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Effect of the waste bottom ash strengthened the problematic clay soil: The use of by-product material

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Abstract

The extraction of industrial by-products such as bottom ash from power plants to the research areas can be lucrative for the economy and environment. In the civil engineering field, the soil condition which is filled with abundant soft clay soil has always been a problematic issue. Previous studies examined the available techniques of ground improvement for instance the installation of a granular pile is an efficient method to treat the soft clay soil, resolving the detrimental issues of lower value of soil's bearing capacity, soil settlement occurrence, greater compressibility, and erodibility. Coherent to that, this research deployed the Vibro-replacement technique in fabricating the single bottom ash column beneath the clay soil to rectify the weak engineering properties of clay soil. The raw kaolin clay and bottom ash were examined through the geotechnical approaches, the distribution of particle size (PSD), Atterberg limit, relative density, pycnometer, hydrometer, falling head, constant head, and standard proctor. Via the Unconfined Compression Test (UCT), 20 specimens from unreinforced and reinforced categories were investigated. The average shear strength value from 5 identical specimens was utilized, considering the Column Penetrating Ratio (CPR), Column Height to Column Diameter Ratio (HDR), and Column Volume Replacement Ratio (CVR). The maximum shear strength improvement occurred in the S1680 sample, recorded at 58.66% at the CPR (0.8), HDR (5.00), and CVR (8.19%). Hence, the research findings verified that bottom ash as a sustainable material can raise the clay's strength effectively.

Keywords: Clay soil, Kaolin, Bottom ash, Ground improvement, Shear strength

1. Introduction

Kaolin classically has a weak geotechnical property, known as problematic soil which causes issues in the construction project [1]. Mohammed et al. [2] stated kaolinite is the most abundant clay material discovered worldwide, which is typically available in a white-grey color powder with the general formula of $Al_2Si_2O_5(OH)_4$. Due to the complexity of its structure, the structure of kaolinite has always been analyzed to modify its engineering properties for industrial, commercial, and construction purposes [3]. Recently, several studies have been conducted to prove that the placing of huge construction projects on soft clay soil such as high-rise buildings by Bolouri et al. [4] and Galliková & Rehman [5] discovered the approach of finite element modeling can be projected successfully with the minimum value of soil settlement. Phan et al. [6] discovered the microbial treatment in soil improvement, plant root reinforcement in enhancing the shear strength of clay soil including the cohesion and friction angle. In addition, Arpajirakul et al. [7] reported the application of microbially-induced calcite precipitation improved the soil's bearing capacity of clay. In addition, Leknoi and Likitlersuang [8] Made use of vetiver grass in stabilizing the unstable slope and controlling the soil erosion as a sustainable model. The above practice restrains the soil particles from dispersing lavishly through the root gripping. In contrast, utilizing the biological method rectifies the natural properties of soil, cutting down the adoption of chemical solutions and proposing the introduction of sustainable tactics. Both authors summarized the deployment of the vegetative approach which is a non-conventional soil improvement technique that presents a significant modification of weak soil properties. Referring to the existing and modified soil treatment approaches, the alteration of weak soil properties, particularly the area consisting of abundant clayey soil to cater for the construction of immense buildings has been realized. Most Southeast Asia countries like Malaysia, has been diligently transforming from developing countries to developed countries by proposing a national plan such as the latest plan of the New Industrial Master Plan (NIMP) 2030. The Ministry of Investment, Trade, and Industry (MITI) Malaysia [9] emphasizes the plan focuses on bolstering the nation's manufacturing sectors which then translates into the surge of land demand for the development of high-end industrial products. Phanikumar and Ramanjaneya Raju [10] provided data regarding the collapse of the structure, structural instability, structure settlement, and other structural issues caused by the problematic clay soil due to inadequate treatment works that have incurred millions of dollars lost in the USA. Unstable soil is always treated thoroughly before a construction project begins with the investigation of site condition, which will focus on the soil investigation report prepared by a group of professionals that generally emphasizes the soil bearing capacity, compressibility, stiffness of soil, and erodibility.

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From the existing knowledge of civil engineering in the geotechnical field, the deployment of soil stabilization and ground improvement techniques can promote the soil-bearing capacity of soil by mixing with foreign materials such as lime and silica fume in stabilizing the soil [11, 12]. At the same time, the Vibro-replacement approach is commonly executed either in on-site construction or even in small-scale laboratory work [13, 14]. The above technique has been extensively practiced to construct a reinforced foundation and ground as well as the monitoring of the movement and displacement of the structure. Furthermore, this improvement technique has also broadened its boundary to utilizing biological methods, which has resulted in the improvement of soil's strength properties. Coherently, the authors proposed that the potential of the combination of classical and biological ground improvement techniques can promote environment conservation, and facilitate the sustainability concept in the construction industry. Similarly, the existing myriad of data regarding sustainable construction in ground improvement techniques has been widely researched in the technique of granular column installation [15-17]. The deployment of granular columns using recycled materials or industrial by-products has numerous advantages such as acceleration of the pore water dissipation, reduction of the risk of soil settlements, avoiding the water accumulation issue due to poor water drainage, enhancement of axial loading withstand ability, and Li et al. [18] reported the promotion of sustainability as a response to the rigorous growing development matter. Nonetheless, the arrangement of granular columns beneath the soils may not be particularly effective as they are influenced by the significant elements that have been affecting the performance in raising the soil's strength, encompassing the column width, column intervals, size of the granular materials used, axial direction of during compression and the horizontal restrain provided by the underlying soils after placement and construction. Consequently, for a better improvement and approach, it plays a significant role in establishing a scientific recuperate development with robust granular column insertion.

In the latter civilization, research has been carried out to resolve the issue of disposal and the generation of industrial waste through utilization and re-application in different fields which include civil engineering projects [19-21].From the perspective of the environment, sustainability, and the budget, a proper design of granular column is vital to resolve the above-mentioned concerns, where the bottom ash, fly ash, plastic aggregate, palm fiber and steel slag can be assigned for the replacement of traditional materials, for instance, gravel and sand [22-24]. Coherently, the application of the above materials in the respective study has been verified to behave like the coarse aggregates via the physical and mechanical properties determination, in which the research results demonstrated a positive outcome in stabilizing the problematic soil. As reported by Chompoorat et al. [25], the authors discovered the mixture of disposal waste like fly ashes with concrete material improved the strength of dredged sediments drastically. The application of the waste can be regarded as its engineering properties, primarily its particle size to substitute the coarse-aggregate, where bottom ash possesses this characteristic before analyzing the shear strength parameters [26]. Bottom ash is a waste material generated from coal-fired power plants, it is produced from the unburned coal which has entrained in the flue gas which is captured and recovered to a certain portion of fly ash and bottom ash. According to previous data, these two by-products, fly ash, and bottom ash represent a percentage of 70-85 and 15-30 wt% of the entire ash generation [26]. In 2019, the coal-fueled power plants in the USA produced approximately 30 million tons of coal fly ash and 9 million tons of bottom ash [27], which has turned into an environmental concern. In Malaysia, a study has reported the existing power plants such as Tanjung Bin in Johor Darul Takzim and Jimah power plant in Negeri Sembilan Darul Khusus have yielded about 9 – 250 tons/day of bottom ash [28]. Due to the tremendous quantity production of the bottom ash generated as a waste, the materials were assessed and led to the proposal of the utilization of the material as a sustainable material in the research areas such as road base construction [25], fly ash mortar [29], ground improvement [30] for the enhancement of the soft clay soil geotechnical properties. The authors deduced the application of bottom ash in playing the role of reinforcement is attributed to the presence of silica, alumina, and iron oxide which expedite the pozzolanic reaction, which subsequently provides additional strength and durability to the mixture compound. The reuse and inclusion of waste materials like bottom ash realize the Agenda of the United Nations, which is the Sustainable Development Goals (SDGs). The incorporation of SDGs in the research by Leknoi et al. [31] and Hong-in et al. [32] has emphasized the importance of land security, responsible production, consumption, and restoration of degraded land and soil (in the 12^{th} and 15^{th} SDGs), and Leknoi et al. [33] stated a low-carbon city should be encouraged coherent with the city development, which public confidence and participation are the most important factors in making the 13^{th} SDGs successful. The above reveals that it suits the current study objectives in promoting sustainable construction.

Bottom ash is physically dark grey in color, granular, porous, and predominantly sand-sized material that is collected from the water-filler hoppers at the bottom part of the furnace. Even though it is a by-product material that can be pounded and ground into the desired size as a cementitious material in the advancement of concrete [34], it can also substitute conventional aggregate like sand which acts as a pragmatic aggregate for the material of granular column [1]. According to the authors, another factor that has made this material available for substitution is the pozzolanic characteristic, which accelerates the chemical reaction to yield compounds that possess cementitious properties. In addition, Shen et al. [30] reported the bottom ash possesses good drainage characteristics, with the permeability coefficient of 5.02×10^{-3} m/s reported from the constant head approach, easing the severe water accumulation issue faced by the clay soil. Chompoorat et al. [35] utilized the deep-soil mixing technique from fly ash to strengthen the mechanical properties and shrinkage cracking characteristics of clay. The inclusion of ashes materials curb the depletion of natural resources, for instance, sand and gravel at the same time increase the clayey soil stabilization period because of the early occurrence of hydration and pozzolanic reactions in the soil samples [36]. The research works by Kampai et al. [37] proved the substitution of ashes materials subside the magnitude of the permeability coefficient and promotes a higher degree of pozzolanic reaction. Coherent to that, the addition of ashes materials, particularly the bottom ash in the ground improvement techniques can incur additional beneficial values to the economy and environment.

Consequently, the environmental advantages of the bottom ash when applied in the civil engineering field reduce the usage of non-renewable aggregates, and it can be linked to the elimination of unnecessary work for the management of the bottom ash and fly ash disposal. Therefore, the association of bottom ash in the treatment of soft clay soil in the ground improvement technique is a green approach to promote sustainable construction with a detailed comprehension of the bottom ash characteristic regarding the characteristic influence afterward. For the current research, this study provided a thorough understanding in regards to the geotechnical properties of kaolin clay S300, bottom ash, and the deployment of single bottom ash-fabricated columns with several designs in enhancing the shear strength parameters of soil. The objectives were established to (1) determine the physical and mechanical properties of the kaolin clay and bottom ash and (2) assess the shear strength parameters after being reinforced with the single 16 mm encapsulated bottom ash column.

2. Methodology

2.1 Materials

Kaolinite is a clay mineral that consists of aluminum, silicon, oxygen, and hydroxide elements based on its general formula. Due to its natural behavior, it is a hydrophilic material and able to produce slurry products when mixed with the ideal amount of water, which provides consistency to the preparation of homogeneous bottom ash reinforced specimens. The use of kaolinite type material, kaolin clay S300 was bought from Kaolin (M) sdn bhd, located in Selangor, Malaysia as depicted in Figure 1(a). This material is available in white-grey powder form as shown in Figure 1(b), and the properties of kaolin clay are tabulated in Table 1.

The current study used the bottom ash as the replaced material for the coarse aggregate in the reinforcement part, due to its availability, cost effective, and effectiveness practically. Figure 2(a) shows the location of the material obtained in this study. This material was purchased from Tanjung Bin Energy (TBE) Power Plant, Johor, Malaysia in Figure 2(b), and the properties of bottom ash are displayed in Table 2. TBE is famously known as the T4 or one of the four (4) coal power plants in Malaysia. TBE is a supercritical coal-fired power plant, and it is the largest within the Southeast Asia region. TBE is owned by the Bursa listed company, Malakoff Corporation Berhad with the majority of shares. The utilization of bottom ash was concealed within the soft clay soil by employing the raining method. The current study applied the Polyester Non-woven Geotextile needle-punched Fabric (MTS 130) to encase the kaolin that was reinforced with the bottom ash column, offering additional reinforcements in terms of drainage, filtration, and separation purposes.

Table 1 The properties of kaolin clay S300

No.	Physical parameter	Value
1	Color	White
2	Natural water content (%)	1.59
3	Specific gravity	2.62
4	Atterberg limit	
	▪ Liquid limit (%)	36
	▪ Plastic limit (%)	26
	▪ Plasticity index (%)	10
5	Sieve analysis	
	▪ Silt (%)	46
	▪ Clay (%)	54

Table 2 The properties of bottom ash

No.	Physical parameter	Value
1	Color	Gray-black
2	Soil classification	
	▪ AASTHO	A-1-a
3	Maximum size (mm)	5
4	Specific gravity	2.33
5	Maximum dry density (Mg/m^3)	0.671
	Minimum dry density (Mg/m^3)	0.549
	In-situ density (Mg/m^3)	0.668
	Relative density (%)	98

(a) (b)

Figure 1 Details of the kaolin clay S300 (a) Kaolin (M) sdn bhd (b) Kaolin clay S300

(a) (b)

Figure 2 Details of the bottom ash (a) Tanjung Bin energy power plant (b) Bottom ash

2.2 Experimental program

The physical and mechanical engineering properties of both involved materials, bottom ash, and kaolin clay S300 were analyzed before accessing the shear strength parameters of the reinforced bottom ash column as demonstrated in Figure 3. The incorporated physical tests under the study were the distribution of particle size (DPS), Atterberg limit test, relative density, and the pycnometer test. For the mechanical section, the properties were explored by the means of standard proctor test as well as the permeability test. After gathering all the relevant data from the physical and mechanical tests, the fundamental geotechnical details of both materials were determined and the subsequent analysis proceeded to the examination of the soil's properties, which was linked to the shear strength parameters and the Unconfined Compression Test (UCT) was the incorporated test under this study. Table 3 presented the incorporated tests under the study with the respective standards based on the American Society for Testing and Materials (ASTM) and British Standards (BS).

Table 3 Laboratory investigation for bottom ash, kaolin clay S300, and reinforced kaolin

Material	Test name	Standard
Kaolin clay S300	Hydrometer	BS 1377: Part 2: 1990:9.6
	Atterberg limit	
	Liquid limit (LL)	BS 1377: Part 2: 1990:4.3
	Plastic limit (PL)	BS 1377: Part 2: 1990:5.2
	Standard compaction	BS 1377: Part 2: 1990:3.3
	Falling head	BS 1377: Part 2: 1990
	Small pycnometer	BS 1377: Part 2: 1990:8
Bottom ash	Sieve analysis	BS 1377: Part 2: 1990:9
	Relative density	BS 1377: Part 2: 1990:4
	Constant head	BS 1377: Part 2: 1990
	Small pycnometer	BS 1377: Part 2: 1990:8
Reinforced kaolin with bottom ash column	Unconfined compression test (UCT)	ASTM D 2166

The sieve analysis test as shown in Figure 3(a) was executed mechanically for 10 minutes after stacking up the sieves used in the experiment where they 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 respectively based on the standard as stated in Table 3. The percentage passing and retained were used to compute the necessary and translated into the plotted semi-logarithmic graph. The graph was used to interpret the similarity of bottom ash under the soil classification standard. For fine-grained analysis, a hydrometer apparatus (see Figure 3b) was utilized to determine the majority size of kaolin clay S300 which passed through the 0.0063 mm or 63 μm of sieve size by the standard stated in Table 3. The result was obtained by soaking the bulb in the water bath with a difference of 5°C of temperature difference, ranging between 25°C of 30°C. The change of state of fine-grained soil of kaolin clay S300 was measured through the execution of the Atterberg limit by the respective standard. For this test, the kaolin used was those passed through the 63 μm of sieve size. With the analysis from the cone penetration test or the liquid limit test in Figure 3(c), the liquid limit value was obtained and the behavior indicator of kaolin clay was retrieved from the plastic index, which was the numeric difference between the liquid and plastic limit value. The relative density test was implemented to analyze the maximum and minimum dry density of bottom ash, and with the values obtained from the test, it was able to generate the result of in-situ density. Thus, the relative density was obtained by using Eq. (1).

$$Dr = \gamma\text{max}(\gamma - \gamma\text{ min})/\gamma(\gamma\text{max} - \gamma\text{min}) \text{ x } 100\% \quad (1)$$

Where Dr is the relative density (expressed in percentage), γ is the unit weight of the material, γmax is the maximum unit weight of the material and γmin is the minimum unit weight of the material.

The hydraulic conductivity or the permeability coefficient was measured by utilizing the existing permeability test, constant head, and falling head test for bottom ash and kaolin clay, based on the ASTM D 2434 and ASTM D 4234 respectively. The tests apply the concept of the difference in terms of the water gathered at different times, and the unit was expressed in terms of m/s in this study.

The following incorporated test under the mechanical section was a standard proctor test, carried out based on the BS 1377-Part 4:1990: 3.3. The possible outcome from this test is the Maximum Dry Density (DD) and the Optimum Moisture Content (MC) value. The 3kg oven-dried kaolin clay that passed through the 4.75 mm sieve was selected to undergo compaction. The procedure was begun with the pre-determined moisture content of 5%, then applied 25 free fall blows of compaction by 2.5kg of the hammer from approximately 15 cm measured from the soil mold. The test was terminated when the value from the compaction curve was not altered more than 0.03 Mg/m^3.

The core experiment during the study was the implementation of UCT, and the test was strictly conducted to ensure the highest value of accuracy of data following the ASTM D 2166. The study tested the prepared homogeneous 300g of unreinforced sample as the control sample (with no bottom ash reinforcement) and the reinforced sample (with bottom ash reinforcement). The sample was placed in the middle of the shearing machine and the deformation indicator and the providing ring dial gauge were set to zero before the shearing process began. The test was halted when the column failure was observed, and the indicators started to drop from the maximum point, or the 15% of strain had been achieved.

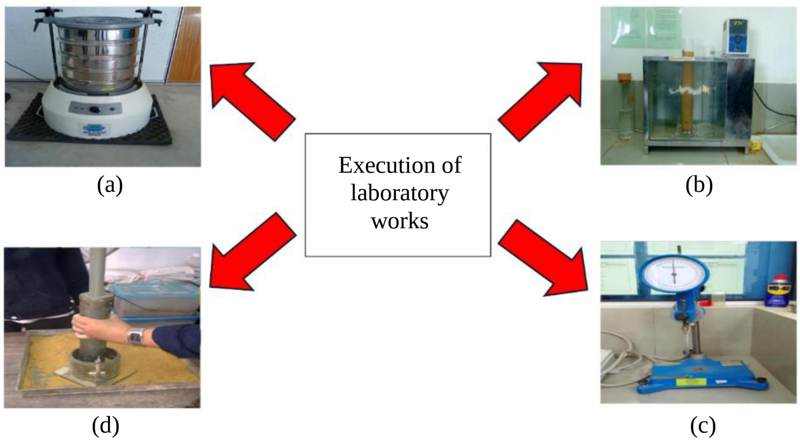

Figure 3 Execution of laboratory works (a) Mechanical sieve analysis (b) Hydrometer apparatus (c) Cone penetration equipment (d) Standard proctor test

2.3 Design of the encapsulated bottom ash column

The design of bottom ash reinforced samples in this study was referred to the technique of stone column from ground improvement and soil stabilization, which the stone column technique involves the fabrication of granular-material column and stabilizing soil approach deals with the mixing of soil with respective foreign material. The conduct of UCT was associated with the design of the bottom ash column, where several elements had been considered. The first consideration was about the D/d ratio, where D is the width or column diameter and d is the size of the bottom ash used. In this study, the design of the D element was set at 16 mm due to the limitation of specimen diameter, and the reference of previous related studies by Shen et al. [30] and Shen et al. [3]. Referring to the result of the sieve analysis, the d value was set at 1.18 mm based on the range of sand particle size and the largest amount of bottom ash retained on the sieve. Besides, the other reason for the selection of a 1.18 mm size of bottom ash was to reserve sufficient area for the insertion of geotextile for the encapsulation function during the granular column construction process. A previous study proposed that the D/d ratio is recommendable to correspond to the prototype structure [38], and a similar study reported the ratio between 4 to 17 substantiated better results of treatment towards the soft clay soil [12]. However, the current study obtained the value of 13.55 which lay within the stated range of ratio. Furthermore, a similar study also confirmed the small-scale laboratory test for the analysis of encapsulated granular columns using foreign materials for instance PP plastic which had a D/d ratio of 8.47 and 13.55 produced the supreme results [1]. Besides, the in-situ density was obtained based on the result from the relative density test and thus, the mass of bottom ash required was computed accordingly as stated in Table 4.

Table 4 Design of bottom ash column in accordance to its density

Column diameter (mm)	Column height (mm)	Column volume (mm^3)	Density of bottom ash (Mg/m^3)	Mass of bottom ash required (g)
16	60	12063.72	0.668	8.06
	80	16084.95		10.74
	100	20106.19		13.43

After the pre-set value of the D/d ratio, the configuration of the bottom ash column installation was designed following Figure 4. Since the study focused on only single-column installation, it was constructed in the center of the prepared specimen to ensure the level of soil disturbance in the surroundings was minimum and equivalent. Apart from that, the design of the column ratios were also analyzed where it had included the Column Penetrating Ratio (CPR), Column Height to Column Diameter Ratio (HDR), and Column Volume Replacement Ratio (CVR). Table 5 summarized the column design which consisted of four (4) categories which included the control group, the S1660 group, the S1680 group, and the S16100 group. For instance, in the S1660 group, S was the single column built, 16 was the column width or column diameter (expressed in mm), and 60 is the column height (expressed in mm). Among the groups, the classification of columns was made based on the column height, where 60 mm and 80 mm were categorized as partially penetrated columns and 100 mm fell under the fully penetrated column.

Table 5 Design of bottom ash column based on the column ratios

Column design	No. of column	CPR	HDR	CVR (%)
Control	-	-	-	-
S1660	1	0.6	3.75	6.14
S1680	1	0.8	5.00	8.19
S16100	1	1.0	6.25	10.24

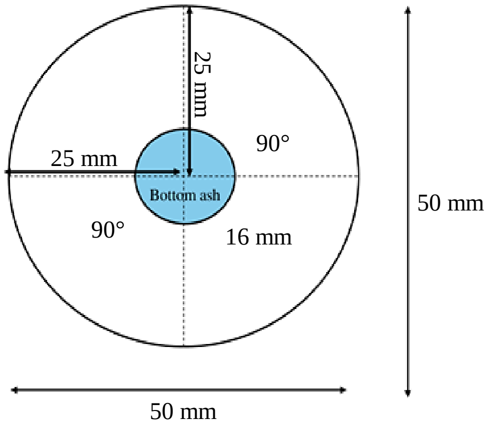

Figure 4 The detail of bottom ash column arrangement beneath the kaolin clay

2.4 Preparation of encapsulated bottom ash column

After gathering all the necessary information, the construction of the bottom ash column began with the preparation of air-dried 300g kaolin clay, then mixed with 19.4% of moisture content which was generated from the compaction curve. The procedure was followed by the pouring of slurry kaolin into three (3) layers into a mold with dimensions of 50 mm width and 100 mm height respectively, and it was compacted for each layer to reduce the air trapped inside the specimen. A drilling bit with a 16 mm diameter (see Figure 5a) created a hole in the prepared specimen, by drilling it into the desired height before extruding out from the mold as stated in Table 4 and Table 5.

After completing the above steps, the mold was moved to the extruder to extrude out the prepared specimen and stored inside a special case (see Figure 5b). The encapsulation process was done by cutting the geotextile into the appropriate length, then it was placed into the specimen. Afterwards, a filter funnel was placed on top of the prepared specimen and the exact amount of bottom ash was transferred into the pre-drilled hole by the raining method. The backside of the drilling bit was then applied to compact the poured bottom ash, ensuring the air voids between the bottom ash were minimized.

(a)

(b)

Figure 5 Bottom ash column preparation process (a) Hole drilling on a prepared specimen (b) Prepared specimen was stored in the special container

3. Results and discussion

This chapter focused on the results obtained through the execution of the geotechnical tests. It was categorized into 3 sub-topics, where 3.1 and 3.2 reviewed the physical and mechanical properties of kaolin clay S300 and bottom ash, 3.3 discussed the influence of the encapsulated bottom ash column towards the kaolin clay, and the last section, 3.4 discussed the influence of the column parameters towards the kaolin shear strength.

3.1 Evaluation of the physical properties of kaolin clay and bottom ash

Figure 6 displayed the PSD of kaolin clay S300 and bottom ash respectively. Figure 6(a), it was demonstrated that kaolin clay is a well-graded soil, that behaves from clay to fine silt soil. This graph was generated by plotting the graph percentage finer against the particle diameter of the kaolin clay and the majority of the particle size detected was between 0.0011 – 0.06 mm. By referring to the soil classification standard of AASTHO and USCS chart as depicted in Figures 7a and b, the kaolin clay fell under the category of A-7-6b, and the symbol of ML denoted the low plasticity silt clay. The result was deduced from the values of Liquid Limit and Plastic Limit, obtained at 36.00% and 26.00% respectively, while the plasticity index was the numerical difference between these two values. From the previous data, the current study obtained the same result in the soil classification [30].

For the reinforcement material, the DPS of bottom ash was analyzed through mechanical sieve analysis, and it is dry by nature thus, this method can meet the specifications of bottom ash. From Figure 6(b), the DPS was well graded, and the significant amount of bottom ash size ranged between 0.3 – 5 mm, however, the largest retained amount was at 1.18mm sieve size. According to the available soil classification method, the bottom ash was categorized as A-1-a or stone fragments, which behaved like gravel and sand aggregate. This research finding result was identical to the data provided by the previous researchers mentioned the bottom ash produced from the TBE power plant has the characteristic of sand in terms of its physical size [3, 39].

From the relative density test, the values of the maximum and minimum dry density of bottom ash obtained were 0.671 Mg/m^3 and 0.549 Mg/m^3 respectively. During the bottom ash column preparation process, the in-situ density was accessed through the raining method and therefore, it obtained 0.668 Mg/m^3. From these values, the relative density of the bottom ash was 98%. Nonetheless, the value of relative density can ensure that the accuracy of the shear strength parameters during analysis and the behavior of bottom ash can provide the vertical drain function.

The following engineering characteristic, specific gravity was determined from the pycnometer test. The specific gravity of kaolin clay was 2.62, and this value has a similar figure to most of the soil. According to previous data, researchers have obtained the values of specific gravity were 2.62, 2.35 and 2.68 [14, 17, 40]. Hence, the above result did not show a greater value fluctuation as compared to the previous data. For bottom ash, the specific gravity was 2.33, while the previous study showed 2.35 using the same source of bottom ash [13]. Comparing these two results, the difference between the values can be interpreted as the preparation process of bottom ash from the power plant was not precisely determined and separated.

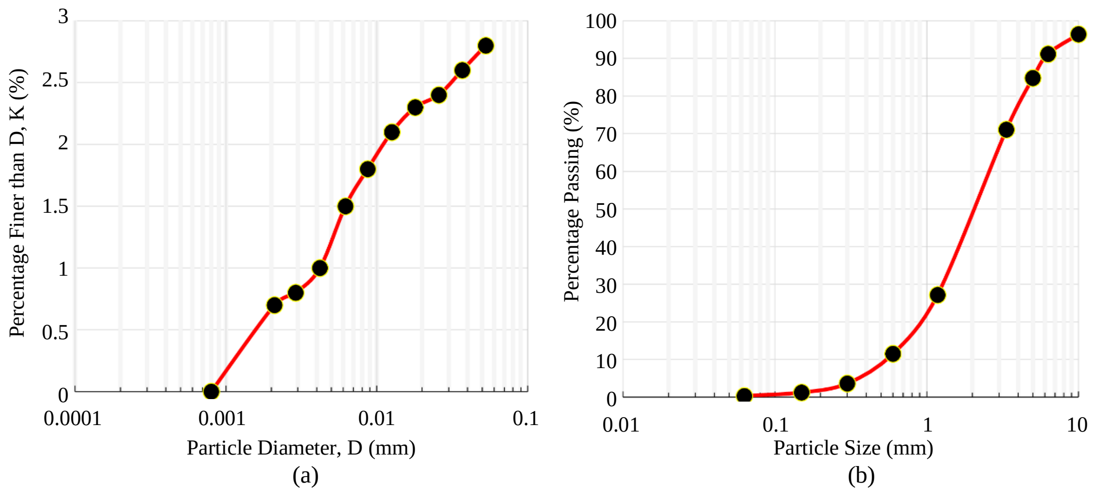

Figure 6 Analysis of particle size distribution (a) Kaolin clay S300 from wet sieving (b) Bottom ash from dry sieving

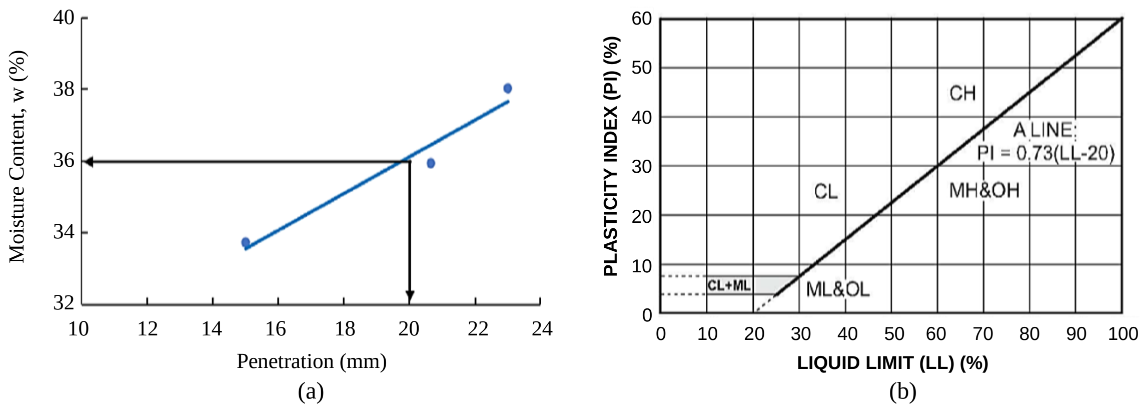

Figure 7 Atterberg limit results (a) Liquid limit (b) USCS plasticity chart for soil classification

3.2 Evaluation of the mechanical properties of kaolin clay and bottom ash

Figure 8 depicted the compaction curve of kaolin clay by the deployment of the Standard Proctor test. The compaction curve demonstrates the relationship between the Maximum Dry Density (DD) and the Optimum Moisture Content (MC) value. From the figure, the DD value and MC value were 1.55 Mg/m^3 and 19.4% respectively, and the MC value was derived for the required volume of water for the mixing process of kaolin clay. Similarly, the above values obtained were 1.65 Mg/m^3 and 18.2% using the same source of kaolin, which was kaolin clay S300 [40]. The discrepancy between the two studies can be linked to the compaction effort and the distance of free fall from the hammer.

For the next mechanical properties, the coefficient of permeability was examined to know the independent efficiency of the material. The permeability coefficient of kaolin clay obtained was 8.96 x 10^{-12} m/s, which was a less permeable soil. Besides, the value also indicates that the kaolin clay is susceptible to poor drainage characteristics, which leads to water accumulation within it. For bottom ash, the coefficient of hydraulic conductivity value was 5.03 x 10^{-3} m/s which is similar to the previous research result [41], which was bigger than the permeability coefficient of kaolin clay. This figure signified that the bottom ash inherited a moderate to high degree of hydraulic conductivity. Analyzing this value, the bottom ash has a permeable characteristic, in which the inflow of water can be easily drained out in a shorter time.

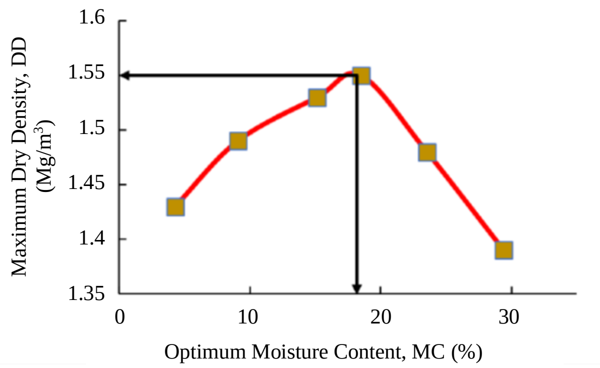

Figure 8 Generation of proctor curve from standard compaction test

3.3 Influence of the installation of encapsulated bottom ash column

Table 6 presented the data obtained after the execution of the UCT. Several important shear strength parameters were recorded, and the shear strength improvement was computed based on the shear strength value of the control sample. The value of shear strength parameters was obtained from five (5) identical samples, where the average value was applied as the final value. From Table 4, the control sample which had no reinforcement showed the value of 8.83kPa, used as the reference value for the calculation of the reinforced specimens. The highest value of shear strength occurred when the S1680 column was sheared, producing the value of 14.01kPa, followed by the S1660 column, recorded at 13.97kPa. The least improvement was shown in the S16100 column with only 12.59kPa of shear strength improvement, or a numerical difference of 3.76kPa as compared to the unreinforced sample. Based on the shear strength improvement result, the study obtained an increasing trend from 58.21% to 58.66%, then began to decrease its value to 42.58%, causing a decrement of 16.08%. Coherent to that, the partial penetrating column, S1680 design was able to withstand the pressure created by the axial load by distributing it effectively to the reinforced section, bottom ash column up to 80% of the kaolin specimen. In contrast, the full penetrating column, S16100 design resulted in the ineffective load transference path that can be attributed to the lower degree of soil cohesiveness due to the extensive drilling process during the bottom ash column installation process. Shen et al. [30] emphasized that the critical column length influences the performance of fabricated stone columns regardless of the granular materials.

Similarly, the result of utilizing bottom ash as the reinforcement produced improvement without the geotextile to encapsulate the specimen [3], but the authors proved that the encapsulation of bottom ash columns increased the shear strength improvement as compared to the specimen with no geotextile encapsulated [41]. Furthermore, the use of geotextile increases the cutting strength of the materials composites, where it functions to bind the replaced bottom ash effectively to act as a granular pile for the load transference from the applied axial loading, where the results and arguments were in line with those researchers as reported in their study [40].

Table 6 The results of shear strength parameters obtained from UCT

Column design	Unconfined compression stress, q_u (kPa)	Shear strength (kPa)	Shear strength improvement (%)
Control	17.66	8.33	-
S1660	27.94	13.97	58.21
S1680	28.01	14.01	58.66
S16100	25.17	12.59	42.58

3.4 Influence of the column ratios towards the kaolin clay shear strength

According to Table 3, the outlined column parameters that affected the result of shear strength parameters were Column Penetrating Ratio (CPR), Column Height to Column Diameter Ratio (HDR), and Column Volume Replacement Ratio (CVR). Figure 9(a) showed the relationship between the shear strength value with the CPR, where the shear strength value from 8.83kPa increased to 13.94kPa at 0.6CPR, then further increased to 14.01kPa at 0.8 CPR, causing a numerical difference of 5.11kPa and 5.18kPa respectively. The shear strength value was dropped to 12.59kPa at 1.0 CPR, producing a reduction of 1.42kPa. The value decrement can be attributed to the early failure of the column at the upper section of the specimen due to the higher level of soil disturbance at 1.0 CPR. Therefore, it caused the remaining reinforced section to generate insignificant improvement. The above figures were linked to the shear strength improvement as shown in Figure 9(b), with improvement values of 58.21%, 58.66%, and 42.58% respectively. Thus, the current study suggested that the ideal value of CVR is 0.8, where the further increment of CVR will lead to the reduction of shear strength. As proposed by a previous study, the disturbance of soil may lead to the reduction of shear strength by different means, for instance, the drilling process [42]. Furthermore, the 1.0 CPR value had extended the bottom ash column to the bottom part of the column, where the load transference might be less effective as compared to 0.8 CPR as the remaining unreinforced part of the column can have a higher value of shear strength.

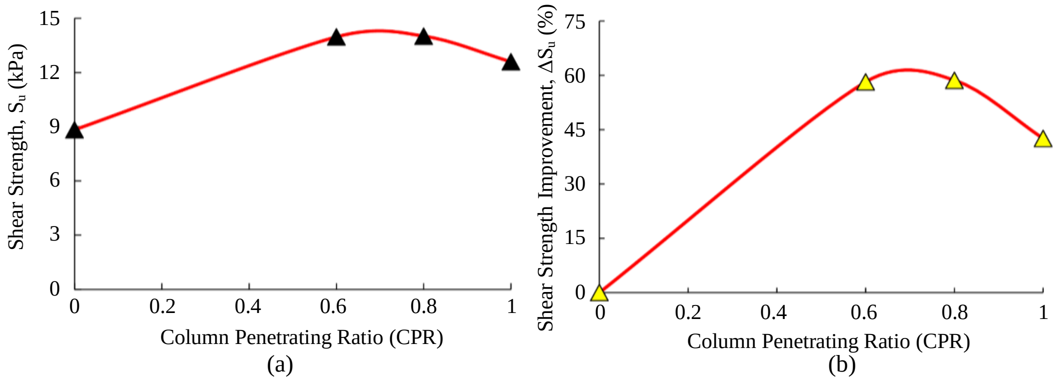

Figure 9 Column penetrating ratio of unreinforced and reinforced samples (a) Shear strength value (b) Shear strength improvement

Figure 10(a) and Figure 10(b) depicted the relationship of HDR with the shear strength value and the relationship of HDR with the shear strength improvement. From both figures, the ideal value of HDR obtained in this study was 5.00, followed by 3.75 and 6.25. As reported by a similar study, the proposed value of HDR should be between 4 – 6 to obtain a better value of shear strength and improvement [13]. The above-suggested values were supported by many researchers, where the studies resulted in improvement albeit different designs and materials were applied in the kaolin clay soil [3, 40]. From the result, the current study acquired the highest value of shear strength improvement at 5.00 HDR, which fell within the proposed range of value.

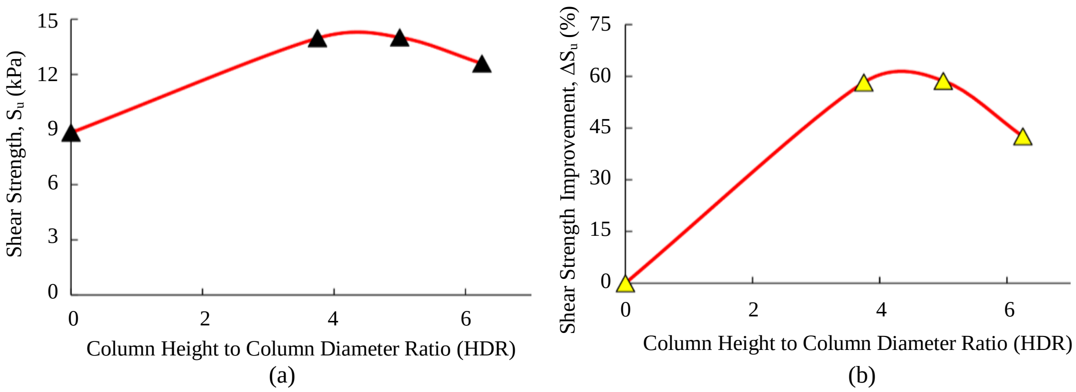

Figure 10 Column height to column diameter ratio of unreinforced and reinforced samples (a) Shear strength value (b) Shear strength improvement

The analysis of the replaced amount of kaolin towards the shear strength and its improvement was expressed in terms of CVR as depicted in Figure 11(a) and Figure 11(b). The ideal amount of bottom ash to produce the maximum value of shear strength was 10.47g. Hence, the required volume to be dug out from the kaolin clay specimen was 8.19% based on the 98% relative density value. Conversely, the largest amount of bottom ash used in the study was 13.43g or 10.24% of its total volume of specimen produced the least value of shear strength and improvement. Thus, the study deduces that the effect of the bottom ash enhancement was not sufficient to subside the effect of soil disturbance during the drilling process which caused the shear strength value to decrease.

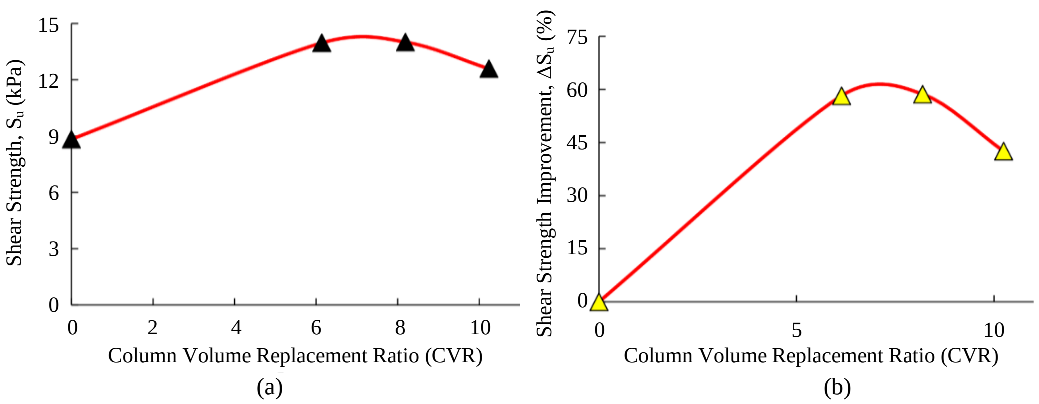

Figure 11 Column volume replacement ratio of unreinforced and reinforced samples (a) Shear strength value (b) Shear strength improvement

4. Conclusions

According to the results obtained, the utilization of bottom ash was a potential material to act as a sustainable material in promoting the sustainability concept in the construction industry. Besides, the bottom ash material presented a similar function as the conventional coarse aggregate in the granular column. Thus, there were several conclusions can be drawn from the study and they are as follows;

- Kaolin clay S300 is a problematic soft clay soil proven by its engineering properties. It behaves as a low plasticity silt clay based on the soil classification standards, AASTHO, and USCS plasticity chart. The values obtained were A-7-6b and ML. The detected particle size of kaolin clay ranges from 0.0011 mm to 0.06 mm, which is extremely fine and falls under the category of fine aggregate with a specific gravity of 2.62. In addition, the proctor curve verifies the OMC and DD values of kaolin, with values of 1.55 Mg/m^3 and 19.4%. The permeability coefficient of kaolin clay validates this material is a less permeable soil, with a value of 8.96×10^{-12} m/s. Therefore, it validates the poor drainage characteristic of kaolin clay, prompting the water accumulation problem.
- Bottom ash is an industrial by-product that has proven excellent engineering properties. The soil classification standard, AASTHO obtained the A-1-a value for bottom ash, confirming the bottom ash behaves like gravel and sand aggregates. The range of particle size is from 0.3 mm to 5 mm, which falls in the group of coarse aggregate with a specific gravity of 2.33. With the assistance of the relative density test, the relative density of bottom ash is produced at 98.00%, signifying it is a very dense material with low compressibility. Furthermore, the coefficient of hydraulic conductivity of bottom ash is 5.03×10^{-3} m/s, categorizing it as a highly permeable material. The association of bottom ash resolves the kaolin water accumulation issue by supplying additional drainage to release the immoderate pore pressure.
- The UCT results yielded a positive outcome regarding all the distinct designs of single encapsulated bottom ash columns. The association of geotextile in the bottom ash column delivers additional reinforcement, with the overall shear strength improvement recorded in all designs of more than 40.00% despite the mild soil disturbance level induced during the drilling process. The delay of the reinforced specimen was observed in terms of bulging condition, compared to the unreinforced sample when undergoing compression from the UCT machine. The peak shear strength magnitude is recorded at the S1680 design, with an improvement rate of 58.66% referencing the control sample. The critical column length in this study is 80 mm (CPR = 0.8), where the stress path of axial load is substantial via the spreading of pressure efficiently throughout the reinforced and unreinforced sections. However, the S16100 design with the extension of column length from 80 mm to 100 mm led to the reduction of shear strength. This design generated the lowest improvement rate, with only 42.58% due to the ineffective load transfer process that caused the earlier bulging of the column. Therefore, the ideal bottom ash amount was 10.74g, and the column ratios of CPR, HDR, and CVR are 0.8, 5.00, and 8.19, respectively.

4.1 Recommendations and limitations of study

Despite the results generated from the respective geotechnical tests achieving the stated objectives. However, several recommendations can be given from the research to improve the data reliability, accuracy, and efficiency of a similar area of study, the stone column technique in the future.

- The shear strength parameters of unreinforced and reinforced samples yielded from the UCT can be utilized to compare with the actual fieldwork on site, as the current study was small-scale research while the construction site covers a larger area. Therefore, the function of the bottom ash column on site can be observed in how the behavior of the bottom ash reacts.
- The identical research can be repeated by using different designs of encapsulated bottom ash columns. For instance, the column diameter and the number of columns to be constructed beneath the kaolin clay.
- The hand posture in the drilling process via the drilling bits was assumed to act perpendicularly to the kaolin sample, and the small change of induced angle was ignored.
- The level of soil disturbance can be reduced by using appropriate drilling machines suited for laboratory scale instead of human drilling.

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