CONSTRUCTION
E-ISSN: 2785-8731
VOLUME 4, ISSUE 1, 2024, 85 – 93
DOI: https://doi.org/10.15282/construction.v4i1.10448

RESEARCH ARTICLE

Shear Strength of Soft Soil Reinforced with Singular Bottom Ash Column

M. S. I. Zaini, and M. Hasan*

Faculty of Civil Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, Lebuh Persiaran Tun Khalil Yaakob, 26300 Kuantan, Pahang, Malaysia

ABSTRACT - Structures construct on soft clays are often affected by stability and settlement problems due to high compressibility, low shear strength and low permeability of soft clay which will lead to bearing capacity failure and excessive settlement. The soft clay samples had the dimensions of 50 mm diameter and 100 mm in height. The bottom ash column had two (2) different area replacement ratios which were 4% and 9% (10 mm and 15 mm diameters respectively) with the bottom ash column penetration ratio of 0.3, 0.7 and 1.0. The results of the unconfined compression test show that there is an improvement in shear strength of soft kaolin clay when reinforced with bottom ash column. For samples with area replacement ratio 4%, the results show the increment of 25%, 37.5% and 50% at height penetrating ratio of 0.3, 0.7 and 1.0, respectively in shear strength. Meanwhile, for samples of 9% area replacement ratio, the shear strength of the soft kaolin clay increased about 14.29, 28.57 and 57.14%, respectively. It can be concluded that by reinforcing the soft clay using singular bottom ash column, the shear strength of the soils increases and become more significant as the area replacement ratios and the column penetration ratios increase.

ARTICLE HISTORY
Received : 16 Mar. 2024
Revised : 17 Apr. 2024
Accepted : 24 Apr. 2024
Published : 06 May 2024

KEYWORDS
Ground improvement;
Bottom ash column;
Shear strength;
Stone column;
Bottom ash;

1.0 INTRODUCTION

Structures construct on soft clays are often affected by stability and settlement problems. It is because the soft soil has the characteristics of high compressibility, low shear strength and low permeability. Therefore, the load induced by the structure may results in bearing capacity failure and excessive settlement [1-3]. Cohesive soils such as soft clay usually settle from compression which consists of elastic settlement and consolidation. The large proportion of the settlement on soft clay is attributed to consolidation process which may continue for a long time depending on the ability of the soil to dissipate excess pore water pressure due to construction load [4-5]. The remedial measure such as insertion of stone column has been widely used in order to overcome this problem [6-7]. This ground improvement technique has been successfully applied to increase the bearing capacity as well as reducing the settlement of the soils and accelerating the settlement process itself [8-9].

In detail, when the stone columns were inserted into the soft soils, a composite soil mass that has greater strength and improved stiffness will be produced compared to the unreinforced soils [10-11]. It will definitely increase the bear-ing capacity of the soils. Furthermore, stone columns also act as a vertical drain in the soils thus accelerating the dissipation of excess pore water pressure that are generated during loading [12]. Stone columns have also been used to improve the slope stability of the embankments on soft ground. In short, stone column can be considered as one of the most practical and versatile techniques for improving the mechanical properties of the soft soils [13-14].

However, with frequent use of traditional aggregates in stone column, eventually, it will cause the exhaustion of the aggregates' natural resources. The engineering properties of most bottom ash are more favorable than traditional aggregates [15-16]. Therefore, it has a high potential to replace conventional aggregates for various engineering purposes. Beneficial use of bottom ash as replacement material in stone column offer an attractive alternative of disposal due to the substantial economic savings which can be attained by the reduction of ash disposal costs and the conservation of natural soils and lands [17-19]. This study is therefore aimed in investigating the enhancement of strength of soft clays when it is reinforced with singular bottom ash column as a replacement for the stone column.

Constructions on the soft clays are often affected by stability and settlement problems due to the soft soil characteristics that are high compressibility, low shear strength and low permeability [20-22]. Therefore, the load induced by construction may results in bearing capacity failure and excessive settlement. Cohesive soils such as soft clay usually settle from compression which consists of elastic settlement and consolidation. The large proportion of the settlement on soft clay is attributed to the consolidation process which may continue for a long time depending on the ability of the soil to dissipate excess pore water pressure due to the construction load. Consequently, an appropriates ground improvement methods such as stone column technique needs to be selected and applied to enhance the mechanical properties of the soft soils to carry any typical structural loads on the soils, thus, to solve all of the problems.

***CORRESPONDING AUTHOR | M. Hasan** | ✉ muzamir@umpsa.edu.my

2.0 METHODOLOGY

The experimental program was designed firstly to characterize the material used which was bottom ash (obtained from Tanjung Bin power plant) and kaolin clay, followed by the shear strength tests on soft kaolin clay reinforced with a singular bottom ash column. The summary of laboratory testing program and the standard used are as shown in Table 1.

Table 1. Laboratory testing program

Material	Test Name	Standard
Kaolin	Atterberg Limit	BS 1377- Part 2: 1990: 4, 5 & 6.5
	Specific Gravity	BS 1377- Part 2: 1990: 8.3
	Particle Size Distribution	BS 1377- Part 2: 1990: 9.5
Bottom Ash	Specific Gravity	BS 1377- Part 2: 1990: 8.3
	Particle Size Distribution	BS 1377- Part 2: 1990: 9.3
	Compaction Test	BS 1377- Part 4: 1990: 3.3
	Direct Shear Test	ASTM D 3080
	Permeability Test	BS 1377- Part 5: 1990
Soft Kaolin Clay reinforced with Singular Bottom Ash Column	Unconfined Compression Test	ASTM D 2166

2.1 Preparation of Soft Kaolin Clay

Two (2) batches of the soft kaolin clay samples had been prepared. The samples were consolidated in a typical 1L compaction mould. The clay was allowed to consolidate under its own weight for a period of two (2) hours. Then, it was consolidated using customized one-dimensional (1-D) consolidation test apparatus under a vertical stress, generated from the air compressor. The initial stress used was 50 kPa and increased another 50 kPa per day until a maximum stress of 200 kPa is reached. The sample was left for a period of six (6) days for the consolidation process to occur slowly. During the 1-D consolidation, drainage was allowed from both ends of the sample through the filter papers, allocated at both ends of the samples.

2.2 Installation of Bottom Ash Column

The shear strength of the soft kaolin clay reinforced with singular bottom ash column was determined via preparation of a physical models or samples. From each batch of the soft clay obtained from 1-D consolidation test, four (4) samples of the soft kaolin clay were formed using samplers (50 mm in diameter and 100 mm in height). The dimensions of the sample were chosen based on the research conducted by Zaini and Hasan [23]. A total of eight (8) samples had been obtained and marked as sample A, B, C and D from the first batch and E, F, G and H from the second batch. Except for samples A and E, all samples were reinforced with bottom ash column. The hole for the bottom ash column was constructed at the centre of the soil samples using auger (known as replacement method) with a pre-determined diameter and height. The bottom ash was then poured into the constructed hole from about 15 mm height above the soil samples to have a consistent density. Shear strength tests were conducted on four (4) cases of samples of different column penetration (column height over samples height, Hc/Hs) ratios which were 0.0 (only soft clay i.e.no column added), 0.3, 0.7 and 1.0. The column diameter had two values which were 10 mm and 15 mm with area displacement ratio (column area to sample area, Ac/As) of 4% and 9% respectively. The unconfined compressive test (UCT) had been conducted on the samples to determine the shear strength. A control sample (no column) was mould which act as a control sample to determine the improvement made when installing the bottom ash column, for each batch of the soft clay prepared. Figure 1 illustrate the column arrangement with penetrating ratio of 1.0 in the sample.

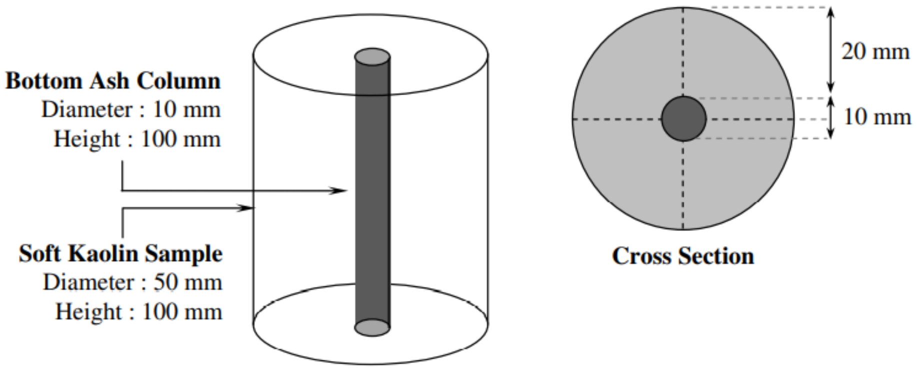

Figure 1. Column arrangement with penetrating ratio of 1.0 in the sample

3.0 EXPERIMENTAL RESULTS

In the study, a series of laboratory testing was conducted according to the standard as mentioned in Table 1 and the shear strength of the reinforced soft clay with singular bottom ash column was tested. There are seven (6) types of laboratory testing conducted in the study which includes Atterberg limit, specific gravity, particle size distribution, compaction, permeability, direct shear and unconfined compression test.

3.1 Atterberg Limit

From the cone penetrometer test, the liquid limit of kaolin used in this study is 38%. The kaolin paste has minimum 38% of moisture content to flow using its own weight. Meanwhile, plastic limit for this kaolin is 27%. It indicates that with this amount of moisture content, the soil is in plastic condition. Therefore, the plasticity index, PI for this kaolin is 9%. On the other hand, the shrinkage limit of the kaolin is 4%. At this point, the solid particles of kaolin are in close contact and the water content in the soil is just sufficient to fill the voids between the particles. The results obtained are in a good agreement with a research conducted by Zaini and Hasan [23].

3.2 Specific Gravity

From the result, the specific gravity of the kaolin clay was quite high with average value of 2.64 compared to natural soils that had specific gravity in the range of 2.6 to 2.8. However, the obtained value was in line with the absolute specific gravity of kaolinite clay which is 2.6 [23-25]. Meanwhile, the specific gravity of Tanjung Bin bottom ash was 2.41. The bottom ash from the same source which was 1.99 [26]. The value was quite low which indicates that even from the same source, the specific gravity of bottom ash is varying from day to day production over time due to the content of iron oxide in the bottom ash. In addition, the tested bottom ash may contain a quantity of porous particles. However, the specific gravity for this bottom ash was in range with the value of specific gravity done by Kim et. al. [15] which is from 2.32 to 2.62. The results obtained are in a good agreement with a research conducted by Zaini and Hasan [23].

3.3 Particle Size Distribution

Figure 2 shows the particle size distribution of kaolin clay used in the study. The particle size distribution graph is the combination from hydrometer test and simple sieve analysis graphs. Generally, the kaolin clay is well graded, ranging from clay to fine sand [27-28]. The majority of the sizes occurred in a range between 0.2 mm and 0.0009 mm [29-30]. According to AASHTO classification system, based on the Atterberg Limit and the particle size distribution graph, this kaolin clay is in A-4 group which is silty soils. Meanwhile, Figure 3 shows the particle size distribution of two (2) samples of Tanjung Bin bottom ash. Bottom ash gradations from the two (2) specimens show similar trend and demonstrate well graded size distribution. The majority sizes occurred in a range between 20 mm and 0.075 mm and ranging from fine gravel to fine sands sizes. Therefore, based on classification of AASHTO system, the bottom ash is in A-1-a which falls into group of stone fragments, gravel and sand. The results obtained are in a good agreement with a research conducted by Zaini and Hasan [23].

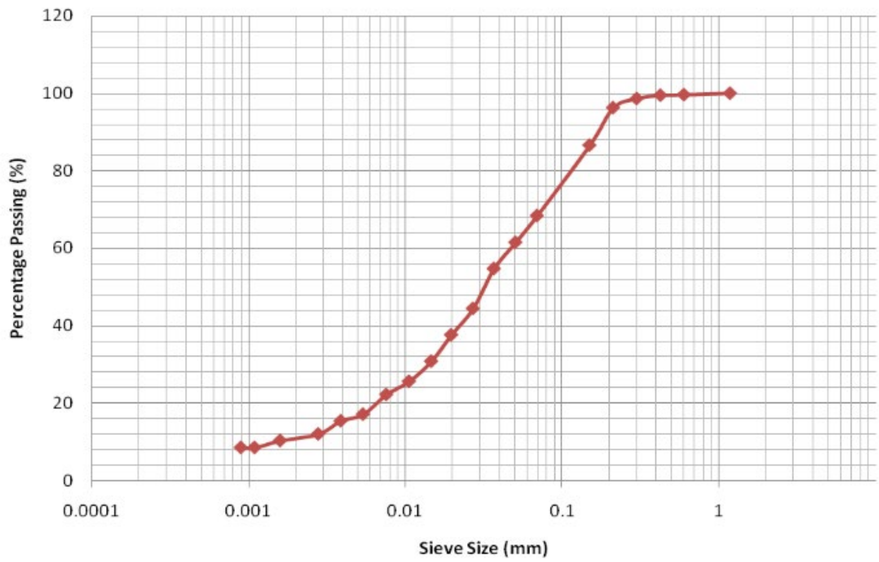

Figure 2. Particle size distribution of soft kaolin clay

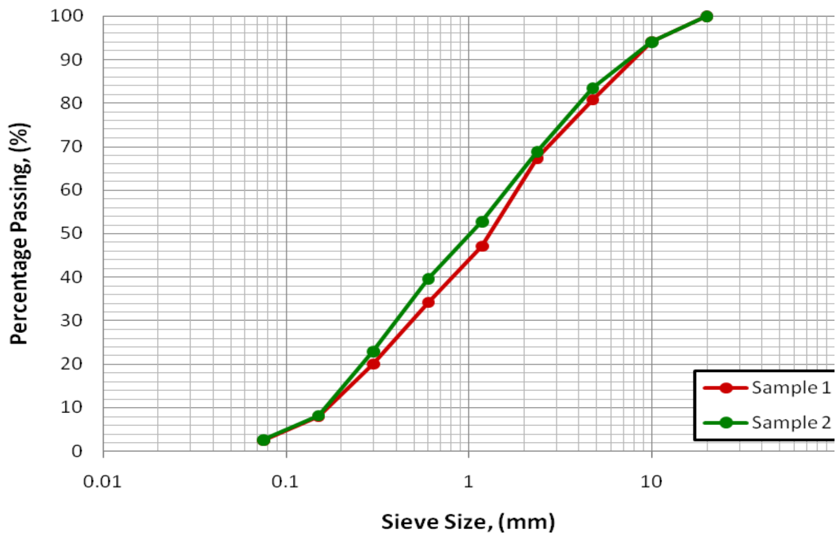

Figure 3. Particle size distribution of Tanjung Bin bottom ash

3.4 Compaction Behaviour

Figure 4 shows the plots of dry density versus the moisture content for bot-tom ash from the light compaction test. The results show that the optimum moisture content, w_{opt} of the bottom ash is 24% with a maximum dry density, d_{max} of 1.321 Mg/m^3 (13.21 kN/m^3). From the previous study on the Tanjung Bin bottom ash [15], it shows that the optimum moisture content is 21.5% and the maximum dry unit weight is 12.85 kN/m^3. Another study done on West Virginia bottom ash show that maximum dry density and the optimum moisture content typically range from 11.6 kN/m^3 to 18.4 kN/m^3 and from 12% to 34% respectively [31-32]. The diversification in the moisture-density relationship is high between the different sources of bottom ash. It may be because of the different low specific gravity and high air void content [33-35]. The results obtained are in a good agreement with a research conducted by Zaini and Hasan [23].

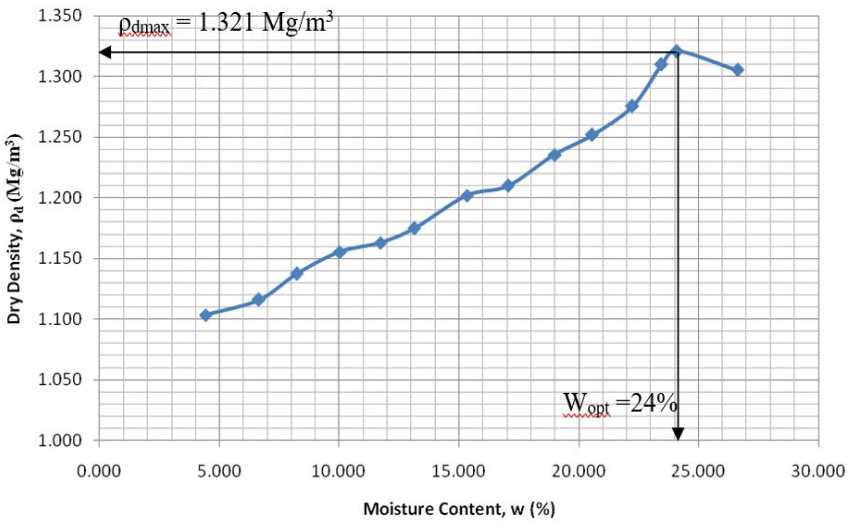

Figure 4. Compaction curve of Tanjung Bin bottom ash

3.5 Permeability

The permeability of the bottom ash was measured by a constant head test. The measured coefficient of permeability is 4.57 x 10^{-4} m/s. It indicates that the bottom ash demonstrates the permeability corresponding to the clean sands and it has medium degree of permeability. The drainage characteristic is considered good. The measured coefficient of permeability for Tanjung Bin bottom ash is 1.72 x 10^{-4} m/s [8]. The value is slightly different because of the increment value of fine contents in the bottom ash. The fines included in bottom ash had a foremost effect on the permeability. Since the gradation of bottom ash and sand are similar, they tend to exhibit similar permeability [3]. The results obtained are in a good agreement with a research conducted by Zaini and Hasan [23].

3.6 Direct Shear

From the result of direct shear test done on bottom ash, the peak cohesion and friction angle were 1.36 kPa and 33.73° respectively. The peak cohesion and friction angle for his samples were 3.8 kPa and 32° respectively [5]. The result is quite similar. Both of this result also quite similar compared to the Indian bottom ash. The peak cohesion and friction angle of Indian bottom ash were varying from 0.1-0.2 kPa and 31° to 37° for compact-ed condition, respectively [9]. From the tests conducted, it shows that the bottom ash has almost similar properties compared to the typical sand and fine gravel. Therefore, it has a potential to be used as the replacement material for stone column. Table 2 and 3 show the summary of kaolin clay and bottom ash properties.

Table 1. Summary of Kaolin clay properties

Properties	Value
Liquid Limit	38%
Plastic Limit	27%
Plasticity Index	9%
Specific Gravity	2.64
Soil Classification (AASHTO)	A-4

Table 2. Summary of Tanjung Bin bottom ash properties

Properties	Value
Particle Size Range	20 mm – 0.075 mm
Soil Classification (AASHTO)	A – 1 – a
Specific Gravity	2.41
Compaction:	
a) Maximum Dry Density	1.321 Mg/m^3
b) Optimum Moisture Content	24%
Direct Shear Test:	
a) Peak Friction Angle	33.73^o
b) Peak Cohesion	1.56 kPa

3.7 Unconfined Compressive Test

The shear strength of the reinforced soft kaolin clay with singular bottom ash column was measured by using the UCT test. This test is limited to determine the shear strength of the cohesive soils only because since there is no lateral support. Table 4 shows the summary of analysis done on the results of unconfined compressive test.

Table 4. Summary of analysis on unconfined compressive test

Sample	Diameter (mm)	Area Replacement Ratio (%)	H_c/H_s	Corrected Deviator Stress (kPa)	Shear Strength (kPa)	Increment in Shear Strength (%)
A	10 mm	4%	0.0 (no column)	19	8	-
B			0.3	20	10	25
C			0.7	22	11	37.5
D			1.0	24	12	50
E	15 mm	9%	0.0 (no column)	14	7	-
F			0.3	16	8	14.29
G			0.7	18	9	28.57
H			1.0	22	11	57.14

Figure 5 and Figure 6 show the corrected deviator stress versus axial strain for sample with 10 mm diameter and 15 mm diameter. From both graphs, the shear strength of the samples increases and become more significant as the area replacement ratios and the column penetration ratios increase.

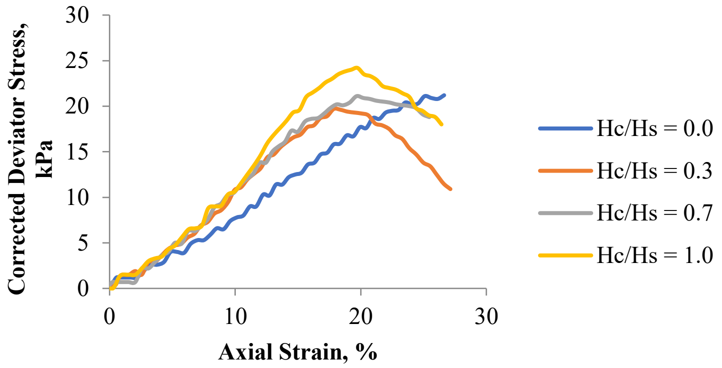

Figure 5. Corrected deviator stress versus axial strain for sample with 10 mm diameter

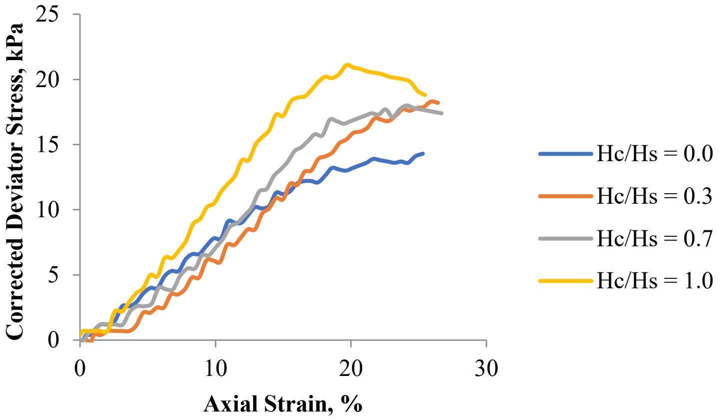

Figure 6. Corrected deviator stress versus axial strain for sample with 15 mm diameter

Meanwhile, Figure 6 and 7 show the shear strength and the improvement made when reinforced with bottom ash column. For 10 mm diameter column with Hc/Hs of 0.3, 0.7 and 1.0, it shows an increment of 25, 37.5 and 50% respectively in shear strength of the soft kaolin clay. As for column with a 15 mm diameter, the shear strength of the soft kaolin clay increased about 14.29, 28.57 and 57.14% for Hc/Hs of 0.3, 0.7 and 1.0 respectively. These significant increases in the shear strength can be considered substantial due to the replacement of a portion of the soft clay by a stronger and stiffer bottom ash column. This increment also has been reported by previous study [2] on the performance of clay samples reinforced with vertical granular columns and on the effect of sand columns on the undrained load response of soft clays [37-38]. Based on Figure 6, the graph still shows the increment in shear strength which indicates that the shear strength is dependent on the confining stress provided by the strength of the surrounding soil to the column. For the first batch with initial shear strength of 8 kPa, when it was inserted by bottom ash column, it produced a slightly higher shear strength compared to the second batch (7 kPa) due to the higher initial shear strength that induced more confining pressure to the column. When a composite soil-granular column system is formed, the surrounding soil will provide lateral support to the column, thus, preventing expansion under load [36]. However, the significant increase is not achieved because of the low confining stress provided by the low strength of the surrounding soil. Using a thinner layer of bottom ash (10 mm) may result in a moderate increase in shear strength compared to unreinforced soil. The relatively smaller thickness of the ash layer might provide some reinforcement but may not significantly alter the soil's mechanical properties. On the other hand, a thicker layer of bottom ash (15 mm) is likely to lead to a more substantial enhancement in shear strength. The increased volume of reinforcement material can offer greater resistance to shear forces within the soil, resulting in a higher overall strength improvement. The results obtained are in a good agreement with a research conducted by Zaini and Hasan [23].

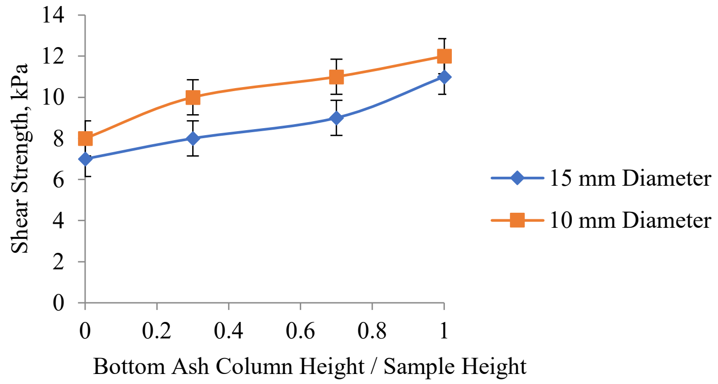

Figure 1. Corrected deviator stress versus axial strain for sample with 15 mm diameter

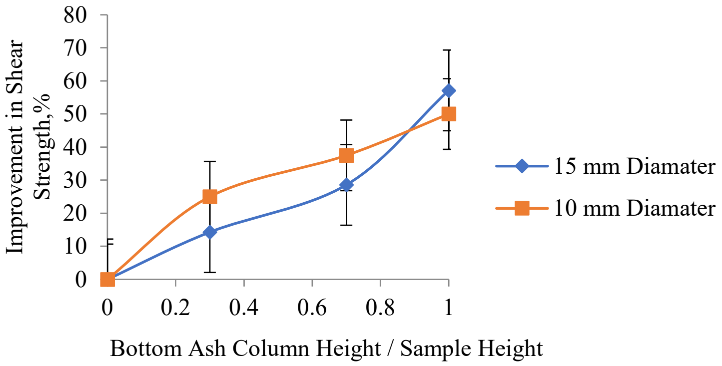

Figure 8. Increment of shear strength at failure for single column of bottom ash

4.0 CONCLUSION

The purpose of this study is to investigate the enhancement of shear strength in the soft kaolin clay when it is reinforced with the bottom ash. Based on the analysis of the results, it can be concluded that According to AASHTO classification system, the kaolin clay used in this study falls into A-4 group, which is silty soils. As for the bottom ash, it falls into A-1-a group which is stone fragments, gravel and sand. In general, bottom ash exhibits quite similar properties with the sand and fine gravel, hence has a good potential to be used as replacement material for stone column improvement soft soils. Besides, the results of the UCT test show that there are improvements in shear strength of soft kaolin clay when it is reinforced with singular bottom ash column. The strength increment indicates that the shear strength of the samples increases and become more significant as the area replacement ratios and the column penetration ratios increase. Lastly, the increased in the shear strength of bottom ash column reinforced soft clay is also dependent on the confining stress provided by the strength of the surrounding soil to the column. It can be concluded that the higher the confining stress, the higher the increased in shear strength. Moreover, in real world cases, understanding the shear strength enhancement provided by singular bottom ash columns can offer engineers a viable solution for stabilizing soft soils. This knowledge can be particularly valuable in areas where soft soils pose challenges for construction projects.

5.0 ACKNOWLEDGEMENT

The authors would like to thank the Faculty of Civil Engineering Technology for providing the experimental facilities and to all technicians at Soil Mechanics and Geotechnics Laboratory. The support provided by Universiti Malaysia Pahang and Hokoko Engineering Co. Ltd in the form of a research grant vote number, UIC201503, RDU202701, RDU223309, and PGRS2003185 for this study is highly appreciated.

6.0 AUTHOR CONTRIBUTIONS

Muhammad Syamsul Imran Zaini: Original draft preparation, Conceptualization, Methodology, Software
Muzamir Hasan: Supervision

7.0 DATA AVAILABILITY STATEMENT

The data used to support the findings of this study are included within the article.

8.0 CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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