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Stabilization of kaolinitic soil using crushed tile column

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Keywords: crushed tile, granular column, lateral load capacity, kaolinitic clay, ground improvement

Abstract. Kaolinitic soil is a problematic soil that causes poor carrying capacity and excessive settlement, resulting in significant damage to buildings and foundations. Therefore, soil enhancements were introduced to improve the engineering characteristics of the soil. Crushed tiles were taken from the construction area to substitute aggregate or natural sand. Hence, the purpose of the study is to investigate the lateral load capacity of the crushed tile column on the kaolin clay at various column dimensions. Reinforced kaolin clay samples were tested via several laboratory tests, including Particle Size Distribution, Atterberg limits test, Relative Density, Compaction test, Permeability test, Unconfined Compression Test, and Unconsolidated Undrained Triaxial Test with encapsulated crushed tile with geotextile encasement. The authors investigated the effects of column diameter, height, area replacement ratio, height penetration ratio, height to column diameter ratio, volume replacement ratio, and confining pressures on the shear strength of the encapsulated crushed tile columns at a diameter of 6 mm and 8 mm and at a height of 25.33 mm, 38 mm, and 76 mm. The findings showed that using crushed tile columns at various above listed parameters can enhance the soil's shear strength up to 52.00 % at the optimal utilization of a single enveloped crushed tile column with a diameter of 6 mm and height of 76 mm. The crushed tile granular column is practical to be implemented to enhance the strength of the problematic soil. However, the limitation of utilizing this approach is that the crushed tile granular column may not be suitable for deeper soil layers. Hence, the study demonstrated the significant enhancement of the lateral load capacity of soft kaolin clay soil by utilizing crushed tile waste as a granular column.

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1. Introduction

In the process of construction, the biggest problem faced by contractors as well as other workers is the foundation settlements. The use of kaolinitic soil in construction projects presents a complex challenge [1]. This type of soil is known for its problematic characteristics that result from changes in moisture content, which cause volumetric alterations [2]. The engineering characteristics issues linked with this type of soil include settlement, insufficient plasticity, greater compressibility, and susceptibility to climate variables [3]. The resulting disasters and costs of recovering and reconstructing structures built on problematic soils are a matter of national concern [4]. Kaolin is one of the most common clay minerals, and it is distributed sensitively among other high-resistance clays [5, 6]. Therefore, unstable soils, such as soft clay soils, are altered to improve their technical properties and increase their cutting strength [7]. Most of the researchers have suggested various methods, including soil stabilization and improvement [8–11], to alter the characteristics of kaolinitic soils.

The use of concrete or granular materials for ground improvement techniques has become increasingly popular in both partially and fully saturated conditions to enhance ground strength, reduce settlement, and control ground movement. This technique has been employed to improve the load-bearing capacity of kaolinitic clay and expedite the consolidation process. The application of granular column ground improvement presents benefits, including reduced compressibility and instability risk, alongside amplified durability and permeability. Bagriacik [3] and Zaini and Hasan [12] conducted thorough investigations on these subjects.

Several factors, such as column width, arrangement, and spacing, properties of the granular material used, degree of pillar material compression, and the lateral restraints offered by the soil beneath, have an impact on the efficacy of granular columns as a ground improvement method. Nonetheless, the application of granular columns may not be efficient in soils with a shear strength endurance below 15 kPa because of insufficient lateral support from the underlying soft soil [13]. To address this issue, it is possible to encase the granular column using materials like bottom ash, masonry, or steel slag, which provides extra support and allows for the use of more robust shear endurance without excessive column swelling. Thus, it is crucial to establish a strong basis for the creation of solutions for dehydrated soil by incorporating imperforate columns. Studies by Zaini et al., [14], Hosseinpour et al. [15], Zhang et al., [16], Supian et al. [17], and Hilal & Hadzima-Nyarko [18] have explored these aspects in detail.

The use of solid waste as a replacement component has been increasing in the last 30 years, and ceramic waste is a significant contributor to this waste stream. However, recycling options for this waste are often overlooked, and the waste is instead shipped to landfills. In the construction industry, powder and fine particle ceramic waste have potential as replacement components. The recycling of ceramic tile waste has been explored in previous research, such as the groundbreaking work of Zanelli et al. [19], and the ceramic industry has also begun recycling its own waste since the early 1990s. However, the lack of information on the effects of residues in the production of ceramic tiles is a significant barrier to widespread recycling.

Incorporating crushed tile waste as a substitute for fragile aggregates in construction projects presents environmental advantages, such as obviating the necessity to discard the waste in landfills and furnishing an alternate source of raw materials. The utilization of crushed tile waste as an eco-friendly option to stabilize soft clay soils is becoming increasingly popular, but it is essential to comprehensively comprehend the characteristics of crushed tile and its effects on problematic soils before adopting it.

The study is conducted to achieve the aim of identifying the role of crushed tile waste as a kaolinitic clay stabilization method whereas to enhance the compressibility and shear strength of consolidated clayey soils. Besides, the used of crushed tile waste column as a gravelly material is to enhance the bearing capacity, reduce settlement and to accelerate the consolidation. This is realized by using the crushed tile waste in stabilizing the kaolinitic clay soil in regard to the specific gravity, particle size distribution (PSD), compaction parameters, Atterberg limits, unconfined compressive strength and shear strength parameters.

2. Materials and Methods

2.1. Materials

Kaolinite is a type of clay mineral that possesses a hydrophobic polymer structure and has a tendency to combine and interact with water to create a consistent soft clay. The kaolinitic clay samples utilized in this investigation were obtained from Kaolin (M) Sdn. Bhd, situated in Malaysia at coordinates 4°9'48.6"N, 101°16'25.32"E. Homogeneous soft clay samples were created using the S300 grade of kaolin powder. Table 1 presents the fundamental properties of the soil that were employed in this investigation. Moreover, the crushed tile is collected from Nico Ceramic Premium Factory Outlet (3°3’35.0”N, 101°31’24.0”E) at Selangor, Malaysia. The company have been established since 2008. In this study, the crushed tile was encased in an open-pore material that possesses significantly wide pore diameter. The substitution technique was used to place the crushed tile in the soft clay. For encapsulating the kaolinitic clay reinforced with the crushed tile column, the MTS 130 Polyester Non-woven Geotextile Needle punched Fabric was chosen.

Table 1. Basic engineering properties of kaolinitic clay

Properties	Unit	Result
Gravel	%	0
Sand	%	46
Clay and Silt	%	54
USCS classification		ML
AASHTO classification		A-7-6b
Initial moisture content	%	0.97
Specific gravity, G_s		2.62
Liquid limit, LL	%	41.30
Plastic limit, PL	%	31.25
Plasticity index, PI	%	10.05
MDD, $\rho_{d(max)}$	g/cm^3	1.55
OMC, W_{opt}	%	18.00
UCS, q_u	kN/m^2	10.46
USS, S_u	kN/m^2	5.23
Cohesion, c	kN/m^2	14.1
Internal Friction Angle, φ	°	23.8

Note: MDD refers to Maximum Dry Density; OMC refers to Optimum Moisture Content; UCS refers to Unconfined Compression Strength; USS refers to Undrained Shear Strength

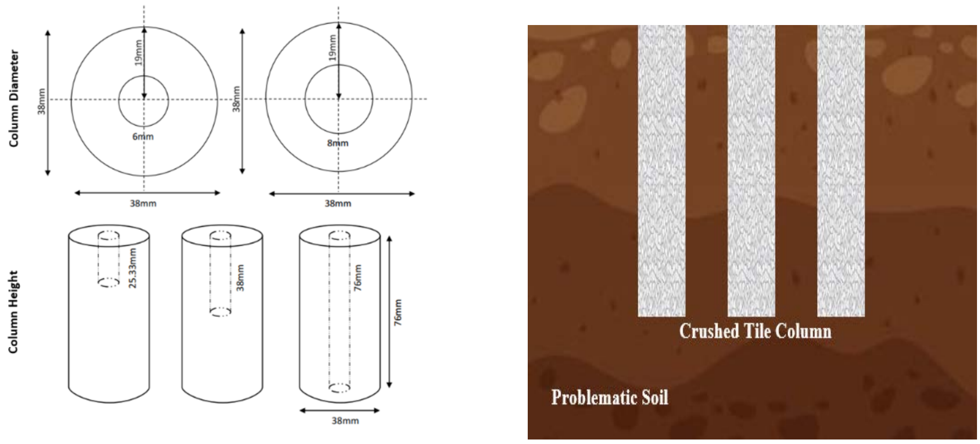
2.2. Samples Preparation

The experimental procedures in this study were conducted in accordance with both ASTM and British standards. Various tests were carried out as highlighted in Table 2. The crushed tile columns used in the strength tests were prepared with uniform density by filling the same volume with the same mass of crushed tile. The cylindrical specimens for UU and UCT tests had a diameter of 38 mm and height of 76 mm, with a density of 3.597 g/cm^3 (Mass = 310 g, Volume = 86.19 cm^3). The kaolinitic clay was admixed with 18.40 % water, which was determined to be the optimum moisture content from the compaction test. Each specimen had a constant mass of 310 g and was compacted in three layers using a customized steel mold with a diameter of 38 mm and height of 76 mm. The mold was designed to compress the kaolin clay into a uniform specimen. The crushed tile column was remoulded to enhance the soil layer and mimic the conditions in the construction section, where soil undulations, tilt, and uneven subsidence can occur due to liquefaction of underlying soil layers.

Table 2. Type of Test in accordance to the standard

Material	Tests	Standard/ Method
Kaolin	Atterberg Limit	ASTM D4318-17
	Sieve Analysis	BS 1377: Part 5: 1990
	Compaction	ASTM D4253-16
	Specific Gravity	ASTM D854-14
	Permeability - Falling Head	ASTM D 2434
Crushed Tile	Sieve Analysis	BS 1377: Part 5: 1990
	Specific Gravity	ASTM D854-14
	Compaction	ASTM D4253-16
	Permeability - Constant Head	BS 1377: Part 5: 1990
Crushed Tile Reinforced Kaolin	Unconfined Compression	ASTM D 2166
	Unconsolidated Undrained Triaxial	BS 1377: Part 7: 1990

The process for reinforcing the kaolinitic clay samples with crushed tile columns followed the same procedure as the unreinforced sample, including mixing the kaolin clay and compacting it in three layers with free-fall blows using a customized steel hammer. Before removing the samples from the mold, holes were drilled with diameters of either 6 mm or 8 mm to prevent the specimens being extruded out of the mold. The crushed tile column was inserted into the pre-drilled hole to maintain a uniform density in all the crushed tile. The mass used to fill the hole was based on the volume of the pre-drilled hole. After the crushed tile installation, the specimens were taken out for the Unconfined Compression Test (UCT). The kaolin specimens were arranged with a single diameter of 6 mm or 8 mm and heights of 25.33 mm, 38 mm, and 76 mm, as shown in Fig. 1.



(a) **(b)**

**Figure 1. Variation of crushed tile column dimension and arrangement;
a) Lab scale; b) On-site Application.**

To prevent excessive bulging of the crushed tile column, a geotextile was used to encapsulate it. The geotextile was sewn into a cylinder shape to fit the diameter of the borehole and carefully placed inside it [14, 20]. Based on multiple pilot test results, the raining method was concluded to be the most effective technique for producing homogeneous crushed tile columns in kaolinitic clay specimens by the researchers.

2.3. Samples Testing

The laboratory tests were carried out on the kaolinitic clay, and crushed tile waste. The samples were tested for basic geotechnical properties (i.e. specific gravity, Atterberg limit and compaction), unconfined compressive strength and unconsolidated undrained. Three replicates were used for each test for basic engineering properties, unconsolidated undrained and five replicates for unconfined compression test.

2.3.1. Specific Gravity

The specific gravity of the kaolinitic clay soil samples was determined with the small pycnometer method. For the kaolinitic soil, the pycnometer was filled to the brim with distilled water and the mass of the pycnometer filled with water was also measured. From these measurements, the specific gravity of the kaolinitic clay specimen was calculated. The same procedure was repeated for crushed tile samples to determine their specific gravity. Specific gravity is an important property to determine the soil-water content, soil-air content, and soil particle density.

After weighing the mould with the material, the material was transferred into a gas jar, which was then filled with distilled water until the water level reached the overflow spout. The volume of the water displaced by the material was measured and recorded. The relative density of the material was calculated as the ratio of the mass of the material to the mass of an equal volume of water. The gas jar method is commonly used for coarse-grained materials with particle sizes between 0.6 mm and 2.36 mm.

2.3.2. Atterberg Limit

The Atterberg limit of a sample was determined through the cone penetration method. The liquid limit will be first determined, followed by the determination of the plastic limit. Then, the plasticity index was calculated.

2.3.3. Standard Proctor Test

Standard Proctor Compaction Test was adopted in this study. The correlation of dry density of soil and moisture content obtained from the compaction test is plotted in a graph to determine the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD). The MDD is achieved at OMC.

2.3.4. Particle Size Distribution (PSD) Test

The distribution of coarse-grained soil is determined by the application of sieve analysis. The test sieves used were with the size 5.00 mm, 3.35 mm, 1.18 mm, 600 µm, 300 µm, 150 µm and 63 µm. The sieves were stacked up together with the largest opening size at the top and the pan under the smallest opening of sieves at the bottom. The sieving process was done by using a mechanical shaker and the proportions of soil left on each sieve were measured using the mass balance. A distribution curve was then plotted with the percentage of particles retained on each sieve. The sieve analysis can be carried out in either wet or dry conditions. In this research, the dry sieve analysis was selected.

2.3.5. Permeability Test

The permeability test was conducted using a constant head permeameter. The test involved applying a constant head of water on a compacted soil sample, measuring the volume of water passing through the sample and calculating the hydraulic conductivity or permeability of the soil. The test was carried out on both kaolin clay and crushed tile specimens at their respective OMC and MDD values to determine their permeability characteristics. The permeability coefficient or hydraulic conductivity of the soil was calculated using Darcy's law.

The falling head test was utilized to determine the coefficient of permeability of kaolin clay. In this test, the sample was placed in a permeameter with a diameter of 8.2 cm and a height of 10 cm. A manometer tube was connected to the permeameter to measure the head of water above the sample. The water was flowed through the sample by gravity, and the time taken for the water level in the manometer tube to fall a certain distance was recorded. The coefficient of permeability was calculated using Darcy's Law, which relates the flow of water to the hydraulic gradient and the properties of the soil.

2.3.6. Unconfined Compression Test (UCT)

Unconfined Compression Test (UCT) was conducted to obtain the unconfined compressive strength of the cohesive soils. This test is the simplest laboratory testing in determining the soil strength by imposing the axial load without lateral confining pressures.

2.3.7. Unconsolidated Undrained (UU) Triaxial Test

The strength parameters of kaolinitic clay enhanced with single enveloped crushed tile columns were determined through the 2.3.7 Unconsolidated Undrained (UU) Triaxial Test. A testing program was designed for UU triaxial tests of both kaolinitic clay and kaolinitic clay enhanced with enveloped crushed tile columns. A total of 21 specimens with varying area replacement ratios were tested. Table 3 shows the coding used for each sample and the corresponding testing program. In order to calculate the strength of kaolinitic enhanced with enveloped crushed tile columns, a confining pressure of 70, 140, and 280 kPa was applied to the sample via the chamber fluid until a 20 % strain was attained. The equipment was then carefully dismantled after the sample was removed.

2.3.8. Statistical Analysis

In this study, numerical analyses were conducted using Microsoft Excel 2010, and linear correlation analysis was utilized to assess the relationships between the independent and dependent variables. Error bars were incorporated to indicate statistically significant differences among the sample results.

3. Results and Discussion

3.1. Specific Gravity

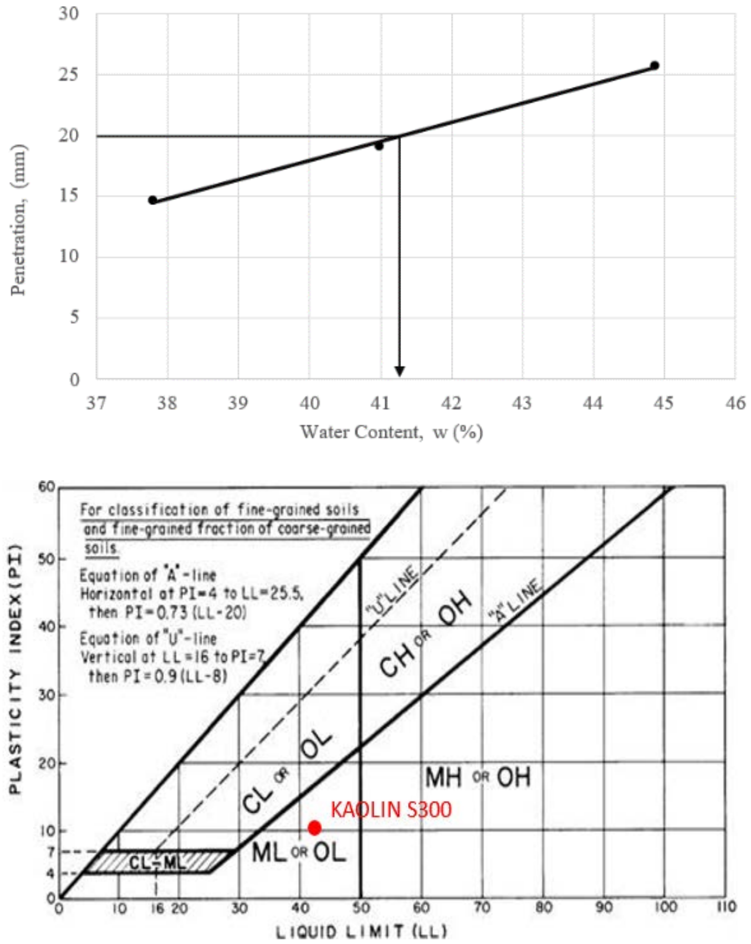
The specific gravity of kaolinitic clay and crushed tile was determined using a small pycnometer. The specific gravity of kaolin was found to be 2.62, falling within the particle density range of most soils, which typically have specific gravities between 2.60 and 2.80 [12, 14, 17]. This suggests that kaolinite, with a reported specific gravity of 2.60, is likely a constituent mineral of kaolin. The specific gravity of crushed tile was measured as 2.57, which differs from the findings reported by Parminder et al. [21] and Yiosese et al., [22] who reported values of 2.24. These findings indicate that crushed tile has a lower apparent specific gravity than sand. Zaini et al. [23] attributed the low specific gravity of crushed tile to its high carbon content, as opposed to high iron content which would produce a high specific gravity. The specific gravity of crushed tile is a crucial factor in determining its quality. Yue et al. [24] have shown in their studies that a specific gravity value below 1.6 indicates poor material quality, which could be due to the presence of a high percentage of pore texture. Table 3 highlights the specific gravity of kaolinitic clay and crushed tile waste in comparison with the other researchers.

Table 3. Specific gravity of kaolinitic clay and crushed tile waste.

Researcher	Specific Gravity	
	Kaolinitic Clay	Crushed Tile Wase
Hasan et al., [7]	2.64	–
Zaini et al., [12]	2.64	–
Zaini et al., [14]	2.62	–
Parminder et al. [21]	–	2.24
Yiosese et al. [22]	–	2.24

3.2. Atterberg Limits

To enhance the condition of clay soil, adjustments to its moisture content can be made. The Atterberg Limit test was performed on kaolin to quantify the water required to attain its liquid limit (wL) and plastic limit (wp). The liquid limit graph was used to obtain the water content corresponding to a cone penetration of 20 mm, which was found to be 41.3 % for kaolin. The graph depicting penetration versus water content is presented in Fig. 2(a). The plastic limit of kaolinitic clay was 31.25 %, which is higher than that of crushed tile at 25.64 %. The plasticity index was calculated as the difference between the plastic limit and liquid limit, and for kaolin, it was 10.05 %, while for crushed tile, it was only 4.09 %. Classification of the soil was often based on the plasticity chart, as shown in Fig. 2(b), where the liquid limit was plotted as an ordinate versus the plasticity index. Based on this chart, kaolin was found to exhibit low plasticity characteristics, and the medium plasticity of kaolin and crushed tile was demonstrated in the figure. Therefore, kaolin can be classified as having low plasticity and is designated as ML.

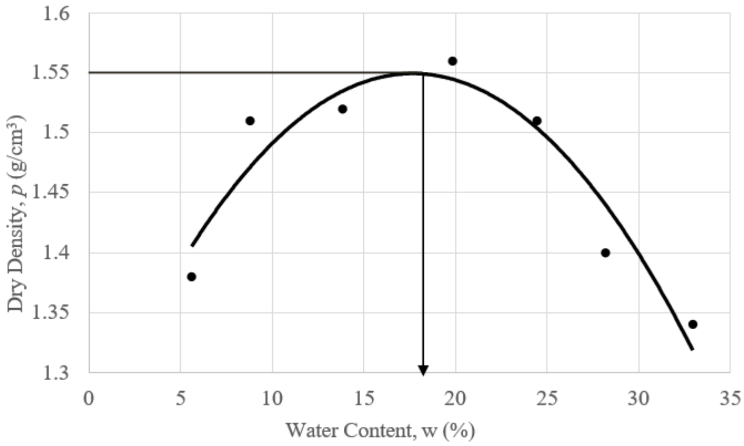


a) b)

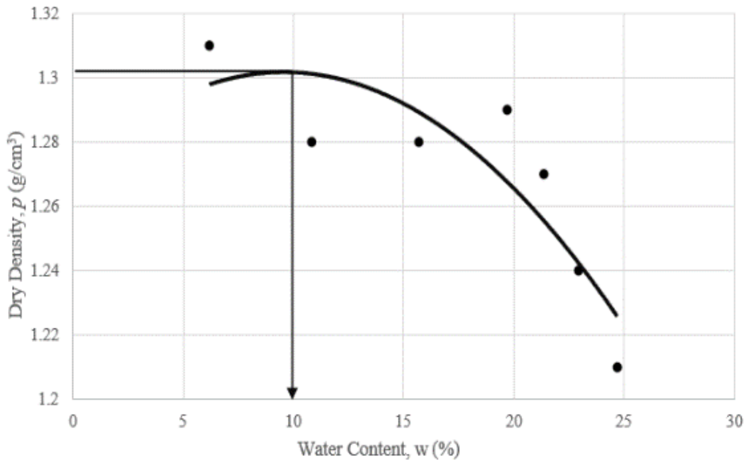
Figure 2. Atterberg limits of Kaolinitic specimen; a) liquid limit of kaolinitic clay and; b) classification of kaolinitic clay based on plasticity chart.

3.3. Standard Proctor Compaction

The relationships between the dry density and water content of kaolin and crushed tile were presented in Fig. 3(a) and Fig. 3(b), respectively. The MDD of kaolin and crushed tile was found to be 1.55 Mg/m^3 (15.20 kN/m^3) and 1.30 Mg/m^3 (12.75 kN/m^3), respectively, at an optimum moisture (w_{opt}) content of 18.0 % and 10.00 %. It is worth noting that kaolin exhibited a higher moisture content than crushed tile due to its high-water content and plasticity. Cabalar et al., [26] reported that when ceramic tile waste (crushed tile) was mixed with clay at a ratio of 30 %, the maximum dry density and optimum moisture content were found to be 1.88 Mg/m^3 (18.45 kN/m^3) and 12.73 %, respectively. This increase was attributed to the replacement of soil grains with higher specific gravity with waste ceramic tile grains having a relatively low specific gravity. Rezaei-Hosseinabadi et al., [27] and Rezaei-Hosseinabadi et al., [28] reported that low specific gravity and high air space content can significantly affect compaction characteristics. Furthermore, the low density of crushed tile makes it suitable for use in construction on low-bearing capacity foundations such as soft soils.



a)

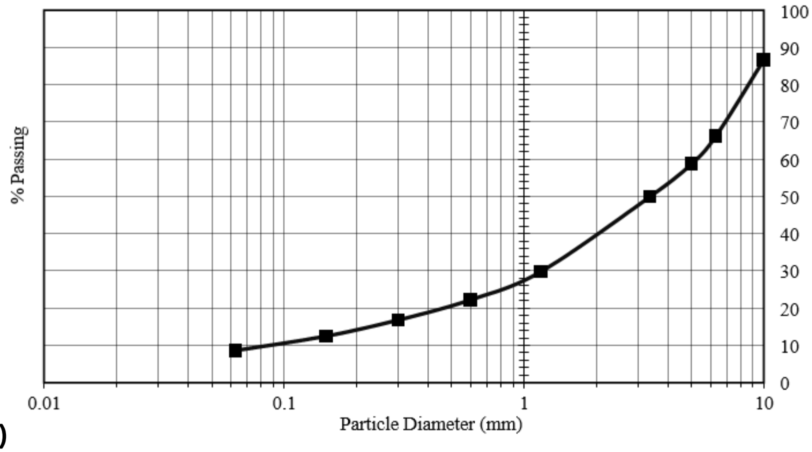


b)

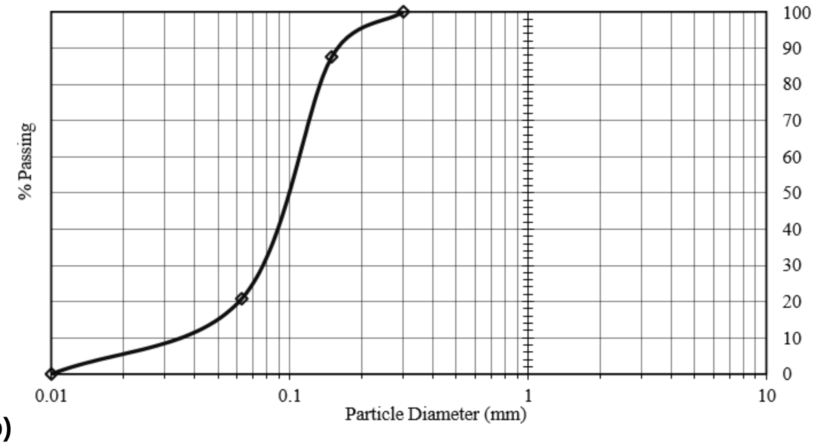
Figure 3. MDD and OMC of; a) Kaolinitic sample and; b) Crushed tile sample.

3.4. Morphology Analysis

A sieve was utilized to perform a sieve analysis of kaolin and crushed tile, and the resulting particle size distribution is presented in Fig. 4. The graph exhibits a well-graded distribution of kaolin particles, ranging from clay to fine silt. The kaolinitic clay particles were observed to have sizes ranging between 0.2 mm and 0.01 mm. Based on the American Association of State Highway and Transportation Officials (AASHTO) classification system, the kaolinitic clay sample was categorized as a clayey soil, belonging to Group A-7-6. Particle size analyses were conducted on crushed tile using the dry sieving method and sieve analysis. Majority of crushed tile particles were found to have sizes ranging between 10 mm and 0.063 mm, corresponding to fine gravel to fine sand sizes, and the size distribution was relatively well graded. The average coefficient of uniformity, Cu, for crushed tile was 60, and the average coefficient of curvature, Cc, was 2.67. Crushed tile with a Cu greater than 4 and Cc between 1 and 3 is classified as well-graded sand (SW) in accordance to the Unified Soil Classification System (USCS). In AASHTO, the soil classification of crushed tile falls under the A-1-A group, which corresponds to sand soil.



a)



b)

Figure 4. Particle size distribution of; a) Kaolinitic sample; b) Crushed tile sample.

3.5. Permeability

The coefficients of permeability for kaolinitic clay and crushed tile were determined using the constant head and falling head tests, and were found to be 2.61×10^{-8} m/s and 5.11×10^{-3} m/s, respectively. The obtained permeability coefficient for kaolin was considerably lower compared to that of crushed tile. The impermeable nature of fine-grained clay soil, including kaolin, is well documented in literature, which is often attributed to their insufficient drainage feature [14].

This study found that the coefficient values of permeability for crushed tile indicate a relatively high level of permeability, which is similar to soils that possess good drainage characteristics, such as clean sand. This high permeability is attributed to the higher maximum dry density obtained in this study. In comparison to Zaini and Hasan [12], the coefficient of permeability in this study is significantly higher, at 5.11×10^{-3} m/s at a dry density of 1.34 g/cm^3. The high fine particle content of crushed tile has a significant effect on permeability, causing the value to reduces as the smaller particle content increases.

3.6. Unconfined Compressive Strength

Table 4 provides a summary of the results of the Unconfined Compression Test (UCT) for the control sample and samples reinforced with 6 mm and 8 mm diameter single crushed tile columns at various column penetration ratios. The shear strengths were determined for area replacement ratios (CARR) of 15.79 % and 21.05 %, as well as height penetration ratios (CHPR) of 0, 0.33, 0.5, and 1.0. The shear strengths were 5.23 kPa, 6.79 kPa, 6.78 kPa, and 7.95 kPa for 6 mm and 8 mm diameter single crushed tile columns with 15.79 % of CARR and CHPR of 0, 0.33, 0.5, and 1.0. For the 21.05 % of CARR, the corresponding shear strengths were 5.23 kPa, 6.63 kPa, 6.75 kPa, and 7.18 kPa, respectively. In addition, the improvement in shear strength for 6 mm column diameter and a CARR of 21.05 % was 29.83 %, 29.64 %, and 52.00 %, while for 8 mm column diameter, the corresponding values were 26.76 %, 29.06 %, and 37.28 %.

The improvement in shear strength of specimens reinforced with crushed tile columns was analyzed and it was found that the improvement in shear strength was greater for 6 mm diameter specimens than for 8 mm diameter specimens. The reason for this is that the area replacement ratio of 8 mm diameter crushed tile columns is greater, which leads to vertical forces being applied to the columns and the columns bulging due to insufficient support from the remaining width of the specimen. This trend is consistent with the findings of previous researchers carried out by Zaini & Hasan [14] and Frikha et al., [29], who also reported that the decrease in shear strength improvement is due to the less confining stress in larger columns.

Table 4. Percentage of improvement shear strength of sample reinforced with crushed tile column.

Sample	Column Dia. (mm)	Column Height (mm)	CARR (%)	CHPR (%)	CVRR (%)	CHR-CDR (%)	UCS (kN/m^2)	AAS (%)	ASS (kN/m^2)	ISS (%)
K	–	–	–	–	–	–	10.46	6.88	5.23	0.00
K-CT6DH1	6	25.33	15.79	0.33	0.008	4.22	13.58	5.56	6.79	29.83
K-CT6DH2	6	38.00	15.79	0.5	0.012	6.33	13.56	5.58	6.78	29.64
K-CT6DH3	6	76.00	15.79	1.0	0.025	12.67	15.89	5.59	7.95	52.00
K-CT8DH1	8	25.33	21.05	0.33	0.015	3.17	13.25	5.57	6.63	26.76
K-CT8DH2	8	38.00	21.05	0.5	0.022	4.75	13.50	6.03	6.75	29.06
K-CT8DH3	8	76.00	21.05	1.0	0.044	9.50	14.36	6.67	7.18	37.28

Note: K, controlled sample; K-CT6D, single encapsulated with column diameter of 6mm and H1, H2, H3, Column Height of 25.33, 38.00 and 76.00, respectively, CARR, Column Area Replacement Ratio, CHPR, Column Height Penetration Ratio, CVRR, Column Volume Replacement Ratio, CHR-CDR, Column Height to Column Diameter Ratio, UCS, Unconfined Compressive Strength, AAS, Average Axial Strain, ASS, Average Shear Strength, ISS, Improvement of Shear Strength

3.7. Kaolinitic Clay Improvement due to the Column Area Replacement Ratio (CARR)

The research investigated the influence of CARR on the shear strength of kaolinitic clays. The study presented the interconnection between CARR and alterations in the strength of kaolinitic clay in Fig. 5. The results indicated a substantial improvement in shear strength when kaolinitic clay specimens were reinforced with enveloped crushed tile columns at various CARRR ranging from 15.79 % to 21.05 %. The shear strength increased from 10.46 kPa for the control sample to the maximum improvement of 15.89 kPa. Moreover, the ASS of a single enveloped crushed tile column with an CARR of 15.79 % applicable for K-CT6DH1, K-CT6DH2, and K-CT6DH3 was slightly greater than that of a single encapsulated crushed tile using 8 mm diameter column (CARR = 21.02 %) resulted in K-CT8DH1, K-CT8DH2, and K-CT8DH3.

Additionally, the use of single enveloped crushed tile columns with 6 mm column diameter resulted in higher ASS of kaolinitic clay compared to a single encapsulated crushed tile column with 8 mm column diameter. The study also found that the CARR substantially modify the strength improvement of kaolinitic clay, which is consistent with the findings of previous studies by Rezaei-Hosseinabadi et al. [27], and Rezaei-Hosseinabadi et al. [28]. The decline in the strength observed when the pillar was fully penetrated due to the significant portion of the soil was extracted from the specimen, disrupting the original condition of the soil.

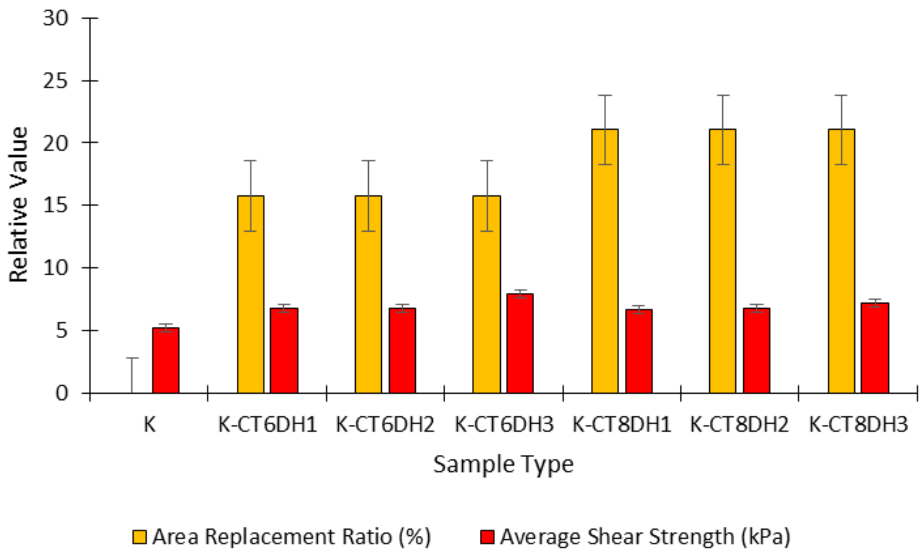
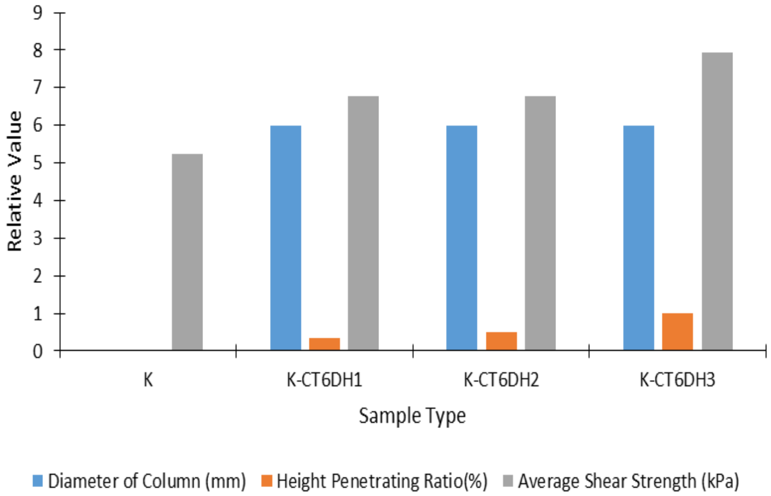


Figure 5. Relationship between the CARR with the ASS.

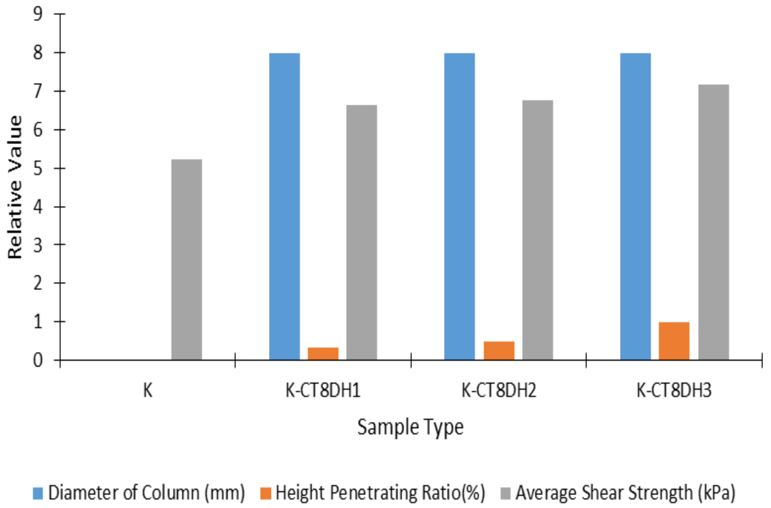
3.8. Kaolinitic Clay Improvement due to the Column Height Penetrating Ratio (CHPR)

This study investigated the effect of penetration height ratio (CHPR) on the average shear strength (ASS) of 6 mm and 8 mm diameter crushed tile columns, as depicted in Fig. 6. The results showed that increasing the CHPR led to a higher shear strength. However, the maximum shear strength values for a single column were determined to be 7.95 kPa for a 6 mm diameter and 7.18 kPa for an 8 mm diameter at a CHPR of 1.0. Furthermore, the study revealed that increasing the CHPR to 1.0 resulted in a 52.00 % increase in shear strength for a 6 mm diameter column, while the maximum increase in shear strength for an 8 mm diameter column occurred at a CHPR of 1.0 with a value of 37.28 %. Based on these findings, the critical CHPR was set to 1.0. Moreover, complete penetration occurs when the height penetration ratio of a crushed tile column is 1.0, meaning that the column will fully support the load when subjected to force. Conversely, height penetration ratios of 0.33 and 0.5 indicate partially penetrated columns. In such cases, the single crushed tile column supports the entire load, while the surrounding soil supports the remaining portion.

The increase in length of the crushed tile columns led to an increase in shear strength, as evidenced by the results. The highest increase in shear strength was observed when the CHPR was 1.0. Therefore, it can be inferred that the greater the CHPR compared to the column height, the greater the improvement in shear strength. Furthermore, the load-carrying capacity also increased when the CHPR was 1.0. However, it should be noted that the increment in shear strength was not solely attributable to the CHPR of single crushed tile columns. The percentage rise in shear strength was considered significant because the substitution of some of the soft clay with stiffer material, such as crushed tile, led to an increase in the CHPR of single crushed tile columns.



a)



b)

Figure 6. Relationship between the CHPR with ASS; a) 6mm diameter column; b) 8mm diameter column.

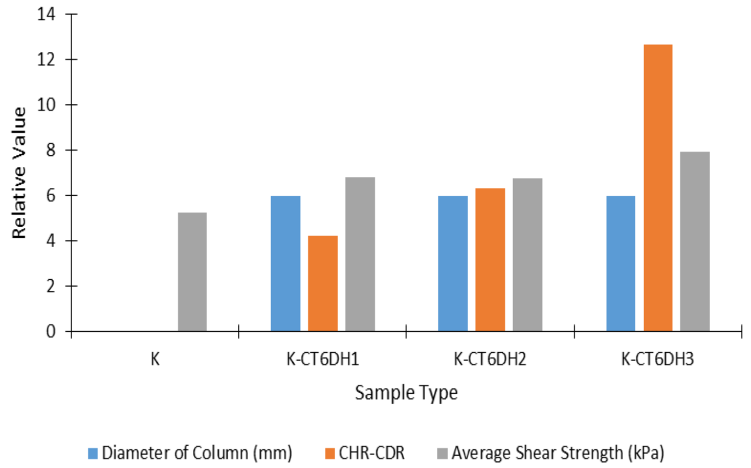
3.9. Kaolinitic Clay Improvement due to the Column Height to Column Diameter Ratio (CHR-CDR)

Fig. 7 depict the variation of average shear strength (ASS) with respect to the height to column diameter ratio (CHR-CDR) for 6 mm and 8 mm crushed tile columns. It was observed that the shear strength increased as the CHR-CDR increased for both column diameters. For a 6 mm diameter column, the maximum shear strength of 7.95 kPa was achieved at a CHR-CDR of 12.67, which was a 52.00 % improvement over the other ratios tested (0.33 and 0.5). Similarly, for an 8 mm diameter column, the highest shear strength of 7.18 kPa was obtained at a CHR-CDR of 9.50, resulting in a 37.28 % improvement over the other ratios tested.

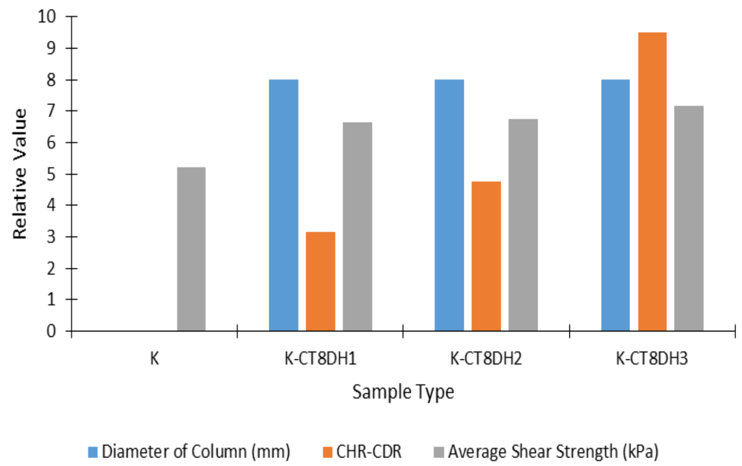
Changes in the column height and diameter resulted in variations of the CHR-CDR value, which was found to affect the shear strength of reinforced kaolinitic clay. Morever, the relationship between CHR-CDR and shear strength was not strictly linear due to the interconnections between CHR-CDR and various column dimensions. Fig. 7 illustrates that the maximum shear strength occurred at a CHR-CDR value of 1.0. Further increases in CHR-CDR value led to a reduction in the strength of the sample.

The findings of this study were consistent with previous research conducted by Zaini & Hasan [14], Rezaei-Hosseinabadi et al. [27], in demonstrating that the maximum improvement in shear strength occurred at the critical column length. According to Hasan et al. [7], the application of crushed tile columns for ground improvement had an influence on the level of strength enhancement in kaolinitic clay. The improvement in shear strength was attributed to the enhanced interlocking between the soil and the granules through the geotextile's surface adhesive, which improved the interface's shear properties.

While an increase in shear strength is observed, it is important to note that the improvement is not solely dependent on the CHR-CDR value of encapsulated crushed tile columns. Furthermore, the use of fully penetrating columns with a larger diameter was found to have a negative impact on the shear strength of the soil. This was attributed to a larger portions of soil being substitute by crushed tile particles, which disturbs the original state of the soil and weakens the structure and bonding between particles, resulting in a reduction in shear strength.



a)



b)

Figure 7. Relationship between the CHR-CDR with ASS; a) 6mm diameter column; b) 8mm diameter column.

3.10. Kaolinitic Clay Improvement due to the Column Volume Replacement Ratio (CVRR)

Fig. 8 presents the average shear strength (ASS) versus volume replacement ratio (CVRR), which illustrates a substantial increase in the undrained shear strength of a kaolinitic specimen owing to the installation of a crushed tile column. Furthermore, Fig. 8 depicts the improvement in shear strength as a function of CVRR for 6 mm and 8 mm crushed tile columns. The results indicate that the highest shear strength is obtained at a CVRR of 0.025, with a value of 7.95 kPa and an increase of up to 52.00 % over the control sample. Similarly, for a crushed tile column with a diameter of 8 mm, the greatest improvement in shear strength occurs at a CVRR of 0.044, with the improvement in 6 mm diameter samples was found to be more pronounced than that of 8 mm diameter samples due to the minimal disturbance caused by drilling and extraction of a small quantity of kaolin from the specimens, as well as the higher confining stresses mobilized by the column. On the other hand, a substantial portion of the soil was extracted during the installation of an 8 mm diameter crushed tile column, leading to a smaller increase in shear strength. Additionally, the absence of confining pressure during the test caused a greater tendency for soil collapse.

The current study aligns with the findings of Hui-Teng et al. [7] and Zaini and Hasan [12] regarding the maximum shear strength improvement investigated in the study. The improvement in strength was attributed to the low value of the CARR, which has an effect on the area around the column. The interlocking and bonding between particles in the area were stronger because the kaolinitic clay was underpinned by the enveloped crushed tile column.

The stiffness of a column with smaller width increases with larger confining stresses. When subjected to a vertical load, the width of the sample that is left between the columns becomes too narrow to support the columns, leading to deformation or bulging. The friction, particle interconnection, and contact linkage between particles affect the shear resistance of soil. Under bending pressures, the volume of soil particles may swell or shrink due to interlocking. If the soil swells, the particle density reduces, resulting in a decrease in resistance, which leads to a reduction in maximum resistance as the shear stress reduces.

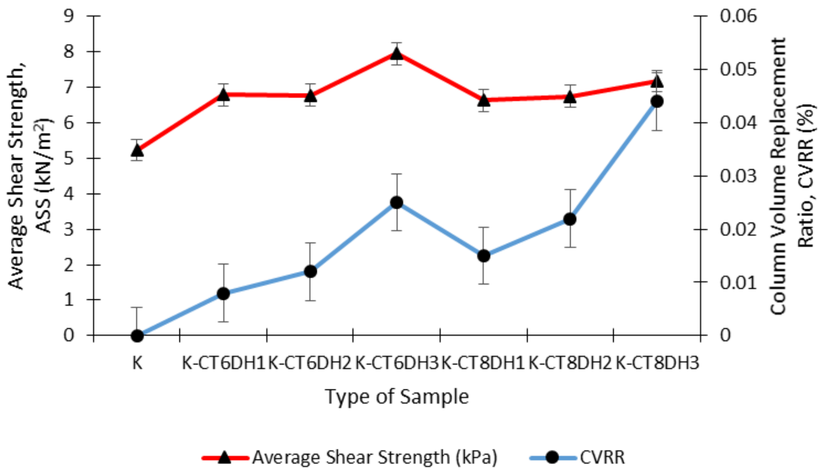


Figure 8. Relationship between the CVRR with ASS.

3.11. Shear Strength Parameters

The study involved conducting Unconsolidated Undrained (UU) tests to evaluate the shear strength of kaolinitic clay reinforced with single enveloped crushed tile columns. Samples of different penetration were examined, each subjected to varying confining pressures of 70 kPa, 140 kPa, and 280 kPa. The aim was to investigate the effective shear stress parameters for the kaolinitic column reinforced with various diameters of the crushed tile column at different values of CARR, CHPR, CHR-CDR, CVRR, cohesion, and friction angle, as presented in Table 3. The results revealed that the kaolinitic clay reinforced with enveloped crushed tile column exhibited a higher effective cohesion than the raw kaolinitic soil sample. In contrast, the effective friction angles showed minimal improvement since the difference from the raw kaolinitic clay was relatively similar. In general, the study demonstrated that reinforcing soft clay with encapsulated crushed tile column leads to noticeable improvements. The cohesion values for the kaolinitic clay and the altered samples with enveloped crushed tile columns were investigated. The cohesion for the kaolinitic clay was found to be 14.1 kPa. For the single column with a diameter of 6 mm and column heights of 25.33 mm, 38.00 mm, and 76.00 mm, the cohesion values were found to be 15.5 kPa, 25.3 kPa, and 14.7 kPa, respectively. Meanwhile, for the single column with a diameter of 8 mm, the cohesion values were 21.9 kPa, 26.3 kPa, and 22.4 kPa for the same column heights.

The highest cohesion value recorded in the study was 26.3 kPa for the K-CT8H2 sample, while the lowest value was 14.7 kPa for the K-CT6H3 sample. The ideal cohesion value for encapsulated crushed tile columns alone was discovered to be at a CHPR of 1.0. The data presented in Table 3 revealed that augmenting the confining pressure led to an enhancement in the cohesion value of the reinforced specimens in comparison to the control specimen. The research identified notable variations in the cohesion values of the reinforced specimens as opposed to the control specimen, signifying a rise in the cohesion value subsequent to the installation of the crushed tile column.

Cohesion is the internal molecular attraction that holds soil particles together and is a measure of the soil's resistance to deformation. A higher cohesion value indicates a stronger adhesive force between soil particles [29, 30]. According to Rezaie et al. [27, 28], the cohesion value significantly increases when the samples are reinforced with sand columns. According to the results obtained in this study, it is clear that the use of crushed tile columns with different diameters can enhance the cohesion value of the samples up to 26.3 kPa.

According to Table 5, the friction angle (φ) of the kaolinitic clay was 23.8°. For single encapsulated crushed tile columns with a 6 mm diameter and column heights of 25.33 mm, 36.00 mm, and 76.00 mm, the friction angles were recorded at 26.4°, 25.9°, 28.4°, respectively. With a column diameter of 8 mm with the same column heights as the 6 mm diameter column, the friction angles were recorded at 2°, 27.3°, 26.9° for the single encapsulated crushed tile columns. The K-CT6H3 sample exhibited the highest friction angle of 28.4°, whereas the K-CT6H2 sample had the lowest friction angle of 25.0°, according to the recorded data.

The study found that the ideal friction angle, which corresponds to the maximum strength improvement, was recorded at 27.3°. Although there was an increase in the friction angle with the installation of the crushed tile column, it was not significantly different from the friction angle of the control sample. The friction angle is a measure of the resistance of a soil to sliding and is defined as the angle between the Mohr-Coulomb failure envelope and the horizontal axis. Higher stresses lead to a higher friction angle. The granule size was reported to affect the behavior of the reinforced clayey soil, including its stiffness, friction angle, and shear strength characteristics, according to previous research [27]. In this investigation, the introduction of crushed tile columns with varying dimensions lead to an increase in both the shear stress and effective shear stress, thereby influencing the friction angle.

Table 5. Value of shear strength parameters.

Cell Pressure (kPa)	Column Dia. (mm)	Column Height (mm)	CARR	CHPR	CHR-CDR	CVRR	c (kPa)	Φ (°)
70 140 280	0	0	0	0	0	0	14.1	23.8
70 140 280	6	25.33	15.79	0.33	4.22	0.008	15.5	26.4
70 140 280	6	38.00	15.79	0.5	6.33	0.012	25.3	25.9
70 140 280	6	76.00	15.79	1.0	12.67	0.025	14.7	28.4
70 140 280	8	25.33	21.05	0.33	3.17	0.015	21.9	27.8
70 140 280	8	38.00	21.05	0.5	4.75	0.022	26.3	27.3
70 140 280	8	76.00	21.05	1.0	9.50	0.044	22.4	26.9

3.12. Linear Correlation Coefficient

In this study, correlations between engineering properties such as CARR, CHPR, CHR-CDR, and CVRR of delicate kaolin and varying diameter and height of column were established. These equations are essential in predicting the optimal model for granular column design. The statistical equation that correlate the parameters for the four studied parameters are presented in Table 6.

Based on the correlation equations presented in Table 6, it can be inferred that higher values of coefficient of determination (R^2 value) indicate that the level of variation in the four parameters studied can be predicted by considering the crushed tile as ground improvement granular column. The regression analysis conducted in this study revealed half of the variation in the parameters can be explained by the utilization of crushed tile column. Hence, the established relationship is the ideal model to forecast the optimal dimensions of granular column. The statistical analysis carried out in this study does not match a previous study due to the use of other alternative to obtain the R^2 value. However, both studies come to the same conclusion that the best design can be achieved by comparing a set of targeted models.

Table 6. Correlation coefficient of parameters studied.

Parameter	Correlation	Column Dia. (mm)	Linear Equation	R^2 Value
CARR	Shear Strength, S_u (kN/m^2)	6	S_u = 0.1231 CARR + 5.23	0.7579
		8	S_u = 0.0771 CARR + 5.23	0.9220
CHPR		6	S_u = 2.5736 CHPR + 5.5101	0.9245
		8	S_u = 1.8095 CHPR + 5.6197	0.7968
CHR-CDR		6	S_u = 0.2035 CHR-CDR + 5.5063	0.9264
		8	S_u = 0.1910 CHR-CDR + 5.6159	0.7994
CVRR		6	S_u = 102.5 CVRR + 5.5344	0.9186
		8	S_u = 41.426 CVRR + 5.6086	0.8043

4. Conclusions

This study examined the effects of crushed tile waste on the lateral load capacity of kaolinitic clay. Based on the outcome of the investigation, the following summary can be drawn:

1. According to the USCS, kaolinitic clay can be categorized as ML which is clayey silts with slight plastic. Kaolin was a clay with a low plasticity index, with a liquid limit of 41.30 % and a plasticity index of 10.05 %. Based on AASHTO, kaolinitic clay is classified as clay soil type A-7-6. Furthermore, the crushed tile is classified as SW, which means that it was well graded with a liquid limit of 29.73 % and a plasticity index of 4.09 %, indicating low plasticity. According to the AASTHO classification system, crushed tile is classified as A-1-a, which includes stone fragments, gravel, and sand.

2. Furthermore, the specific gravity of kaolinitic clay was found to be 2.62 and the specific gravity of the crushed tile waste was determined to be 2.57.

3. In addition, kaolinitic clay has a maximum dry density of 1.55 kg/m^3 and an optimal moisture content of 18.00 %. The crushed tile had a maximum dry density of 1.30 kg/m^3 and a moisture content of 10 %.

4. The shear strength of a column depends on the CHPR. A maximum increase in shear strength was observed when the CHPR was at 1.0, and a decrease in shear strength was observed when the column height decreased. When the CHPR was less than 1.0, the load-carrying capacity decreased. The increase in shear strength investigated in the study was not solely owing to the CHPR but also because of the substitution of stiffer material, such as crushed tile, for some of the soft clay. The maximum shear strength was achieved at a CHR-CDR of 12.67 for a column diameter of 6 mm and CHR-CDR of 9.5 for a column diameter of 8 mm.

5. Apart from the influence of crushed tile columns on the strength parameters of clay reinforcement, the confining pressure is also an important factor in determining the strength and compressibility of kaolinitic clay. Insufficient dispersion of excess pore water from the clay specimens was observed due to clogging phenomena between the clay and the crushed tile columns. The results of the experiments conducted in this study have provided evidence that the introduction of enveloped crushed tile columns can cause a change in the cohesion (c) and friction angle (ϕ) of kaolin clay samples from their original values of 14.1 kPa and 23.8°, respectively. The highest improvement was observed in the single enveloped crushed tile

column with 8 mm column diameter, where the cohesion increased up to 26.3 kPa and the friction angle increased up to 27.3°.

The study, therefore, concludes that the used of crushed tile waste firmly influenced the lateral load capacity of kaolinitic clay as an ideal ground improvement. In this study, it was found that the utilization of crushed tile as granular column was effective in improving the strength of kaolinitic clay soils. The strength improvement was up to 52.00 %, and the optimum enhancement was achieved with a utilization of crushed tile with a column diameter of 6 mm and column height of 76 mm. The correlation analysis showed that the level of variation in the four parameters studied (CARR, CHPR, CHR-CDR and CVRR) could be predicted by considering the crushed tile as granular material for ground improvement technique, with a higher coefficient of determination (R^2 value) indicating better predictability. This approach can lead to cost savings and promote the use of eco-friendly materials in soil improvement. Therefore, this particular study showed that the 6 mm column diameter and 76 mm column height of the crushed tile should be recommended as the most ideal column dimensions that can be used by practitioners to enhance the strength of kaolinitic clay for construction application. The technique of ground improvement by crushed tile waste is vital to improve the strength of weak soils especially clay during construction such as deep and shallow foundations. Ground improvement with crushed tile waste is now a very economical way of transforming weak soil into a suitable soil for construction purposes. Using this method, it is possible to construct infrastructure and buildings on soil with low specific gravity and high air void content, which would typically require expensive soil stabilization techniques. The use of granular columns reduces the need for excavation and replacement of weak soil, allowing significant cost savings and faster construction times.

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