, shear strength, soft clay soil, acrylonitrile butadiene styrene, granular column.

1.0 INTRODUCTION

Engineers and geotechnical engineers are classifying soils according to their physical and engineering characteristics and how they use them to design and support structures. In the case of soil improvement and foundation design, each soil type offers its unique challenges [1]. Clay is widely distributed, with large mineral reserves of considerable industrial value for various applications [2]. Soils with substantial percentages of fine particulates, such as soft and clay soils with high moisture content, peat soils, and loose sand deposits located above or below the water table, are classed as soft clay [3]. Clay particles absorb and release water, causing soils to expand and compress [4]. Soft clay soils can be defined as having high compressibility and low soil-bearing capacity. This will substantially damage houses and earthworks, such as the foundations. Clay has weak mechanical characteristics and is unstable in water [5]. Building structures on soft clay soils can cause problems when it comes to land shifting and settling, especially in the case of sunken foundations. An irregular settlement may allow the superstructure to be toppled, whereas a standard settlement issue may emerge in the case of an excessive settlement of the foundations [6].

As a result, ground modification methods may be required to alter soil qualities. There are several ways to improve the qualities of soft clay, including sand drainage, piling, stone (granular) columns, mixing, and others. The stone column has recently gained prominence in the field of geotechnical engineering and is widely utilised across the world, including Malaysia. This method is commonly utilised for road and rail bed construction, lightly filled foundations, and storage tanks [7]. The stone column is an innovative and economical ground improvement method commonly used in buildings. Economic growth is linked to the economic advantages derived from the building, resulting in construction profits and public and government gains from ventures. Natural resources are depleting, and using stone columns is considered unfriendly to the community. Recycling material from waste or factory by-products is the safest option. As the market for plastic products grows, the plastic industry produces more waste regularly. Leftover materials and compost make up the waste. Granular columns are widely used to improve soft deposit productivity for reducing base settlement and increasing load-bearing power [8].

The materials that were chosen in this research were kaolin and acrylonitrile butadiene styrene (ABS). ABS is a thermoplastic polymer commonly used in injection moulding. This plastic engineering is popular due to its low manufacturing cost and the simplicity of plastic makers to process the material. This blend of fabrics and plastics offers ABS superior performance, brilliance, durability, and resistance qualities, stronger than plain polystyrene [9]. This material was obtained from Toray Plastics (M) Sdn. Bhd., Penang. The second material, S300 kaolin powder, was used to make soft clay, which is easy to obtain, and the cost is acceptable to conduct a continuous homogeneous soft clay test. Kaolin is a white-coloured material that is also known as China clay. The kaolin powder was purchased in Selangor, Malaysia.

The key purpose of this study is to analyse the use of kaolin and ABS for soil improvement. In this research, ABS is utilised as a stabilising agent as it can stabilise subgrades and enhance the bearing capacity of foundations in the form of an ABS column. The ABS used for soil enhancement is fresh and has not been investigated by researchers. Previous studies have been done using kaolin clay, which also investigated the shear strength of specific materials. Vranna [10] suggested the use of colloidal silica gel. The findings suggest that colloidal silica may be used in situations where hydraulic containment, decreased deformation, and increased shear resistance are desirable. Yee [11] studied bottom ash and silica fume. Installing a single non-encapsulated bottom ash mixed with a silica fume column increased the shear strength of soft clay. Hasan [12] suggested the use of lime bottom ash to increase the shear strength of soft clay. The implementation of group-enclosed lime bottom ash columns enhanced clay soil shear strength. In his research, Suffri [13] used crushed coir fibres, and fibre incorporation affected the soil's undrained shear ability. Hong [14] evaluated the use of polypropylene and concluded that the parameters of the polypropylene column used to strengthen the sample significantly influenced the shear strength enhancement of the kaolin clay. Hasan [15] and Hasan [16] recommended using bottom ash and crushed brick, respectively. Both outcomes are similar, where it can be inferred that installing a single crushed brick and bottom ash column can improve the shear strength of soft clay. Bao [17] used carbon fibres to increase the strength of soft clay soil. Increased fibre content increased the unconfined compression of soil specimens greatly.

In several previous investigations, according to Hasan [18], soil improvement using reinforced sand columns of varying lengths was utilised to evaluate the influence of column penetration on the enhancement of the load-carrying capacity of the specimens. Many experts have proposed the "critical column length" concept, in which the significant length of a stone column is generally between 4 and 8 times the column's diameter [18]. Foda [19] and Mohamed [20] proposed a minimum of L/D = 4 and advised the design of a stone column to minimise axial stress. The critical column length is the shortest column that, independent of settlement, can sustain the maximum strength without buckling [21]. In their experimental research, Salam [22] and Hadri [23] showed that a minimum L/D ratio of 6 was required to achieve the ultimate axial tension in the column. According to the results, in order to improve the undrained shear strength of clay soil, the depth of penetrating ratio is more important than the height over the diameter of the column ratio. Naseer [24] accepted their scientific investigation's premise of a crucial column length equivalent to around six column diameters. Jalali [25] discovered that the penetration of butadiene rubber and the formation of butadiene rubber columns have led to a reduction in soil collapse. Adding Polypropylene fibres increased the shear strength of the composites in both soils while not affecting the soils' initial stiffness [26]. The shear strength increased with fibre inclusion in the drained tests for a given mean effective stress, as shown by an increase in apparent cohesiveness. Moreover, the shear strength was unaffected by pore water pressure development in the undrained experiments. The results of the drained and undrained tests show that fibre content has a bigger effect on perceived cohesiveness than friction angle [27]. Implementing ABS as an upgrade in soft soil minimises the waste issue, which is currently fully disposed of in large amounts in landfill sites. The cost of soil enhancement can be minimised by using this material as ABS is a waste material. In addition, this approach would improve soft soil's bearing capacity and decrease the base structure's settling. It has also been shown that this is a long-term construction that greatly increases the availability of suitable sites at a lower price.

The authors encountered limitations in the undrained shear strength test. Laboratory experiments are usually unstable in very soft to soft clay due to unforeseen damage to the specimens. Hasan [18] and Nedunchelian [29] also encountered the same problem in their studies. Next, in order to understand the behaviour of materials, the basic qualities of the materials employed must first be identified. For example, most ABS properties are obtained from the manufacturer, which may vary from day-to-day production, even from the same source over time. Additional research should be conducted to study the installation of a group of ABS columns in soft clay.

Furthermore, the spacing between the columns should be established to avoid overlapping zones surrounding the ABS columns and deterioration in sample performance in load-carrying capacity. In order to obtain the correct critical column length, the researchers have considered the values that vary from 4 to 8. Thus, the critical column length from 4 to 8 was applied to avoid further confusion.

2.0 METHODOLOGY

Various laboratory experiments were performed on kaolin and ABS plastic to determine their physical, mechanical, and morphological properties. All experiments in this study were conducted in conjunction with the American Society for Testing Material (ASTM) and British Standard European Norm (BS EN). The laboratory works for determining the physical properties were Atterberg limit, relative density, specific gravity, moisture content, and sieve analysis. The standard compaction test and permeability test determined the mechanical properties. Meanwhile, the scanning electron microscopy (SEM) test was conducted for the morphological test. The unconfined compression test (UCT) and unconsolidated undrained test (UUT) were carried out on kaolin clay samples reinforced with a single column with different diameters and ABS heights. The diameter of the column used was 8, 12, and 16 mm, and the penetrating depth ratio used was 0.5, 0.75, and 1.0.

2.1 Unconfined Compression Test and Unconsolidated Undrained Test

2.1.1 Soft Clay Preparation

The soft clay samples have a 50-mm diameter and a 100-mm height. The kaolin sample was dried in an oven, and only 19.5% water was added, which is the optimum quantity for kaolin. The water content of 19.5% for kaolin clay was obtained from the standard proctor test conducted in the laboratory. Approximately 300 g of mixed kaolin was used to fill the compaction mould. After regular soil mixing, the sample was placed in a custom plastic mould and compacted into three layers. Each layer was compacted with ten free-fall blows of 3.1 kg of custom steel weight. The specimens with a 50-mm diameter and a 100-mm height were grown. The density and size of each kaolin sample should be preserved by this accuracy because the weight of the soil and the volume of the mould are almost similar, although slight faults in the material are expected to develop during the process. In order to conserve the pore pressure within the sample, the samples were removed from the mould and put into a dedicated container for 24 h prior to the UCT and UUT.

2.1.2 Installation of Acrylonitrile Butadiene Styrene column (ABSC)

Before the construction of the acrylonitrile butadiene styrene column (ABSC), the kaolin specimen was drilled with a drill bit with a respective diameter of 8, 12, and 16 mm, with the specimens remaining within the mould to prevent their extension. In order to achieve equal density in each ABS column, the quantity of ABS utilised to fill the hole was determined by the volume of the pre-drilled hole. This process preserved the density of 1.04 × 10^{-3} g/mm^3 for each specimen. For partially penetrating columns, the height of the column used was 50, 75, and 100 mm. The samples were removed from the mould after the holes were drilled on the specimen and filled with ABS prior to testing.

2.1.3 Pattern and Size

The column's diameter (D) and the granular material's particle size (d) are critical factors in determining the appropriate column length to engage in the design study. According to a previous study [28], it is desirable to use a D/d ratio similar to that used in the design of experimental structures. In this study, the column diameter was 8, 12, and 16 mm, whereas the size of ABS particles was 1.18 mm. According to the model experiments, the D/d ratio ranged between 4 and 20. Consequently, the area ratio provided as the column area to the specimen area (A_C/A_S) is 13.31%, 20.35%, and 27.65%, respectively. The height penetration ratio specified as the column height to the specimen height (H_C/H_S) is 1.0. Figure 1 indicates the structure of single columns with 8, 12, and 16 mm diameters in soil specimens. Figure 2 shows the formation of real ABSC samples prior to the UCT.

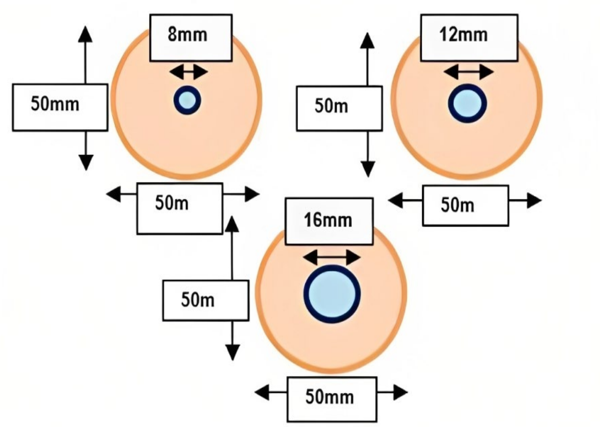


Figure 1 Detail of column arrangement for ABSC installed in kaolin sample

Figure 2 Formation of ABSC in kaolin sample

2.1.4 Unconfined Compression Test (UCT)

There were four batches (controlled, 8, 12, and 16 mm) of kaolin specimens prepared using three penetration ratios of 0.5, 0.75, and 1.0, with five specimens per sample. Every specimen has the same penetration ratio of 1.0. The UCT considers the average value at the same penetration ratio. The kaolin sample was used as a controlled sample to assess the shear strength of the non-reinforced sample without strengthening the ABS column, with a penetration ratio of 0. The specimen hole was replaced by an enclosed column of 8, 12, and 16 mm with ABS resin. The enclosure was constructed of low-strength geotextile.

2.1.5 Unconsolidated Undrained Test (UU)

There were four batches (controlled, 8, 12, and 16 mm) of kaolin specimens prepared using three penetration ratios of 0.5, 0.75, and 1.0, with five specimens per sample. Each specimen has the same penetration ratio of 1.0. The UUT considers the average value at the same penetration ratio. The kaolin sample was used as a controlled sample to assess the shear strength of the non-reinforced sample without strengthening the ABS column, with a penetration ratio of 0. The specimen hole was replaced by an enclosed column of 8, 12, and 16 mm with ABS resin. Each sample was tested with three different pressures (50, 100, and 200 kPa), which were used in a previous study [29]. The data and graphs were recorded and plotted in the GDS software.

The results of the tests are represented as the major stress difference curves against strain. Mohr circles are displayed in terms of the total stress at maximum main stress differential conditions (considered failure). The mean undrained shear strength was measured, and the failing (Mohr) enclosure was formed tangentially to the Mohr circles to obtain the undrained cohesion interception and the degree of shearing resistance.

3.0 RESULTS AND DISCUSSION

Various laboratory tests were performed to determine the physical properties of kaolin clay and ABS: the Atterberg limit test, relative density test, specific gravity test, dry sieve test, and moisture content test. Meanwhile, the standard compaction test and the permeability test were performed to evaluate the mechanical properties of kaolin clay. Finally, a SEM test was performed to assess the morphological characteristics of ABS. Aside from the engineering characteristics of the materials used in this research, the UCT and UUT were conducted to measure the strength of soft clay reinforced with ABS columns. The data obtained should be compared to those obtained by previous studies for validation purposes.

3.1 Physical and Mechanical Properties

Table 1 outlines the important properties of the kaolin clay and ABS used in this study.

Table 1 Basic properties of kaolin clay and ABS

Material	Test	Parameter	Results
Kaolin	Soil Classification	AASHTO	A-6
	Atterberg Limit	USCS	ML
		Liquid Limit	38.43%
		Plastic Limit	28%
		Plasticity Index	10.43%
	Specific Gravity	Specific Gravity	2.63
	Compaction	Max Dry Density	1.53 g/cm^3
		Opt Moisture Content	19.50%
	FallingHead Permeability	Coefficient of Permeability	4.806 × 10^{-12} m/s
ABS	Range Size	-	1.18-3.35mm
	Relative Density	P_d-max	1.090 g/cm^3
		D_r	1.040 g/cm^3
		P_d-min	0.563 g/cm^3
	Specific Gravity	Specific Gravity	1.091 g/cm^3
	Constant Head Permeability	Coefficient of Permeability	1.027 × 10^{-4} m/s

For kaolin, the plastic limit value is 28%, and the liquid limit value is 38.43% at a penetration of 20 mm. Thus, the plasticity index for kaolin is around 10.43%. As a result, high-plasticity clays are more likely to be less porous and more compressible and to consolidate under load over a longer period than low-plasticity clays [30]. The density of ABS can be measured using a vibrating table. The ABS's minimum density is 0.563 g/cm3, while its highest density is 1.09 g/cm3. Every ABS column in the kaolin has a density of 1.04 g/cm3. The average specific gravity of the kaolin obtained from the specific gravity test using a pycnometer is 2.63. This number is consistent with [31], which indicates that the normal range of soil-specific gravity values is between 2.40 and 2.78. However, earlier research indicates that the basic gravity of kaolinite clay is 2.6 [32]. It is assumed that components comprised of plastics will have a relatively low specific gravity. Soils with a specific gravity of less than 2.0 are classified as organic soils in the soil family. The specific gravity of ABS achieved in the pycnometer test is 1.091. The kaolin was properly graded, ranging from fine silt to fine sand [33]. The particle size distribution curve has a diameter of 0.018. The results indicate a uniformity coefficient of 3.89 and a gradient coefficient of 1.27, with a homogeneity parameter of 1.67 for sorting coefficients. It was also discovered that 97% of the kaolin passed the 0.5-mm test, while around 51% passed the 0.063-mm test. ABS is only available in one colour, shape, and size, which is in yellowish white pallet with a round shape. Based on the test results, the thickness of ABS is mostly limited to a maximum of 1.18 mm. The size of 99% ABS remained at 1.18 mm, whereas the size of 1% ABS remained at 0.60, 3.35, and 5.00 mm.

According to Hasan [18], the maximum dry density and the kaolin optimum moisture content are 1.55 mg/m3 and 19.40%, respectively. Based on the compaction test, the dry density is 1.53 g/cm3, and the moisture content is 19.5%. The type of non-disturbed sample examined is clay below 10-7 based on the standard permeability coefficient for different soils. According to Kumari and Mohan [34], the kaolin properties illustrate its impermeable characteristics and indirectly reflect its poor drainage qualities, which are frequently linked with clay. According to the particle size distribution, the ABS particle size ranged between 1.18 and 3.35 mm, which can be classified as coarse aggregate. This test revealed that the granular ABS in this study has a permeability of 1.027 × 10-4 m/s.

3.2 Morphological Properties

The substance utilised in this experiment is novel, and little study has been conducted. SEM testing is required to determine the composition of ABS for a better understanding of its physical characteristics. The testing was done using SEM + energy dispersive X-ray (EDX). Figure 3(a), (b), and (c) show the images in the SEM device at 1,000×, 200×, and 500× magnification, respectively. As the magnification increases, the element can be seen clearly. The white object is carbon, where ABS is majorly made up of carbon. The composition of ABS plastic is shown in Table 2. Another component that makes up ABS is oxygen.

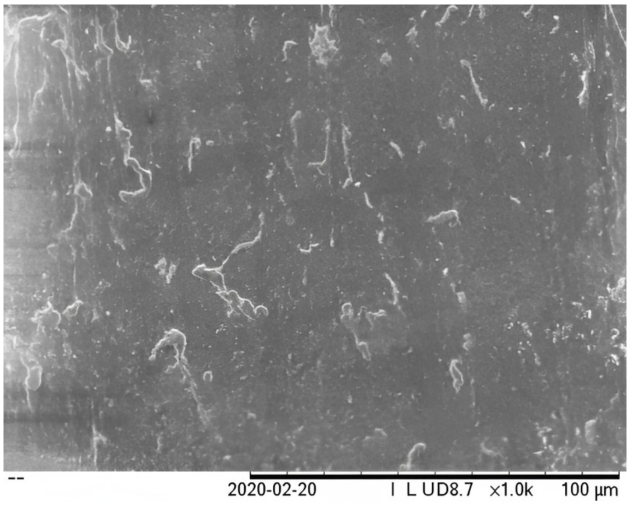


Figure 3 (a) Image of ABS at 1,000× magnification

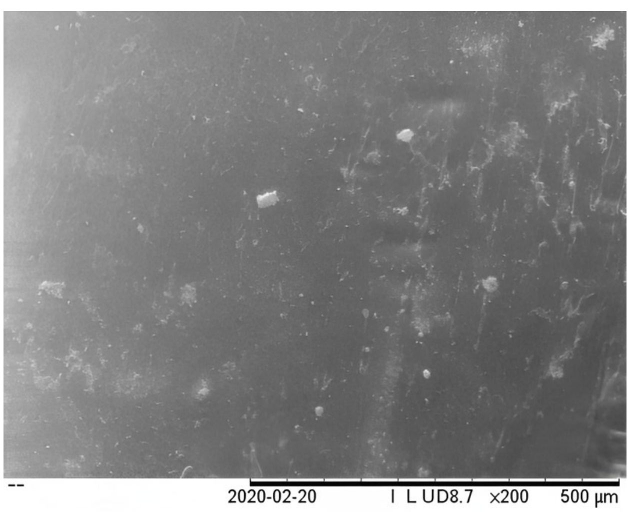


Figure 3 (b) Image of ABS at 200× magnification

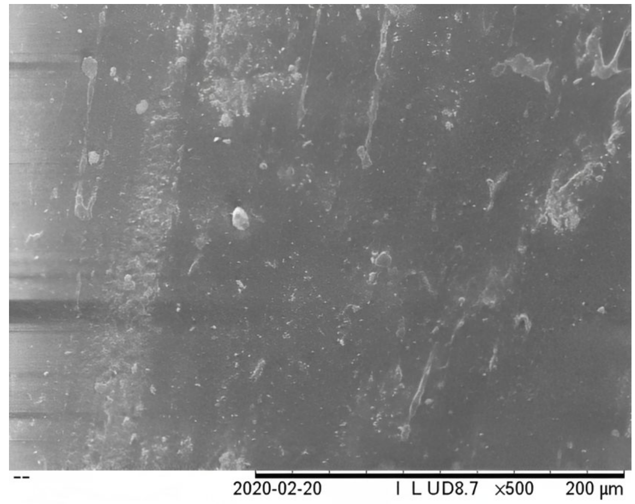


Figure 3 (c) Image of ABS at 500× magnification

Table 2 Summary results of SEM test for ABS

Element	Weight %	Weight %, σ	Atomic %
Carbon	95.031	0.327	96.223
Oxygen	4.969	0.327	3.777

Based on the results, ABS is chosen as a subgrade in this research because ABS is a thermoplastic, and thermoplastics in nature are rigid and tough. With the aid of laboratory testing, it can be concluded that ABS is suitable for use as a subgrade in this research as it shows the property of a good desorption agent. Its small size and the property of a good desorption agent justify the use of ABS as a subgrade to improve the shear strength of kaolin clay.

3.3 Unconfined Compression Test (UCT)

The shear strength of soft kaolin clay reinforced with ABS columns was determined using the UCT. Fifty samples from 10 batches were examined with varied area replacement ratios (13.31%, 20.35%, and 27.65%) and column penetrating height ratios (0.5, 0.75, and 1.0). Five samples of tests were performed on each penetration ratio to acquire the average shear strength, and a controlled sample with no reinforcement of ABS column must be produced.

All three findings for the column diameter of 8, 12, and 16 mm demonstrate a steady increase in shear strength. However, the shear strength of an 8-mm diameter column is higher than that of 12- and 16-mm diameter columns. The shear strength of the samples after reinforcement of ABS columns and the same action improved at 13.31%, 20.35%, and 27.65% with specific penetration ratios of 0.5, 0.75, and 1.0. Table 3 presents the trend of shear strength. The shear strength declining pattern in all three columns is nearly identical, decreasing from 50-mm column height to 75-mm column height, and then increasing from 75-mm column height to 100-mm column height.

Table 3 Summary of unconfined compression test

Sample	H_C/D_C %	Average Max Deviator Stress,q kPa	Average Shear Strength kPa	Improvement of Shear Strength %
Kaolin	-	11.1134	22.2269	-
8-50	1.28	22.5532	45.1064	102.94
8-75	1.92	19.3216	38.6432	73.86
8-100	2.56	19.8594	39.7188	78.70
12-50	2.88	16.5100	33.0200	48.56
12-75	4.33	15.4251	30.8502	38.80
12-100	5.77	16.3142	32.6284	46.80
16-50	5.13	16.6720	33.3440	50.02
16-75	7.69	16.0692	32.1384	44.59
16-100	10.26	16.4629	32.9258	48.13

3.3.1 The Effect of Area Penetration Ratio

Pandey [30] and Kazmi [31] discovered that the area replacement ratio and the column-over-column diameter ratio increased in sand-column studies. The increase in the area replacement ratio enhanced the shear strength of soft clay. However, in this research, the acquired findings contradict the preceding assertion. Figure 4 depicts a graph of shear strength improvement against the area replacement ratio, A_C/A_S, which indicates that increasing the diameter of the ABS column from 8 mm to 12 mm may reduce shear strength. However, increasing the diameter of the ABS column from 12 mm to 16 mm slightly improves shear strength. At the heights of 50, 75, and 100 mm, in terms of area replacement ratio, the shear strength of 13.31% is greater than the shear strength of 20.35% and 27.65%. The area ratio of 13.31% has the highest shear strength improvement among the three ratios because ABS has low compression resistance as the particles are large and there are spaces between each particle. As it is highly compressed and the spaces between the particles are significantly reduced, the 13.31% area replacement ratio improved more than the 20.35% and 27.65% area replacement ratios for all column heights of 50, 75, and 100 mm. Furthermore, the large surface area of ABS resin in interface with the top conical plate increased compression strength significantly.

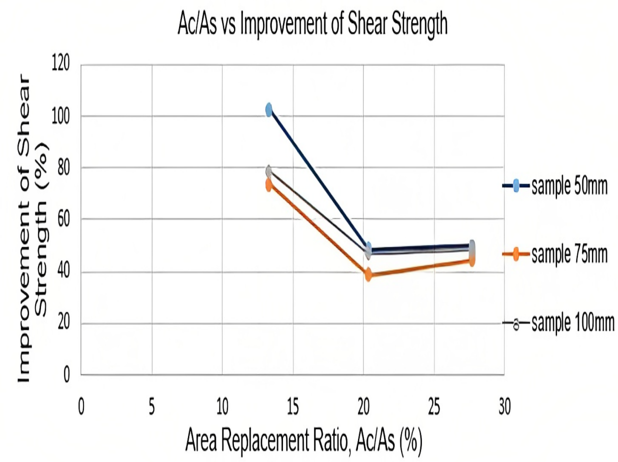


Figure 4 The graph of A_C/A_S versus the improvement of shear strength

3.3.2 The Effect of Column Penetration Ratio

Figure 5 shows the connection between decreasing shear strength and a subsequent increase with different column penetrating height ratios (0.5, 0.75, and 1.0) for 13.3%, 20.35%, and 27.65% replacement ratios. As the column penetration ratio increases, the shear strength of the area replacement ratios decreases and subsequently increases. The highest increase in shear strength occurred at the column penetration ratio of 0.5. As ultimate straining develops at a depth around 1.5 times the diameter of the column, encasing the stone column to a depth corresponding to two times its diameter can significantly enhance its load-carrying capability [35].

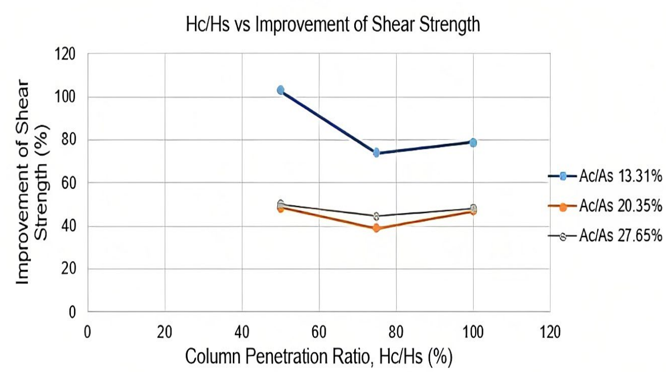


Figure 5 The graph of improvement of shear strength versus the column penetration ratio, H_C/H_S

Figure 6 depicts the enhancement in shear strength as represented by the ratio of column height to diameter. In previous studies, according to Hasan [16], Hasan [18], Nedunchelian [29], and Hasan [12], the crucial column length is between 4 and 8 times the column diameter (D_C), which is depicted in Figure 6 by the red region. The results support the crucial column length hypothesis because the big columns employed for the specimens and the size of ABS granules, the ratio of the height of the column, H_C to the column's diameter, and the D_C are within the allowable limits for the samples.

Table 4 Summary of cohesion and friction angle tests

Sample	Cell Pressure kPa	H_C/D_C	C, kPa	Φ
Kaolin-1	50			
Kaolin-2	100	-	22	24.43
Kaolin-3	200			
8-50-1	50			
8-50-2	100	1.28	28	28.03
8-50-3	200			
8-75-1	50			
8-75-2	100	1.92	29	27.26
8-75-3	200			
8-100-1	50			
8-100-2	100	2.56	28	28.43
8-100-3	200			
12-50-1	50			
12-50-2	100	2.88	32	28.43
12-50-3	200			
12-75-1	50			
12-75-2	100	4.33	31	27.95
12-75-3	200			
12-100-1	50			
12-100-2	100	5.77	23	28.89
12-100-3	200			
16-50-1	50			
16-50-2	100	5.13	30	27.89
16-50-3	200			
16-75-1	50			
16-75-2	100	7.69	31	26.61
16-75-3	200			
16-100-1	50			
16-100-2	100	10.26	28	28.45
16-100-3	200			

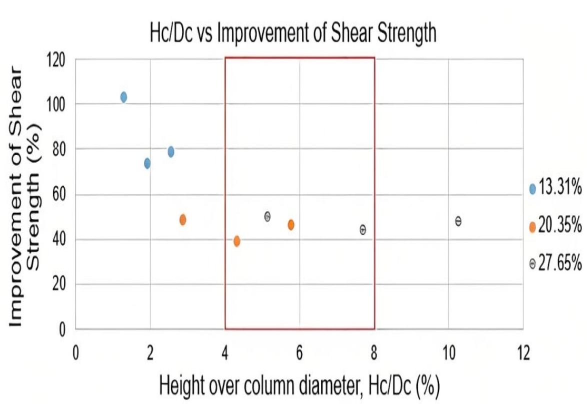


Figure 6 The graph of improvement of shear strength versus the ratio of height over column diameter, H_C/D_C

3.4 Unconsolidated Undrained (UU) Test

3.4.1 The Effect of ABS Column on Shear Strength

The UUT was conducted for three samples of varying column diameters and cell pressures to determine the shear strength. The efficient shear stress coefficients for the kaolin specimen reinforced with different diameters of ABS at various penetrating column ratios (H_C/H_S) and the column's height over the column's diameter (H_C/D_C) were determined, as shown in Table 4. For the UUT, the cell pressures used were 50, 100, and 200 kPa for three samples in each set to compute the average shear strength.

Souhir [36] demonstrated that the particle size of the column showed a substantial impact on the shear strength parameters, friction angle, and stiffness of reinforced clayey soil. In this study, the cohesiveness of the specimens with ABS reinforcement is greater than that of the controlled kaolin specimen. In contrast, the effective friction angle is equivalent to the controlled kaolin specimen with modest development. In general, the ABS specimens outperform the controlled kaolin specimen.

The cohesiveness, c, of the controlled kaolin specimen is 22 kPa. For the 8-mm diameter column, the range of c is 28–29 kPa, with the maximum cohesion obtained at a penetrating height ratio of 0.75. Similarly, the c ranged from 23 to 32 kPa for a column diameter of 12 mm, with the highest value obtained at a height penetration ratio of 0.5. The cohesiveness, c, ranged from 28 to 31 kPa for a column diameter of 16 mm, with the greatest value obtained at a penetrating height ratio of 0.75. As per Nedunchelian [29], the polypropylene-reinforced sample increased in apparent cohesiveness up to a penetrating height ratio of 0.5, after which it decreased.

The friction angle, ϕ, is 24.43 for the controlled kaolin specimen, whereas the ϕ varied from 27.26 to 28.43 for a column diameter of 8 mm. Meanwhile, the ϕ ranged between 27.95 and 28.88 for a column diameter of 12 mm. Lastly, the ϕ with a column diameter of 16 mm ranged from 26.61 to 28.45. Table 5 summarises the improvement of shear strength.

Table 5 Summary of improvement of shear strength

Sample	Max Deviator Stress, σ kPa	Improvement Of Max Deviator Stress kPa	Axial Strain, ε %	Average Axial Strain %
Kaolin-50	162.97		11.25	
Kaolin-100	252.98	-	12.57	12.53
Kaolin-200	373.18		13.77	
8-50-50	173.04	6.18	9.95	
8-50-100	301.84	19.31	13.10	13.52
8-50-200	441.98	18.44	17.52	
8-75-50	174.45	7.04	9.72	
8-75-100	307.79	21.67	13.58	13.4
8-75-200	428.54	14.83	16.90	
8-100-50	176.86	8.52	11.18	
8-100-100	271.71	7.40	12.23	12.99
8-100-200	449.31	20.40	15.57	
12-50-50	190.50	16.89	9.10	
12-50-100	303.65	20.03	11.69	11.36
12-50-200	460.02	23.29	13.30	

12-75-50	184.75	13.36	7.79	
12-75-100	308.15	21.81	11.94	12.34
12-75-200	446.10	19.54	17.29	
12-100-50	165.41	1.50	11.92	
12-100-100	255.74	1.09	14.62	14.80
12-100-200	439.31	17.72	17.87	
16-50-50	180.44	10.72	11.87	
16-50-100	279.01	10.29	13.00	14.27
16-50-200	444.53	19.12	17.93	
16-75-50	173.35	6.37	9.62	
16-75-100	268.05	5.96	12.12	13.02
16-75-200	420.75	12.75	17.31	
16-100-50	180.18	10.56	9.42	
16-100-100	299.94	18.56	11.22	11.42
16-100-200	451.76	21.06	13.62	

For specimens with a cell pressure of 50 kPa and a penetrating height ratio of 0.5, the deviator stress improved for the diameters of 12 and 16 mm, and the deviator stress improved for the diameter of 8 mm with a height penetrating ratio of 1.0. As the column was driven to a depth of 100 mm, the disruption generated by removing a considerable volume of kaolin would have made it weaker. On the other hand, the samples with a cell pressure of 100 kPa showed a distinct pattern, with the maximum improvement for a height penetrating ratio of 0.75 for the diameters 8 and 12 mm, and the highest improvement for the diameter of 16 mm for a height penetrating ratio of 1.0. Due to the consistent shape of ABS particles and their regulated arrangement inside the column, the potential of having fewer voids inside the column is reduced when there is an increase in height and cell pressure. As a result, the deviator stress increases.

Lastly, the specimens with a cell pressure of 200 kPa produced a different pattern from the previous two. The highest deviator stress was observed at a penetration ratio of 1.0 for the columns with diameters of 8 and 16 mm. The column's high pressure and lack of encapsulation from within allow the ABS particles to come into contact with the column wall and enter the kaolin [29].

4.0 CONCLUSION

The study determines if the shear strength of soft clay soil improves following reinforcement using ABSC with three different column diameters and three different penetration lengths. The conclusions can be formed based on the findings. The installation of ABSC improved the shear strength of kaolin clay. It demonstrates that installing 8-, 12-, and 16-mm diameter ABSCs with penetration ratios, H_C/H_S of 0.5, 0.75, and 1.0 enhanced the shear strength of kaolin clay. Previous studies show the optimal critical column length was approximately 4 and 8 times the diameter of the installed column. The area ratios of 20.35% and 27.65% support the critical column length concept. The biggest improvement in shear strength occurred with the column's diameters of 8, 12, and 16 mm and a height penetration ratio of 0.5, with values of 102.94%, 48.56%, and 50.02%, respectively. The UCT results revealed that the column diameters of 8, 12, and 16 mm with a penetrating column ratio of 0.5 improved the column penetration ratio.

The UUT was conducted to evaluate the shear strength of soft clay reinforced with an ABS column. The friction angle, ʋ, increased significantly from 8.92% to 18.21%. The physical characteristics of ABS particles and their surface can explain this finding. Furthermore, there was an improvement in cohesiveness, c, which increased from 4.54% to 45.45%. For cell pressures of 50, 100, and 200 kPa, the deviator stress against axial strain at failure was measured. For columns with diameters of 12 and 16 mm, the highest deviator stress was found at a penetrating height ratio of 0.5 and a cell pressure of 50 kPa. ABS can be used as a reinforcing material because it has significantly better shear strength and permeability than kaolin clay. The results show that installing ABS columns enhances the resilience and deformability of clay samples, although the enhancement level depends on several factors.

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