Magazine of Civil Engineering

ISSN 2712-8172

journal homepage: http://engstroy.spbstu.ru/

Research article

UDC 691.1

DOI: 10.34910/MCE.132.4

Construction of coconut shell column for the enhancement of expansive soil

N.J. Shen , ***M. Hasan*** , ***N.N. Anuar***

Universiti Malaysia Pahang Al-Sultan Abdullah, Kuantan, Pahang, Malaysia

✉ *muzamir@ump.edu.my*

Keywords: expansive clay, coconut shell, ground improvement, shear strength, foundation, stiffness, experimental investigation, sustainable development, reinforcement

Abstract. The authors used the crushed coconut shell to make granular columns which were obtained from the market area of Kuantan, Pahang. The coconut was crushed into a similar size of coarse aggregate for the replacement of non-renewable resources like sand and gravel. From its general properties, a coconut shell is hard and can withstand a certain value of exerted value regardless of compression or tension. Besides, the coconut shell is an agricultural product and is found abundantly after human consumption. For this research, the stone-column method was used. The installation of a single coconut shell column was implemented through the Vibro-replacement technique on the soft clay soil. Before accessing the shear strength parameters, the evaluation of the physical and mechanical properties of coconut shells and kaolin was executed via the appropriate geotechnical laboratory approaches. The shear strength parameters were analysed with the control and reinforced specimens through the Unconfined Compression Test (UCT). For the shear strength value, the average value from 4 specimens was utilized as the final value. A total of 16 samples were constructed for all the specimens, reinforced design comprised of 13 mm column diameter, and column heights of 60 mm and 80 mm were categorized as partially penetrated columns while 100 mm was a fully penetrated column. The highest shear strength improvement was recorded when the column height was 100 mm, resulting in 28.51 %, whereas the least was recorded when 60 mm of height was constructed, only 17.28 %. Conclusively, the positive results of shear strength improvements were yielded by the utilization of coconut shells and proved that it was practical and economical.

Funding: UMPSA Research Grant. RDU223309, Post Graduate Research Scheme (PGRS). PGRS2303122, MYBRAIN 2.0 Scholarship by the Ministry of Higher Education of Malaysia

Citation: Shen, N.J., Hasan, M., Anuar, N.N. Construction of coconut shell column for the enhancement of expansive soil. Magazine of Civil Engineering. 2024. 17(8). Article no. 13204. DOI: 10.34910/MCE.132.4

1. Introduction

Kaolin is a claystone composed mostly of kaolin minerals that are white or nearly white and can be beneficiated or fired to become white or nearly white [1]. Kaolin is a type of fine aggregate that has higher moisture content, and higher compressibility as compared to coarse aggregate like gravel. Higher moisture content with compressibility is likely to link with low soil bearing capacity which can cause soil settlement if a structure is placed on it. As reported by Karkush et al. [2], the authors discovered that soft clay soil possesses an undrained shear strength value of below 40 kPa, compressibility index value of 0.19 to 0.44, and moisture content of 40 % to 60 % to its total mass. Furthermore, Al-Ani et al. [3] defined the expansive soil as the rise in volume when subjected to moisture content. When the soil or ground-bearing capacity is not ample for catering to the structure [4], the selection of the best alternatives for a building from the available techniques depends on whether the decision-makers are owners, contractors, or other stakeholders [5]. Ground improvement techniques to improve the soil are often implemented at the pre-construction stage so that the mentioned issue can be addressed providing a safe structure to the occupants. The increase of soil's strength or bearing capacity by developing effective solutions can be executed through the correct design of the foundation system [6]. Jawad et al. [7] mentioned the shear strength of soil is dependent on the interaction of soil particles and its pore fluid, which is expressed at the microscopic level. Without a proper geotechnical case study of the site condition, the wrong choice may be implemented regarding the type of foundation of the structure, which can lead to excessive material waste [8]. Construction of stone columns is a technique for stabilizing the considered weak clay, silt, or loose sands so that it is suitable for the building of embankments, bridge abutments, and other buildings [9]. The principle of the Vibro-replacement method involves the radial displacement of soil through a deep vibrator and further refilling the specific coarse aggregate or granular material to the pre-drilled diameter [10]. This can be further explained as about 10–40 % of soft clay soil will be replaced with compacted granular material, which provides better strength and stiffness than the original soil [11]. This is done to release the excess pore water pressure flowing within the subsoil as the constructed granular column acts as a drainage path to discharge the additional water content [12].

In recent years, many Southeast Asia countries including Malaysia have been actively developing the country. Some famous projects that are handled by foreign investors in Malaysia include the East Coast Rail Line (ECRL), Malaysia-China Kuantan Industrial Park (MCKIP), and Bandar Malaysia [13]. Huge infrastructure projects in Malaysia have covered a larger area and mostly intersect from state to state, using the different conditions of land for the entire project like the Lebuhraya Pantai Timur 2 (LPT 2) between Kuantan and Kuala Terengganu, where the geotechnical works like soil improvement and ground improvement of the existing foundation have been done before the construction project [14], [15].

Historically, the ground improvement technique is used for soil stabilization, but it depends on the nature of the strata. The techniques comprising soil improvement using additives, mechanical methods, admixtures, electrokinetic and thermal methods [16], [17]. Karkush et al. [18] deployed the grouting cement gel and silica fume in stabilizing the soft clay soil, by leveraging the cementitious properties of concrete and pozzolanic activity induced by silica fume. Previous researchers like Karkush et al. [19] altered the properties of soft clay soil via the mixture of crushed concrete and produced a positive result of shear strength improvement. Among these methods, the construction of stone columns is under the category of mechanical methods, where the substitution of foreign granular materials such as Polypropylene (PP) and bottom ash to replace the coarse aggregate regardless of the type of coarse aggregate used, this technique is to increase the soil bearing capacity at the same time decreasing the settlement of shallow footings as well as slabs [20]. Referring to the above materials, bottom ash, and PP materials are found to increase the shear strength of kaolin within 30–60 % [21], [22]. Other than these materials, the utilization of coconut shells which behave like coarse aggregate has the potential to replace gravel at reduce the natural resource depletion by producing a better environmentally friendly structure in civil engineering applications [23]. From other perspectives, coconut shell is a naturally biodegradable material, improving the performance of structure has become a significant interest for many researchers, where the addition of coconut shell in concrete increases its tensile strength [24]. Researchers have also studied environmentally friendly techniques for the usage of recycled sludge in soil improvement [25], even the consolidation of soil using drained-timber rods [26]. However, the selected coarse-aggregate type material must be free-draining, hard, and inert [27]. The selection of a coconut shell to construct the granular column is predicted to have increased the shear strength improvement rate as the coconut shell has durability characteristics, high toughness, and abrasion-resistant properties [28]. Sujatha et al. [29] verified the durability of coconut shell, which is comprised of lignin content that causes it to be more weather resistant, low cellulose content within the structure causes it to absorb less water. Coherent to that, recycled aggregate is also much easier due to low-cost issues as well as wide availability rather than natural resources [30]. To comply with the sustainability concept practice in construction, increasing the greenery index, application of coconut shell can be a potential and practical material in replacing the coarse aggregate for the granular column construction.

2. Methods

This chapter discussed the methods and materials used to conduct the relevant laboratory works by complying with the American Society for Testing and Materials (ASTM) and British Standard (BS) in order to achieve the objectives of this study as tabulated in Table 1. The first part focused on the materials involved, followed by the experiment setup.

Table 1. Relevant laboratory works and its standard.

Objective	Experiment	Standard
Determination of engineering properties of kaolin clay S300 and crushed coconut shell	Atterberg limit	
	Liquid limit	BS 1377: Part 2: 1990: 4.3
	Plastic limit	BS 1377: Part 2: 1990: 5.3
	Pycnometer	BS 1377: Part 2: 1990: 9.6
	Sieve analysis	BS 1377: Part 2: 1990: 9.6
	Hydrometer	BS 1377: Part 2: 1990: 8.3
	Relative density	ASTM D 4052
	Standard compaction	BS 1377: Part 2: 1990: 3.3
	Constant head	ASTM D 2434
	Falling head	ASTM D 2434
Determination of shear strength parameter by reinforcing the kaolin clay with crushed coconut shell column	Unconfined compression	ASTM D 2166

2.1. Materials

In this research, the vibro-replacement method as a ground improvement method was first determined after considering the estimated amount of materials to utilise and the restricted condition, small-scale laboratory test. The primary material of the study, Kaolin Clay S300 which was purchased from Kaolin (M) Sdn. Bhd, Selangor, Malaysia. The main intention of Kaolin Clay S300 selection was due to its natural properties, where it can easily be broken when in contact with the hydrogen (H^+) and hydroxide ion (OH^-), and it is a hydrophilic substance [31]. It was made available in powder form and white as shown in Fig. 1. This material was used for the column preparation and the nature properties of this material show that it was suitable to meet the research objective as shown in Table 2 [32]. The analysis showed that it comprised silt and clay, with no sand content and thus, it can first be classified as fine aggregate. Besides, the reinforcement material, coconut shell was selected as it met the requirements of being a granular-type material. A typical coconut shell is tough and hard to withstand physical loading, with a shell thickness of approximately 2–8 mm [33]. From Table 3, it was crucial to notice the natural moisture content of a coconut shell was low having a value of 4.20 % therefore can be a potential material to reduce the effect of water accumulation in kaolin clay. It was taken from Kuantan, Pahang, and then processed by grinding it in a machine into small pieces.

Figure 1. Kaolin clay S300 [22].

Table 2. Properties of kaolin clay S300 [32].

No.	Physical Parameters	Value
1	Colour	White
2	Natural water content (%)	1.58
3	Specific gravity	2.59
	Atterberg limits:	
4	Liquid limit, w_L (%)	78
	Plastic limit, w_p (%)	39
	Plastic Index, I_p (%)	39
	Sieve analysis:	
5	Sand (%)	0
	Silt (%)	47
	Clay (%)	53

Table 3. Properties of coconut shell [24].

No	Physical and Mechanical Properties	Coconut Shell
1	Maximum size (mm)	12.5
2	Moisture content (%)	4.20
3	Water absorption (24h) (%)	24.00
4	Specific gravity	1.05 to 1.20
	SSD * apparent	1.40–1.50
5	Impact value (%)	8.15
6	Crushing value (%)	2.58
7	Abrasion value (%)	1.63
8	Bulk density (kg/m^3)	650
	Compacted loose	550
9	Fineness modulus	6.26
10	Shell thickness (mm)	2–8
11	Impact value (%)	8.15

2.2. Laboratory Works

The flow of the laboratory works was referred to in Fig. 2. The first objective of the study was to assess the general properties of both materials, kaolin clay S300 and crushed coconut shell. The relevant tests were conducted by complying with the suitable standard to classify its physical and mechanical properties which included the Atterberg limit test, pycnometer test, sieve analysis test, hydrometer test, relative density test, standard compaction or standard proctor test, constant head test and falling head test. The second objective was achieved by conducting the UCT, where the crushed coconut shell column was built beneath the kaolin clay. All the relevant information was tabulated in Table 1.

The Atterberg limit test was mainly designed for fine-grained soil where the soil can exist depending on the volume of water and it had a liquid limit test and plastic limit test, based on BS 1377: Part 2: 1990: 4.3 and BS 1377: Part 2: 1990: 5.3. By using cone-penetration method, the liquid limit for the prepared kaolin clay which passed through the 425 μm sieve was determined. After the liquid limit test, the procedure was followed by moulding the kaolin into a spherical mould to determine the plastic limit. For specific gravity, was determined by a small pycnometer test based on BS 1377: Part 2: 1990: 9.6. This test was applied for both materials, where the materials were put inside a chamber after the preparation process. Fig. 2 (a) showed the determination of crushed coconut shells of specific gravity using kerosene. The particle size was determined by conducting sieve analysis or dry mechanical sieve analysis for crushed coconut shell based on BS 1377: Part 2: 1990: 9.6 while hydrometer test was carried out for kaolin clay S300 in accordance to BS 1377: Part 2: 1990: 8.3. Sieve analysis was for coarse type material, where the sieve sizes used were 200 mm, 14 mm, 10 mm, 5 mm, 3.35 mm, 2 mm, 1.18 mm, 0.6 mm, 0.3 mm, 0.15 mm and 0.0063 mm as shown in Fig. 2 (b). The kaolin clay was analysed under hydrometer as shown in Fig. 2 (c) as more than 50 % of the particles were finer than 63 μm.

Furthermore, the Standard Compaction Test was carried out based on BS 1377: Part 2: 1990: 3.3. A 2.5 kg hammer with a 1 litre capacity of mould was deployed during the process as shown in Fig. 2 (d). The amount of kaolin clay used in this test was approximately 3.0 kg of oven-dried kaolin clay that passed through the 4.75 mm sieve size. Before accessing the shear strength parameters, the permeability which split into the constant head test and falling head test which shared both standards, ASTM D 2434 were conducted as depicted in Fig. 2 (e). Both tests determined the permeability using measuring both heads of water and the volume of water that flew through.

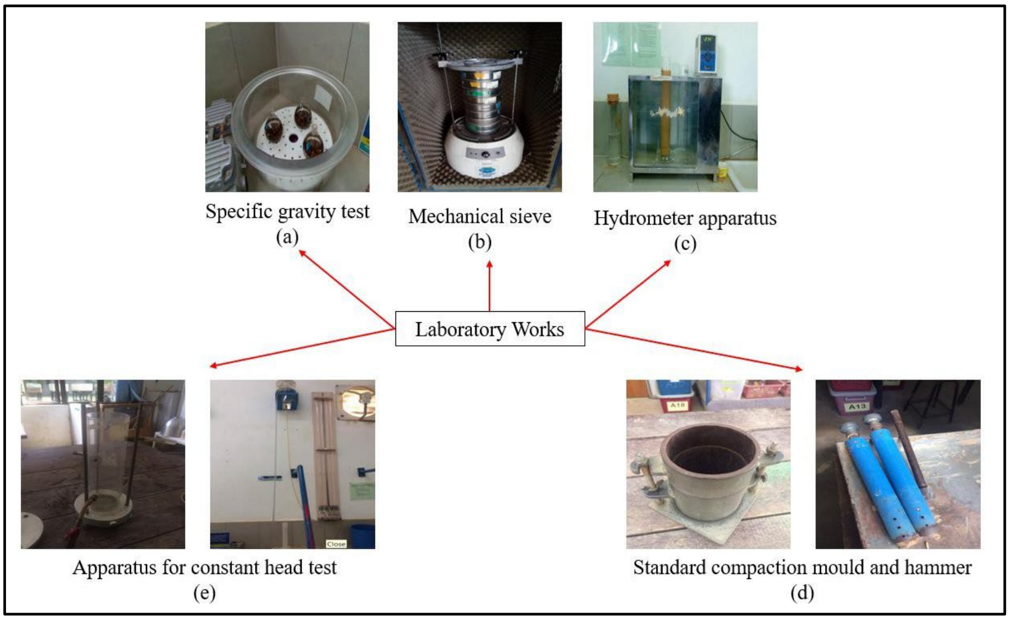


Figure 2. Flow of laboratory works (a) Pycnometer test (b) Dry sieve analysis (c) Hydrometer test (d) Standard compaction test (e) Constant head test.

The second objective was based on the UCT based on ASTM D 2166 by exerting the axial compression from the top towards the specimen at a constant deformation rate as shown in Fig. 3. Before conducting the UCT, the crushed coconut shell column was properly designed by considering the column parameters as well as the sieve size of the coconut shell. The column parameters which included column penetrating ratio (H_c/H_s), column height to column diameter ratio (H_c/D_c), and volume replacement ratio (V_c/V_s) were tabulated in Table 4. The granular column which was made up of crushed coconut shell, was split into the partially penetrated column and the fully penetrated column. Besides, the D/d ratio which indicated the Diameter of the column, D divided by the Diameter of the crushed coconut shell, d was also determined beforehand so that it was compared with another set of data. A similar study that used the polypropylene (PP) columns as reinforcement with the D/d value of 8.47 and 13.55 recorded shear strength improvement [22]. In this study, the D value was fixed at 14 mm, and the d value used in was 2 mm thus producing the ratio of D/d was 7. After several considerations and calculations, the detailed arrangement of the column built within the 50 mm kaolin column was drawn and illustrated in Fig. 4.

Figure 3. The specimen was compressed under UCT machine.

Table 4. Design dimension of crushed coconut shell column.

No.	No. of Column	Design	Diameter	Height (mm)	H_c/H_s	H_c/D_c	V_c/V_s
1	1	Control	NA	100	-	-	-
2	1	S1360		60	0.6	4.6153	0.0405
3	1	S1380	14	80	0.8	6.1538	0.0540
4	1	S13100		100	1.0	7.6923	0.0676

*S1360 – "S" indicates as single column, "13" indicates the column diameter and "60" indicates the column height. All the dimensions are expressed in mm. NA – Not Available

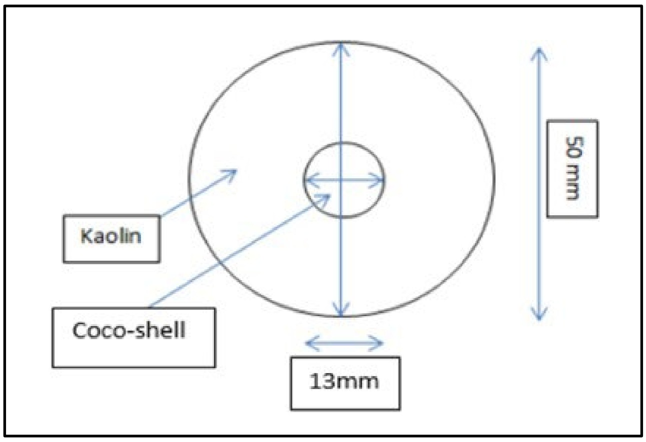


Figure 4. Arrangement details of a crushed coconut shell column.

For the process of column construction, it was shown in Fig. 5. The kaolin clay was mixed with approximate 20 % of water to its total weight, 300 g based on the value obtained from Standard Compaction Test. The prepared kaolin was transferred to the customized mould and compacted, followed by the drilling process. A 13 mm drilling bit was used to drill a hole in the middle of the prepared specimen based on the arrangement as shown in Fig. 4. The specimen had been prepared and the crushed coconut shell was poured inside through a filter funnel by raining method.

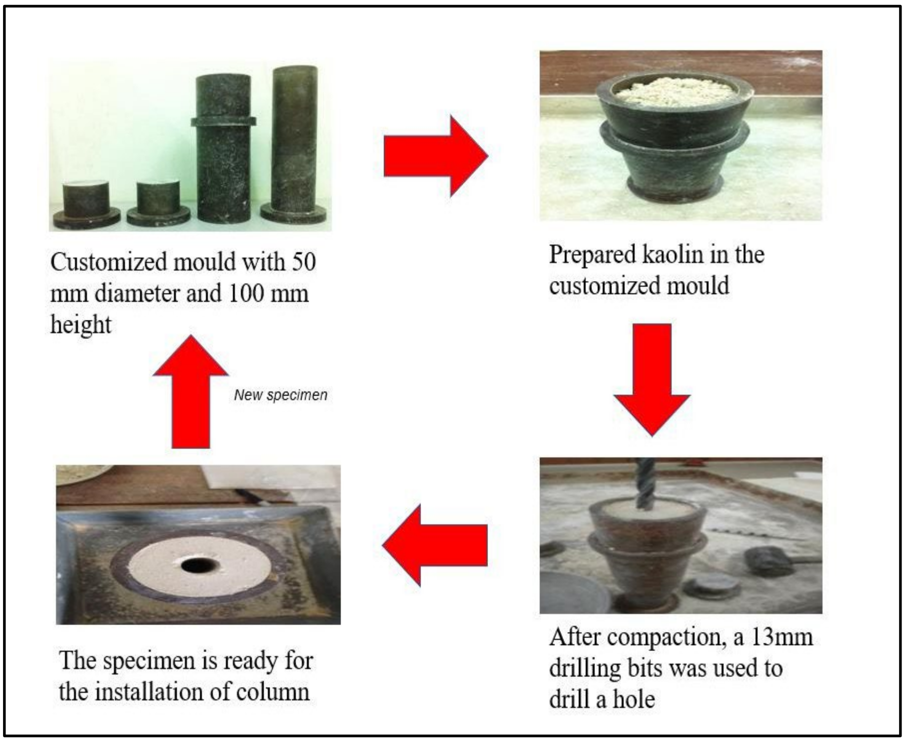


Figure 5. Crushed coconut shell column preparation process.

3. Results and Discussion

This chapter focused on the value obtained after conducting the related laboratory works, it was split into the engineering properties of kaolin clay S300 and the crushed coconut shell, efficiency of the materials used and the correlation of shear strength parameters in accordance to the specific parameters.

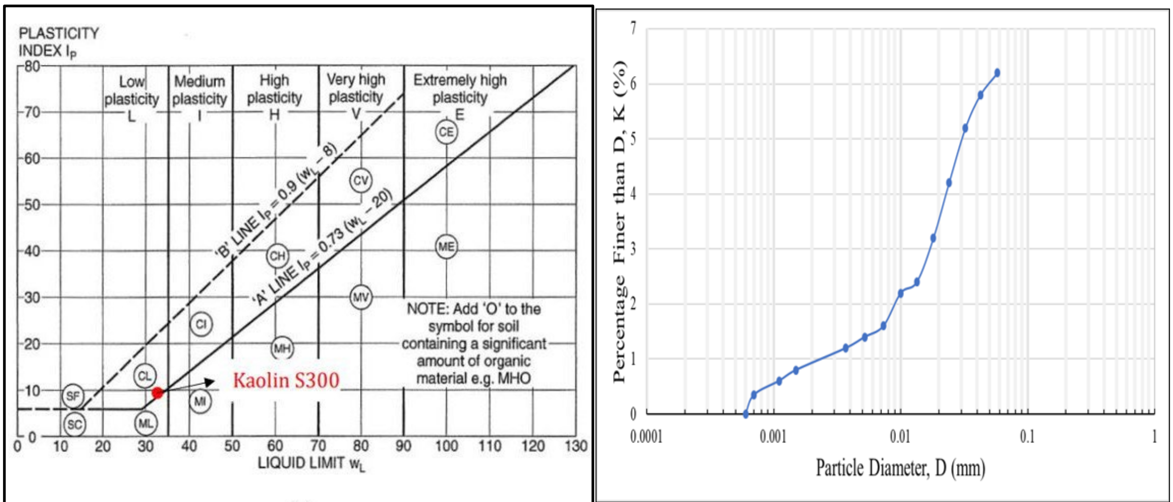
3.1. Engineering Properties of Kaolin Clay S300 and Crushed Coconut Shell

The engineering properties of these materials involved in the research were determined based on the tests as stated in Table 3. The properties of kaolin clay S300 was tabulated in Table 5 while crushed coconut shell properties was tabulated in Table 6.

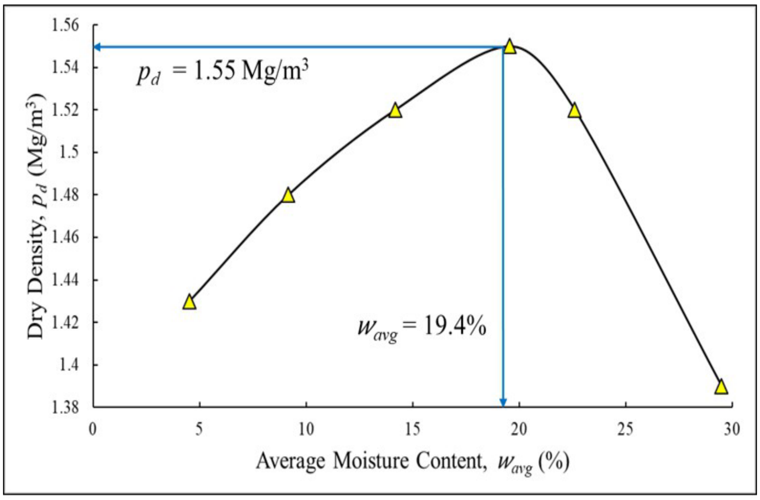
Table 5. Kaolin clay S300 properties.

Test	Parameter	Value
Soil Classification	AASHTO	A-6
	USCS (Plasticity Chart)	ML
Atterberg Limit	Plastic Limit, w_p (%)	26
	Liquid Limit, w_L (%)	36
	Plastic Index, I_p (%)	10
Standard Compaction	Optimum Moisture Content, w_{opt} (%)	19.40
	Maximum Dry Density, $\rho d(max)$ (Mg/m^3)	1.55
Small Pycnometer	Specific Gravity, Gs	2.62
Falling Head Permeability	Coefficient of Permeability, k (m/s)	8.96 x 10^{-12}

From this table, it was noticed that the kaolin clay was a soft clay soil. In terms of its particle size, it fell under ML based on the USCS chart, or inorganic silt with very fine sands as shown in Fig. 6 (a). The results were inferred referring to the plastic limit value of 26 % and a liquid limit value of 36 % and hence, obtaining the value of the plastic index was 10 %. Referring to AASHTO, it had A-6 value. This value indicated that kaolin was a clayey soil. Although it was a clayey soil, it was a well-graded soil with more than 75 % of the amount passed through the #200 sieve size based on the hydrometer test as depicted in Fig. 6 (b). The above findings were significant as compared to the results by Syamsul et al. [21], which reported the similar results by inferring kaolin clay S300 was a highly compressible soil. Regarding the Maximum Dry Density (MDD) and Optimum Moisture content (OMC), the compaction graph was plotted and the values were determined according to the graph in Fig. 6 (c). The association of the MDD and OMC values in the coconut shell column preparation process demonstrated a vital role as it provided the fundamental reference between the relationship of water volume required and the kaolin clay to acquire the highest efficiency of product. The falling head permeability test proved that the kaolin clay S300 was less permeable with the value of 8.96 x 10^{-12} m/s, where it was susceptible to water accumulation issue. As reported by previous results, the authors obtained the value of permeability value at 8.89 x 10^{-12} m/s from kaolin clay, proving the soil can deform easily when axial loading was applied [34].



(a) (b)



(c)

Figure 6. Kaolin clay S300 properties (a) USCS chart (b) Particle size distribution (c) Compaction curve from standard compaction test.

For crushed coconut shell, it was a well graded particle and behaved like gravel or sand type, with A-2 value based on the AASHTO. A-2 signified that this material was a clayey gravel sand, and the majority of the particle size was ranging within 2–9 mm as shown in Fig. 7. The constant head permeability test showed it was a highly permeable material with the value of 2.32 x 10^{-3} m/s, promoting a good drainage system for discharging the excessive accumulated water within itself. The minimum and maximum dry density value of coconut shell obtained from the study were 0.497 g/cm^3 and 0.596 g/cm^3 respectively, and the values were utilized in the column preparation process. From the obtained values, the in-situ density was generated by applying the raining method, where the average density of coconut shell obtained was 0.58 g/cm^3 and therefore, the relative density was approximately 87.50 %. Nonetheless, an average higher value of relative density did not only accelerate the dissipation of excessive pore water pressure generated within the soil, but the compacted coarse material of crushed coconut shell potentially acted a stiffer reinforcement beneath the soil.

Table 6. Crushed coconut shell properties.

Test	Parameter	Value
Soil Classification	AASHTO	A-2
Small Pycnometer	Specific Gravity, Gs	1.70
Relative Density Test	$\rho_{d(min)}$ (g/cm³)	0.497
	$\rho_{d(max)}$ (g/cm³)	0.596
Constant Head Permeability	Coefficient of Permeability, *k* (m/s)	2.32 x 10^{-3}

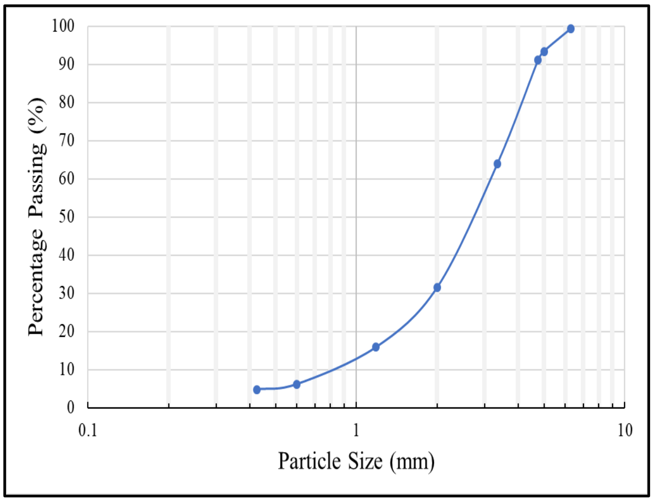


Figure 7. Particle size distribution curve of coconut shell.

3.2. Analysis of Shear Strength Parameters

The shear strength values were obtained from UCT, and further parameters were calculated and analysed. The average deviator stress, exerted loading, strain, stress and shear strength values were analysed with the appropriate graphs and tables. For Table 7, it demonstrated the strain, stress and exerted loading on the control sample, and the reinforced specimens of S1360, S1380, and S13100. The variation of stress with strain against in responds to the exerted load by the UCT machine was plotted in Fig. 8.

Table 7. Parameters of shear strength for stress, strain and exerted load

Specimen	Strain (%)	Stress (kPa)	Exerted load (kN)
Control	1.85	7.12	0.0586
S1360	2.79	8.35	0.0870
S1380	2.88	8.98	0.0930
S13100	2.71	9.15	0.0880

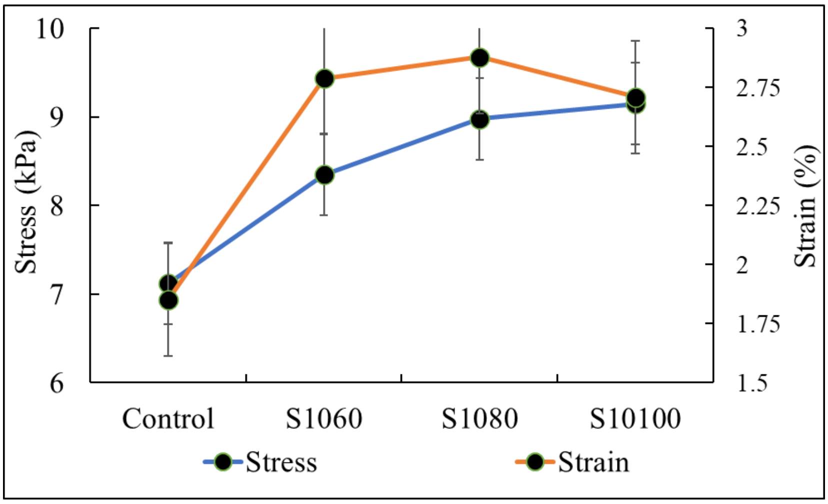


Figure 8. The variation of stress and strain of specimens against the exerted load.

Table 7 showed that the S13100 column was able to withstand the largest stress, 9.15 kPa while the least was by S1360, only recorded 8.35 kPa. The increase in the content of replaced coarse material, crushed coconut shell will directly result in the enhancement of stress. Although the increment trend was observed by increasing the column height, the increment of stress only recorded 0.17 kPa from the S1380 column to the S13100 column which was lesser compared to the increment from the S1360 column to the S1380 column, recorded 0.63 kPa. This may be due to the disturbance of the nature state of kaolin clay, where it was replaced with foreign material, crushed coconut shell and thus causing the reduction of shear strength [35]. From Table 7, it was inferred that the increase of strain value halted at 2.88 %, then decreased to 2.71. The above phenomena was interpreted as the S13100 column was not sheared completely and failure occurred before the axial loading was effectively transferred to the bottom part of the reinforced column. Although the S1380 column was not reinforced thoroughly, the bottom part of the unreinforced soil performed better than the reinforced part of the S13100 column which was attributed to the coarse coconut shell substitution that did not cancel out the effect of soil disturbance during the drilling process. For both strain and exerted load category, the value increased as the column height increased, but showed reduction after the peak value by the S1380 column. The detailed performance of reinforced column was analysed by interpreting the data of shear strength parameter in Table 8. All the shear strength improvement of reinforced specimens, S1360, S1380, and S13100 were computed in accordance to the shear strength value of control specimen.

Table 8. Parameters of shear strength deviator stress, shear strength and its improvement.

Specimen	Deviator stress (kPa)	Shear strength (kPa)	Shear strength improvement (%)
Control	14.24	7.12	-
S1360	21.36	8.35	17.28
S1380	23.71	8.98	26.12
S13100	21.89	9.15	28.51

As mentioned previously, the shear strength of soil was reduced by the replacement of foreign material, the shear strength values and its improvement were affected by the substitute effect. By using the control sample as the calculation reference, the shear strength improvement showed an increment from 17.28 % to 26.12 %, then increased again to 28.51 %. As reported by the previous study, the authors utilised the single and group bottom ash columns resulted in an identical trend [21]. Coherent to that, the difference between the shear strength improvement rate between the 80 mm and 100 mm column height marked a smaller rate as compared to the 60 mm and 80 mm respectively, where the loosened particles of kaolin soil that incurred by the drilling activity contributed to the reduction of strength of the entire specimen [36]. From the perspective of column parameters, the column height, column diameter, and the amount of replaced coarse material can exert immense influence on the performance of the column through its shear strength value. The analysis continued with the correlation techniques by correlating the shear strength parameters in sub topic 3.3, where it simplified the complexity of the relationship between the dependent and independent variable of an engineering system by statistical method [37].

3.3. Correlation of Shear Strength Improvement versus Column Penetrating Ratio

Referring to Table 8, the highest shear strength improvement was recorded at S13100 column with the value of 28.51 % with the H_c/H_s value of 1.0, followed by the S1380 column with 0.8 H_c/H_s resulted in 26.12 % of improvement rate. The increment of shear strength improvement was directly proportional to the column penetrating ratio, from 0.6 to 1.0 produced the improvement rate of 17.28 % to 28.51 % respectively. Similarly, the S1380 column with a 0.8 of H_c/H_s recorded a moderate value of improvement, with only 26.12 %. This was due to the bulging of the column occurring at the top part of the column extended to 80 mm, whilst the remaining part of the column was less functional to receive the load from the reinforced section. Precisely, a column height with 100 mm coconut shell reinforcement can produce the highest value of improvement, whereas the 60 mm produced the least improvement with 13 mm diameter of kaolin clay. The regression method with the correlation equation of R^2= 0.9857 was presented in equation (1). Fig. 9 showed the correlation of shear strength improvement versus column penetrating ratio.

$$\Delta Su = 29.693\left(H_c/H_s\right) + 0.1618. \quad (1)$$

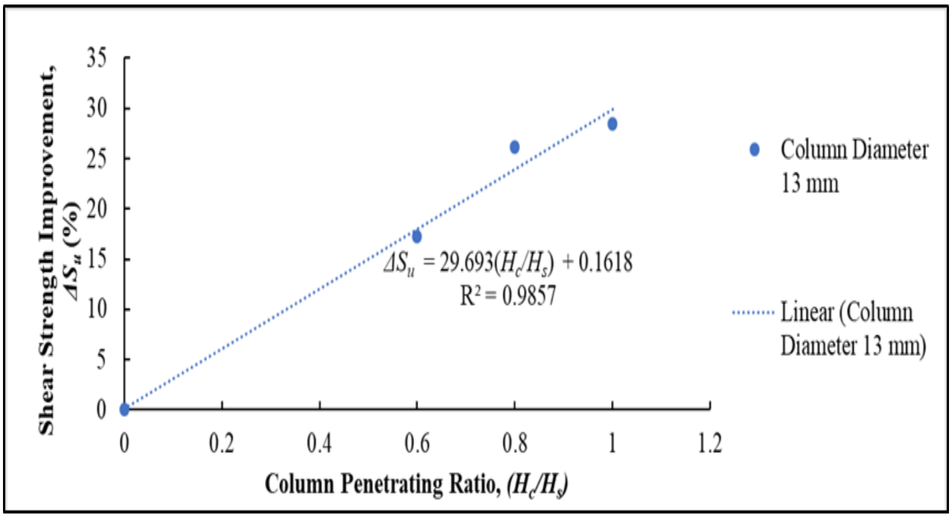


Figure 9. Correlation of shear strength improvement versus column penetrating ratio.

3.4. Correlation of Shear Strength Improvement versus Column Penetrating Ratio

For this sub-topic, the column penetrating height was examined in accordance to the width of the column. The Hc/Dc ratio varied from 4.6153 to 6.1538, then increased to 7.6923. The favourable value of column height to column diameter ratio lied within the range of 4–6 [38], where in this study it did not really indicate in the range values, where 7.6923 of H_c/D_c produced the largest shear strength improvement and thus, further study on this specific ratio is required to determine the behaviour of column parameters. Previous research explained the above situation by considering the critical column length factor and the suggested value was within approximately 6 times its diameter value [39], where this study presented about 7.69 times. The obtained ratio of this value was classified as the nature of the coarse material, crushed coconut shell which performed differently as compared to other potential materials for instance bottom ash. Equation (2) showed the correlations of the crushed coconut shell column in accordance with the kaolin clay shear strength improvement with R^2 = 0.9857. Fig. 10 showed the correlation of shear strength improvement against column height to column diameter ratio.

$$\Delta Su = 3.8601\left(H_c/D_c\right) + 0.1619. \quad (2)$$

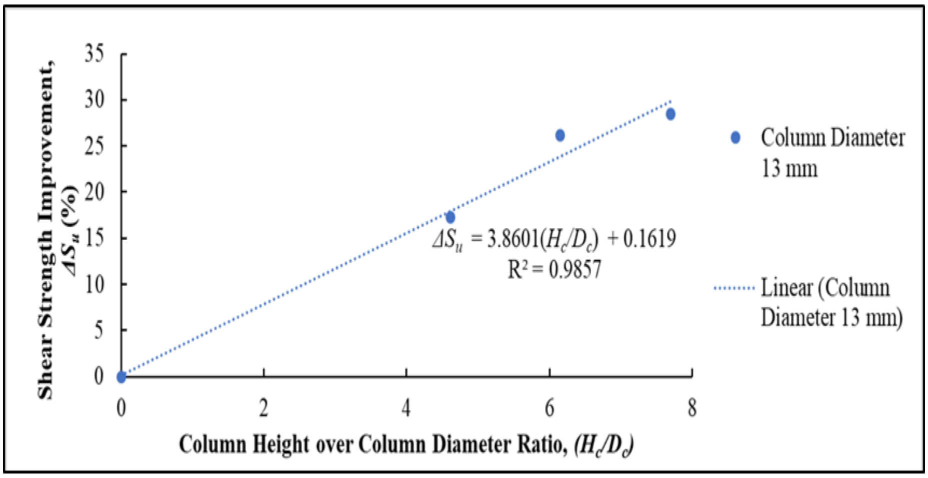


Figure 10. Correlation of shear strength improvement versus column height over column diameter ratio.

3.5. Correlation of Shear Strength Improvement versus Volume Replacement Ratio

Based on Table 4 and 8, the volume replacement ratio with the value of 0.0676 showed the highest rate of shear strength improvement while the least was recorded when the value was 0.0405, yielding a different of shear strength improvement of 11.23 %. From both values, it was noticed that the volume alteration of column was from 2535 π cm^3 to 4225 π cm^3 or an increment of 66.91 % which produced the shear strength difference of 2.03 kPa. This result data was supported by the study using PP column as a reinforcement material in enhancing the soil bearing capacity of kaolin, where the authors reported the change of about 66.81 % of the volume will generate the additional shear strength value of 4.05 kPa [22]. The additional substituted amount of coarse material where in this study crushed coconut shell increased the capacity of the penetrating column, enhanced the stiffness of the column, and promoted the ability to carry additional load. The more particles of crushed coconut shell inside the specimen, the higher the ability to withstand a larger pressure from the axial loading hence, preventing the earlier failure of the column from occurring during the shearing process. The regression equation (3) showed the value of R^2 = 0.9854. Fig. 11 demonstrated the correlation of shear strength improvement against volume replacement ratio.

$$\Delta Su = 439.38\left(V_c/V_s\right) + 0.1718. \quad (3)$$

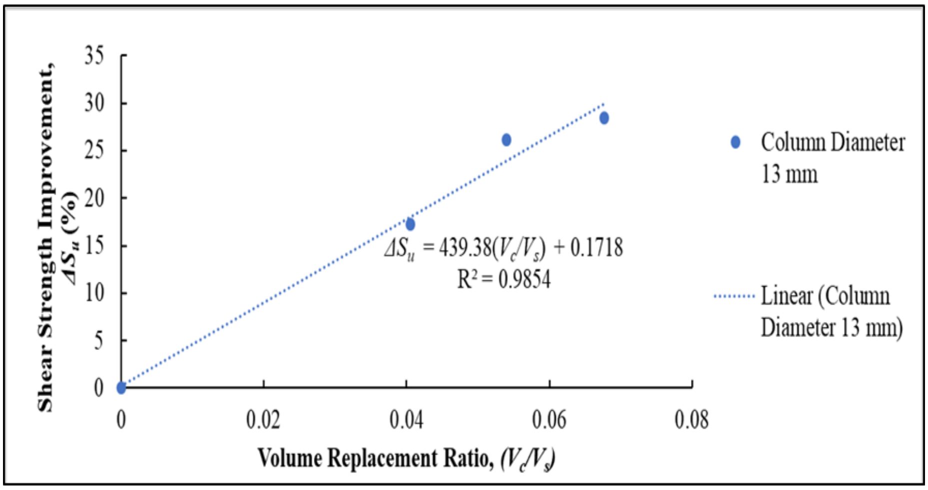


Figure 11. Correlation of shear strength improvement versus volume replacement ratio.

4. Conclusion

This chapter summarised the results gathered from the respective geotechnical tests, which encompassed the determination of the physical and mechanical properties of research materials, kaolin clay S300, and coconut shell, together with the investigation of reinforced specimens via the implementation of UCT. Both of the objectives were achieved and the deduced conclusions were as follows:

1. The kaolin clay soil, type S300 was a problematic soft clay soil, which was examined by the soil classification through the AASHTO and USCS plasticity chart. Both standards concluded the kaolin soil was an inorganic silt soil with slight plasticity. In addition, the deployment of standard compaction test verified the kaolin had the OMC of 19.40 %, and a MDD value of 1.55 Mg/m^3, produced from the proctor curve. The coefficient of permeability of kaolin also signified it can cause the water accumulation issue, by having an extremely low value of 8.96 x 10^{-12} m/s.

2. The coconut shell that was grinded was analysed through geotechnical approaches and found to behave like a coarse aggregate with the AASHTO value of A-2. This value verified it was a gravel-sand type material, with the coefficient of hydraulic conductivity value of 2.32 x 10^{-3} m/s. The computed relative density value was 87.50 % following the minimum, maximum, and in-situ dry density, suggesting it was a very dense material. Thus, the association of this material was a potential substitute for resolving the soil swelling matter through the provision of additional drainage to the kaolin soil.

3. The fabrication of a singular coconut shell column beneath the kaolin clay soil recorded positive results, with the range of shear strength enhancement from 1.23 kPa to 2.03 kPa in reference to the control specimen shear strength value. This study verified the insertion of a singular coconut shell column can prolong the failure of soil, by raising the soil-bearing capacity to 28.51 %. Therefore, the current research suggested the optimum design of reinforced specimen possessed the values H_c/H_s =1.0, H_c/D_c = 7.6923, and V_c/V_s = 0.0676. Coherently, the fully penetrated column design delivered the highest value of improvement, showing that a larger amount of grinded coconut shell was able to distribute the axial load effectively.

References

1. Pruett, R.J. Kaolin deposits and their uses: Northern Brazil and Georgia, USA. Applied Clay Science. 2016. 131(2015). Pp. 3–13. DOI: 10.1016/j.clay.2016.01.048
2. Karkush, M., Jabbar, A. Improvement of Soft Soil Using Linear Distributed Floating Stone Columns under Foundation Subjected to Static and Cyclic Loading. Civil Engineering Journal (Iran). 2019. 5(3). Pp. 702–711. DOI:10.28991/cej-2019-03091280.
3. AL-Ani, S.M.A., Karkush, M.O., Zhussupbekov, A., Al-Hity, A.A. Influence of Magnetized Water on the Geotechnical Properties of Expansive Soil. Lecture Notes in Civil Engineering. 112. Springer Science and Business Media Deutschland GmbH, 2021. Pp. 39–50.
4. Nicholson, P.G. In Situ Reinforcement2015. 371–387 p. ISBN:9780124080768.
5. Turskis, Z., Daniūnas, A., Zavadskas, E.K., Medzvieckas, J. Multicriteria Evaluation of Building Foundation Alternatives. Computer-Aided Civil and Infrastructure Engineering. 2016. 31(9). Pp. 717–729. DOI:10.1111/mice.12202.
6. Maltseva, T., Bai, V., Erenchinov, S., Esipov, A., Chumanova, N. Bearing capacity of frame-gantry pile foundations. Magazine of Civil Engineering. 2023. 122(6). DOI:10.34910/MCE.122.7.
7. Jawad, S., Karkush, M. Shear strength and chemical properties of soft clayey soil treated with magnetized water. Magazine of Civil Engineering. 2023. 124(8). DOI:10.34910/MCE.124.6.

8. Sánchez-Garrido, A.J., Navarro, I.J., Yepes, V. Evaluating the sustainability of soil improvement techniques in foundation substructures. Journal of Cleaner Production. 2022. 351(March). DOI:10.1016/j.jclepro.2022.131463.
9. Piccinini, I.D. Ground Improvement with Stone Columns - Methods of Calculating Settlement Improvement Factor. University of Glasgow. 2015. (April). DOI:10.13140/RG.2.1.2159.2486.
10. Mani, K., Nigee, K. Focus on Ground Improvement. International Journal of Innovative Research in Science, Engineering and Technology. 2013. 2(11). Pp. 6451–6456. URL: www.ijirset.com.
11. Boumekik, N.E.I., Labed, M., Mellas, M., Mabrouki, A. Optimization of the ultimate bearing capacity of reinforced soft soils through the concept of the critical length of stone columns. Civil Engineering Journal (Iran). 2021. 7(9). Pp. 1472–1487. DOI:10.28991/cej-2021-03091737.
12. Wang, W., Deng, X., Wang, Y., Peng, L., Yu, Z. Impacts of infrastructure construction on ecosystem services in new-type urbanization area of North China Plain. Resources, Conservation and Recycling. 2022. 185(April). Pp. 106376. DOI:10.1016/j.resconrec.2022.106376. URL: https://doi.org/10.1016/j.resconrec.2022.106376.
13. Lim, G., Li, C., Ji, X. Chinese financial statecraft in Southeast Asia: an analysis of China's infrastructure provision in Malaysia. Pacific Review. 2022. 35(4). Pp. 647–675. DOI:10.1080/09512748.2020.1868556. URL: https://doi.org/10.1080/09512748.2020.1868556.
14. bin Hasan, M., binti Yusuf, N., binti Noor Shahrudeen, N.A., Kassim, A.M.H. Strength of soft clay reinforced with group crushed polypropylene (PP) columns. Electronic Journal of Geotechnical Engineering. 2015. 20(22). Pp. 12291–12308.
15. Aljanabi, Q.A., Chik, Z., Kasa, A. Construction of a new highway embankment on the soft clay soil treatment by stone columns in Malaysia. Journal of Engineering Science and Technology. 2013. 8(4). Pp. 448–456.
16. Bilal, M., Talib, A. A study on advances in ground improvement techniques. Advances in Geotechnical Engineering. 2016. (April). Pp. 322–330. DOI:10.13140/RG.2.1.4865.4965.
17. Karkush, M., Ali, N.A. Electrokinetic enhancement of microbial induced calcite precipitation used in improving the shear strength of soft clay. Smart Geotechnics for Smart Societies. CRC Press, 2023. Pp. 155–163.
18. Karkush, M.O., Ali, H.A., Ahmed, B.A. Improvement of unconfined compressive strength of soft clay by grouting gel and silica fume. Springer Series in Geomechanics and Geoengineering. 2018. Pp. 546–550. DOI:10.1007/978-3-319-97112-4_122.
19. Karkush, M.O., Yassin, S. Using Sustainable Material in Improvement the Geotechnical Properties. 15(4)2020. 2208–2222 p.
20. BRÛLÉ, S., SERANAJ, A., PIQANI, A. Seismic Behavior of a Building Founded on Loose Soil Improved by Stone Columns. Researchgate.Net. 2020. (December). URL: https://www.researchgate.net/profile/Stephane-Brule/publication/347648602_Seismic_Behavior_of_a_Building_Founded_on_Loose_Soil_Improved_by_Stone_Columns_INTERNATIONAL_SYMPOSIUM_ON_DURRES_EARTHQUAKES_AND_EUROCODES/links/5fe2f160299bf1408837574d/Seismic-Beh.
21. 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. (February). DOI:10.1007/s11356-023-25966-x. URL: https://doi.org/10.1007/s11356-023-25966-x.
22. Hasan, M., Zaini, M.S.I., Hong, N.A.W., Wahab, A., Masri, K.A., Jaya, R.P., Hyodo, M., Winter, M.J., Sholichin, M., Haribowo, R. Sustainable ground improvement method using encapsulated polypropylene (PP) column reinforcement. IOP Conference Series: Earth and Environmental Science. 2021. 930(1). DOI:10.1088/1755-1315/930/1/012016.
23. Verma, S.K., Shrivastava, S. Use of coconut shell as partly substitution of coarse aggregate - An experimental analysis. AIP Conference Proceedings. 2019. 2158(September). DOI:10.1063/1.5127145.
24. Gunasekaran, K., Kumar, P.S., Lakshmipathy, M. Mechanical and bond properties of coconut shell concrete. Construction and Building Materials. 2011. 25(1). Pp. 92–98. DOI:10.1016/j.conbuildmat.2010.06.053. URL: http://dx.doi.org/10.1016/j.conbuildmat.2010.06.053.
25. Mochida, Y., Olabamiji, O.J., Kasahara, K. Study on Development of Soil Improvement Pile Method Using Recycled Soil. International Journal of GEOMATE. 2021. 20(82). Pp. 28–33. DOI:10.21660/2021.82.Gx249.
26. Chai, X.J., Deng, K., He, C.F., Xiong, Y.F. Laboratory model tests on consolidation performance of soil column with drained-timber rod. Advances in Civil Engineering. 2021. 2021. DOI:10.1155/2021/6698894.
27. Zukri, A., Nazir, R. Sustainable materials used as stone column filler: A short review. IOP Conference Series: Materials Science and Engineering. 2018. 342(1). DOI:10.1088/1757-899X/342/1/012001.
28. Gunasekaran, K., Kumar, P.S., Lakshmipathy, M. Study on properties of coconut shell as an aggregate for concrete Self-compacting lightweight concrete View project Coconut shell concrete View project .Study on Pruperties of Goconut Shell as an gate fur Concrete. 2011. (January 2011). URL: https://www.researchgate.net/publication/284088249.
29. Sujatha, A., Balakrishnan, S.D. Properties of Coconut Shell Aggregate Concrete: A Review. 2021. 83. Pp. 759–769. DOI:10.1007/978-981-15-5644-9_60.
30. Gupta, A., Gupta, N., Shukla, A., Goyal, R., Kumar, S. Utilization of recycled aggregate, plastic, glass waste and coconut shells in concrete - A review. IOP Conference Series: Materials Science and Engineering. 2020. 804(1). DOI:10.1088/1757-899X/804/1/012034.
31. Zaini, M.S.I., 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). Pp. 352–366. DOI:10.30880/ijie.2023.15.01.032.
32. Damoerin, D., Prakoso, W.A., Utami, Y. Improving shear strength of clay by using cement column reinforcement under consolidated undrained test. International Journal of Technology. 2015. 6(4). Pp. 709–717. DOI:10.14716/ijtech.v6i4.1206.
33. Gunasekaran, K., Annadurai, R., Kumar, P.S. Plastic shrinkage and deflection characteristics of coconut shell concrete slab. Construction and Building Materials. 2013. 43. Pp. 203–207. DOI:10.1016/j.conbuildmat.2013.02.019. URL: http://dx.doi.org/10.1016/j.conbuildmat.2013.02.019.
34. Hoque, M.I., Hasan, M., Mim, N.J. Shear Strength of Soft Clay Reinforced With Single Encased Stone Dust Columns. Jurnal Teknologi. 2023. 85(5). Pp. 27–34. DOI:10.11113/jurnalteknologi.v85.19879.
35. Najjar, S.S. A State-of-the-Art Review of Stone/Sand-Column Reinforced Clay Systems. Geotechnical and Geological Engineering. 2013. 31(2). Pp. 355–386. DOI:10.1007/s10706-012-9603-5.
36. Hasan, N.M., 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). Pp. 117–131. DOI:10.22075/jrce.2024.32181.1925. URL: https://creativecommons.org/licenses/by/4.0/.

37. Egbe, J.G., Ewa, D.E., Ubi, S.E., Ikwa, G.B., Tumenayo, O.O. Application of multilinear regression analysis in modeling of soil properties for geotechnical civil engineering works in Calabar South. Nigerian Journal of Technology. 2018. 36(4). Pp. 1059. DOI:10.4314/njt.v36i4.10.
38. Hasan, M., Jusoh, W.N.W., Chee, W.S., Hyodo, M. The undrained shear strength of soft clay reinforced with group encapsulated lime bottom ash columns. International Journal of GEOMATE. 2018. 14(46). Pp. 46–50. DOI:10.21660/2018.46.45208.
39. Najjar, S.S., 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). Pp. 1263–1277. DOI:10.1061/(asce)gt.1943-5606.0000328.

Information about the authors:

Ng Jun Shen*, PhD*
ORCID: https://orcid.org/0000-0002-6113-1237
E-mail: jshenng98@gmail.com

Muzamir Hasan, *PhD*
ORCID: https://orcid.org/0000-0002-2700-236X
E-mail: muzamir@ump.edu.my

Nurrul Nisya Anuar*,*
E-mail: nurrulnisyaanuar@gmail.com

Received 10.11.2023. Approved after reviewing 26.11.2024. Accepted 29.11.2024.