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THE UNDRAINED SHEAR STRENGTH OF SOFT CLAY REINFORCED WITH GROUP ENCAPSULATED LIME BOTTOM ASH COLUMNS

Muzamir Hasan[1,2,3], *Wan Nursyafiqah Wan Jusoh[1,3], Wong Suk Chee[3] and Masayuki Hyodo[4]

[1]Centre for Earth Resources Research & Management, Universiti Malaysia Pahang, Malaysia;
[2]Earth Resources & Sustainability Centre, Universiti Malaysia Pahang, Malaysia;
[3]Faculty of Civil Engineering & Earth Resources, Universiti Malaysia Pahang, Malaysia;
[4]Department of Civil and Environmental Engineering, Yamaguchi University, Japan.

*Corresponding Author, Received: 28 Dec. 2017, Revised: 11 Jan. 2018, Accepted: 20 Dec. 2018

ABSTRACT: This research was aimed to investigate the role of group encapsulated lime bottom ash columns in improving the shear strength by using laboratory scale model. Kaolin was being used as soil sample and lime bottom ash as the reinforced columns. The reinforced kaolin samples were tested by using Unconfined Compression Test (UCT). A total 7 batches of kaolin sample had been tested and each batch consist of 3 specimens represent sample without lime bottom ash column, partially penetration and fully penetration for group lime bottom ash columns. The specimen used was 50 mm in diameter and 100 mm in height. The height of the group columns was 60 mm, 80 mm and 100 mm with 10 mm and 16 mm column diameter. The group encapsulated lime bottom ash columns was installed in the triangular pattern, as it was much easier to maintain the location of installed columns and the spacing in between the columns. The improvement of shear strength of group encapsulated lime bottom ash columns with area replacement ratio of 12.00 % (10 mm column diameter) and 30.72 % (16 mm column diameter) was 29.00 %, 44.17 %, 29.75 % and 1.00 %, 3.92 %, 7.33 % at sample penetration ratio, H_c/H_s of 0.6, 0.8 and 1.0 respectively. It can be concluded that the shear strength of soft clay could be improved by the installation of group encapsulated lime bottom ash columns. However, the improvement of shear strength of 10 mm group encapsulated lime bottom ash columns was increased more significant compared to 16 mm group encapsulated lime bottom ash columns.

Keywords: sand columns, sustainable construction, group encapsulated lime bottom ash columns

1. INTRODUCTION

Sustainable development is a balance between economic growth and environmental protection in a population. The unmanageable waste products and uncontrollable usage of natural resources gives a huge impact on the earth and as well as endanger human's health. On the poor ground with low load-bearing capacity and high compressibility such as soft clay will lead to foundation settlement. Ground improvement method such as stone column is required to improve the properties of soft clay. As mentioned by Marto *et al*. (2013) [1], the properties of the silt and clay deposit can be greatly improved by stone column method and as well as increase the stability of cohesive soil.

Stone column is the method where it is installed in soft cohesive soils by replacing the portion of soil with granular material such as sand or gravel to improve the bearing capacity, reduce the settlement and accelerate the dissipation of excess pore water pressure. The theoretical frameworks for estimation of bearing capacity and settlement of foundations reinforced with stone columns have been developed by many researchers such as Hughes (1974) [2], where it is discovered that the bulging is one of the characteristics of the stone column. Moreover, the experimental and numerical analysis on single and group stone column was conducted by Ambily and Gandhi (2007) [3], Hasan *et al*. (2011) [4] and Black *et al*. (2007) [5].

According to Mahmud (2003) [6], the coal-burning power plant is the main source of energy in Malaysia, thus lots of waste from coal ash will be produced and this will lead to environmental issues and disposal waste problems. By utilizing the bottom ash, the sustainable development can be achieved and it also can reduce the cost of construction. As eloquently stated by Kumar and Stewart (2003) [7], the properties of bottom ash are quite similar with sand, thus the bottom ash has the potential to act as a replacement of sand in a granular column. In addition, lime was used as a stabilizing in bottom ash column and helped increase the bonding between the bottom ash particles.

In the past of several years, many researchers have come up with the idea of "critical column length" where the load carrying capacity will not participate in improvement on soft cohesive clays if the column exceeds the optimum length. As proposed by Muir Wood, Hu & Nash (2000) [8], McKelvey *et al*. (2004) [9], Hughes & Withers (1974) [10], the value for "critical column length" is between 4 to 8 times the diameter of the column.

Current research is undertaken to determine the basic and mechanical properties of soft kaolin clay, lime, and bottom ash. This paper discusses the result of the undrained shear strength of soft clay reinforced with group encapsulated lime bottom ash columns and their correlation with the various dimension of group encapsulated lime bottom ash columns.

2. MATERIALS AND METHOD

Small-scale modeling column specimens with 50mm in diameter and 100mm in height were prepared by using bottom ash as granular materials and kaolin as the soft clay. All the experiments were carried out at Soil and Geotechnical Laboratory of Universiti Malaysia Pahang. The standard used as references was British Standard (BS) or the American Society of Testing Material (ASTM), as it was subjected to the suitability and availability of the equipment in the laboratory for the respective tests. Table 1 shown a list of tests and standard used.

2.1 Lime Bottom Ash Samples

The 10 mm and 16 mm diameters of lime bottom ash were used. Each diameter will have three different lengths of columns which were 60 mm, 80 mm, and 100 mm with three specimens in each type of length. Auger drill bit with the diameter of 10 mm and 16 mm was used for drilling the holes in the kaolin specimens for the installation of lime bottom ash columns, it is called as replacement method. Since to prevent expansion of kaolin, the kaolin specimens were remained inside the mold and during the drilling process. After that, geotextile was prepared according to the columns size and inserted into the drilled holes in each kaolin specimens. Then, lime bottom ash was poured into the geotextile which can avoid the leakage of lime bottom ash. Next, by using the steel extruder, the specimen was pushed out from the mold. Lastly, the specimen was ready for the unconfined compression test (UCT).

2.2 Installation of Group Lime Bottom Ash Columns

The process of installing group encapsulated lime bottom ash columns into the kaolin specimen was very difficult, as the kaolin specimen was soft and sensitive. In order to construct homogeneous group lime bottom ash columns in the clay specimens, raining method was used based on several pilot tests. The freefall of lime bottom ash by pouring it into the predrilled hole at a predetermined height (as shown Figure 1). To ensure the final product of each specimen for UCT test were similar, the falling height was set at 10 mm above from the surface of clay specimen. The smoother end of auger drill bit was used to smooth out the surface of the drilled hole. This was to make sure the lime bottom ash can be installed properly in the drilled hole. The mass of lime bottom ash supposed to fill the pre-drilled hole was measured and prepared based on the known volume of a pre-drilled hole in order to maintain the uniformity of pre-set density for the final product of lime bottom ash column. The density of various dimensions of bottom ash column installed in kaolin specimens was tabulated in Table 1. All the lime bottom ash columns which used to reinforce in kaolin specimen were following this method. Figure 2 showing the arrangement of installed columns. Table 2 shown a list of tests and standard used.

Fig 1 Installation of bottom ash in soft kaolin clay specimen

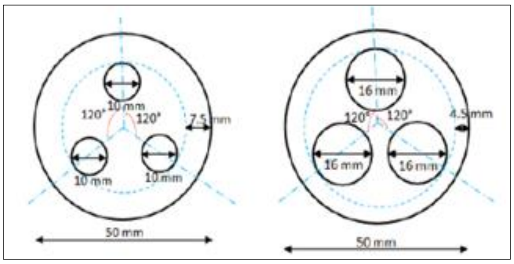

Fig.2 Arrangement of installed columns in clay specimen

Table 1 The density of various dimensions of bottom ash column installed in kaolin specimens

Diameter of group lime bottom ash column specimen (mm)	Length of group lime bottom ash column specimen (mm)	Volume of column (mm^3)	Density of bottom ash (g/mm^3)	Mass of bottom ash (g)
	60	4712.39		3.20
10	80	6283.19		4.27
	100	7853.98		5.34
	60	12063.72	0.00068	8.20
16	80	16084.95		10.94
	100	20106.19		13.67

Table 2 A list of tests and standard used

Materials	Tests	Standards
Kaolin	Hydrometer	BS 1377: Part 2 1990: 9.6
	Standard Compaction	BS 1377: Part 4 1990: 3.3
	Falling Head Permeability	ASTM D 2434
	Specific Gravity	BS 1377: Part 2: 1990: 8.3
	Atterberg Limit	
	Liquid Limit	BS 1377: Part 2: 1990: 4.3
	Plastic Limit	BS 1377: Part 2: 1990: 5.3
Lime	Hydrometer	BS 1377: Part 2 1990: 9.6
	Specific Gravity	BS 1377: Part 2: 1990: 8.3
	Atterberg Limit	
	Liquid Limit	BS 1377: Part 2: 1990: 4.3
	Plastic Limit	BS 1377: Part 2: 1990: 5.3
Bottom Ash	Dry Sieve	BS 1377: Part 2: 1990: 9.3
	Specific Gravity	BS 1377: Part 2: 1990: 8.3
	Standard Compaction	BS 1377: Part 4: 1990: 3.3
	Constant Head Permeability	ASTM D 2434
Bottom Ash with Lime	Standard Compaction	BS 1377: Part 4 1990: 3.3
Soft Kaolin Clay Reinforced with Group Encapsulated Lime Bottom Ash Columns	Unconfined Compression Test (UCT)	ASTM D 2166

3. RESULTS AND DISCUSSIONS

3.1 Physical and Mechanical Characteristics of Kaolin, Quicklime and Bottom Ash

The physical and mechanical properties of kaolin clay, quicklime, and bottom ash have been summarized in Table 3. Kaolin clay had similarity characteristic with soft clay. Quicklime was mixed with bottom ash to increase the bonding between bottom ash particles. Other than that, bottom ash had shown that its characteristics were similar to typical sand and fine gravel. Therefore, there is high a potential for bottom ash to be one of the recycled aggregates that can be used as replacement materials for the sand column.

3.2 Effect of Group Lime Bottom Ash Columns on Shear Strength

Generally, the shear strength increase with area replacement ratio. However, the improvement of shear strength does not merely depend on area replacement ratio, but the penetration ratio of the encapsulated bottom ash column as well. Table 4 shown the shear strength results and its improvement.

Figure 3 and Figure 4 shown the correlation line for sample shear strength and improvement shear strength of group encapsulated lime bottom ash columns. From Figure 2 the value of correlation cohesion, R2 for diameter 10 mm and 16 mm were 0.7461 and 0.7566 respectively. Whereas, From Figure 3 the value of correlation cohesion, R2 for diameter 10 mm and 16 mm were 0.7461 and 0.7569 respectively. The nearer the correlation cohesion, R2 to value 1, the higher the accuracy of the results.

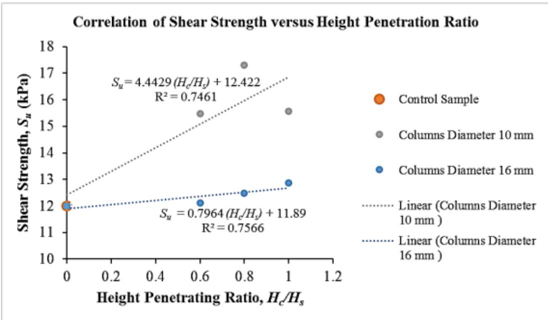

Fig.3 Correlation graph of shear strength with height penetration ratio for group lime bottom ash columns with diameter 10 mm and 16 mm.

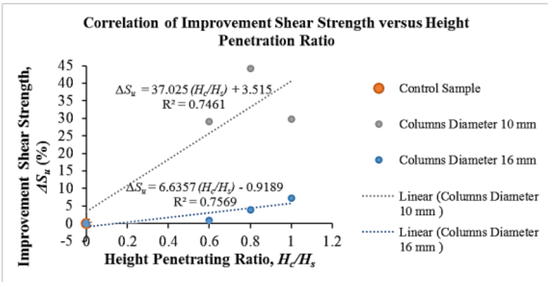

Fig.4 Correlation graph of improvement shear strength with height penetration ratio for group lime bottom ash columns with diameter 10 mm and 16 mm.

Table 3 Physical and mechanical properties of kaolin, quicklime, and bottom ash

Test	Parameter	Kaolin	Lime	Bottom Ash
Soil Classification	AASHTO	A-6	A-7-5	A-1-a (0)
	USCS (Plasticity Chart)	MI	MV	-
Atterberg Limit	Plastic Limit, w_p (%)	26	72	-
	Liquid Limit, w_L (%)	36	61	-
	Plastic Index, I_p (%)	10	11	-
Standard Compaction	Optimum Moisture	19.40	24.00	23.60

	Content, w_{opt} (%)			
	Maximum Dry Density, $\rho_{d(max)}$ (Mg/m^3)	1.55	1.07	1.313
Small Pycnometer	Specific Gravity, G_s	2.62	2.40	2.33
Falling Head Permeability	Coefficient of Permeability, *k* (m/sec)	8.96 x10^{-12}	-	-
Constant Head Permeability	Coefficient of Permeability, *k* (m/sec)	-	-	5.03 x10^{-3}

Table 4 Shear strength results and its improvement

Height Penetration Ratio, H_c/H_s	Shear Strength, S_u (kPa)			Average Shear Strength, S_u (kPa)	Improvement of Shear Strength, ΔS_u (%)
	1	2	3		
Controlled Sample					
0	11.59	12.43	11.98	12.00	-
Group Encapsulated Lime Bottom Ash Columns (10 mm)					
0.6	15.38	15.67	15.38	15.48	29.00
0.8	16.28	18.28	17.35	17.30	44.17
1.0	16.16	15.47	15.07	15.57	29.75
Group Encapsulated Lime Bottom Ash Columns (16 mm)					
0.6	12.10	12.09	12.17	12.12	1.00
0.8	12.35	12.70	12.35	12.47	3.92
1.0	12.98	13.02	12.64	12.88	7.33

The improvement of shear strength obtained from 10 mm diameter column is higher compared to 16 mm diameter column due to the fact of disturbance occurred since a large amount of kaolin was drilled and taken out from the samples, thus it affecting the natural state of the soil and resulting reduction in the shear strength of the samples. The performance of 10 mm column diameter is better than 16 mm column diameter was because of the mobilization of the higher confining stresses in the column.

3.3 Morphological Properties

From the Scanning Electron Microscope (SEM), the particles of the lime bottom ash were grayish, spherical and had rough, gritty surface textures. The surfaces of the particles were observed to have pores and dusty. It is shown that it has similar results to the result obtained by Thaarrini & Ramasamy (2016) [1], who mentioned that bottom ash contains spherical shaped particles similar to Fly ash. The physical characteristics of the bottom ash also reported being similar to Asokbunyarat *et al.* (2015) [2], who reported that spherical structures with an irregular surface texture were detected in the bottom ash samples.

Figure 4 shown the morphology images of lime bottom ash by SEM at 20 μm magnification. Quicklime was mixed with bottom ash to increase the bonding between bottom ash particles.

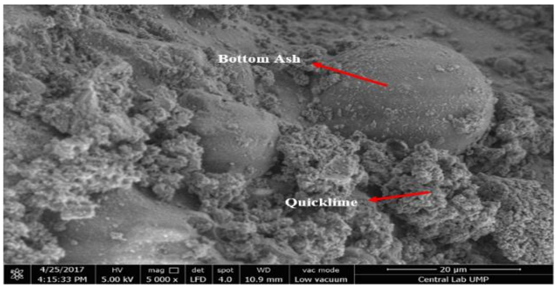

Fig 4. Morphological images of lime bottom ash by SEM at 20μm magnification.

4. CONCLUSIONS

Based on laboratory test performed, the following conclusions can be drawn:

1. Based from the Unified Soil Classification System (USCS) prove that kaolin can be characterized as MI, which indicates that kaolin was medium plasticity silts based on its liquid limit and plasticity index of 36 % and 10 % respectively. Moreover, the result for the specific gravity of kaolin was 2.62. The result shows that maximum dry density, $\rho_{d(max)}$ for kaolin was 1.55 kg/m^3 with optimum moisture content 19.40 %. Besides, the measured permeability coefficient of kaolin was 8.96 x 10^{-12} m/s.
2. Based on AASTHO, the bottom ash that used in this study was categorized as A-1-a group which consisting predominantly of stone fragments or gravel, either with or without a well-graded binder of fine material. According to compaction test, the result showed that maximum dry density for bottom ash was 1.313 Mg/m^3 with optimum moisture content 23.60 %. Besides, the measured permeability coefficient of bottom ash was 5.03 x 10^{-3} m/s. It showed a medium degree of permeability of bottom ash, representing a good drainage characteristic, and generally corresponding to clean sands. Moreover, the result for the specific gravity of bottom ash was 2.33.
3. Based on the Unified Soil Classification System (USCS) proven that quicklime can be characterized as MV, thus it was low plasticity silt with the liquid limit of 72 % and plasticity index of 11 %. On top of that, the result for the specific

gravity of kaolin was 2.40. According to the AASHTO classification system, this kaolin to be classified as clayey soil, A-7-5. This meant that this material was moderate plasticity indexes in relation to liquid limit and which may be highly elastic as well as subject to considerable volume change. In addition, from the compaction test, the result showed that maximum dry density, $\boldsymbol{\rho_{d(max)}}$ for kaolin was 1.07 Mg/m^3 with optimum moisture content 24.00 %.

4. The installation of group encapsulated lime bottom ash columns had shown the improvement in term of shear strength of kaolin. However, the improvement of shear strength does not merely depend on the column penetration ratio of the group encapsulated lime bottom ash columns only. The percentage of increment can be considered substantial as the penetration ratio of group lime bottom ash columns was increased where a portion of soft clay was replaced with the stiffer material such lime bottom ash. The 10 mm diameter of group encapsulated lime bottom ash columns with area replacement ratio of 12 % shown the improvement of shear strength were 29.00 %, 44.17 % and 29.75 % at sample penetration ratio, H_c/H_s of 0.6, 0.8 and 1.0 respectively. Furthermore, the 16 mm diameter of group encapsulated lime bottom ash columns with area replacement ratio of 30.72 % shown the improvement of shear strength were 1.00 %, 3.92 % and 7.33 % at sample penetration ratio, H_c/H_s of 0.6, 0.8 and 1.0 respectively

5. The presence of group encapsulated lime bottom ash columns has increased the shear strength of the soft soil. For the group encapsulated lime bottom ash columns of diameter 10 mm with penetration ratio H_c/H_s of 0.6, 0.8, and 1.0, shown the shear strength increased to 15.48 kPa, 17.30 kPa, and 15.57 kPa respectively. For the group encapsulated lime bottom ash columns of diameter 16 mm with penetration ratio H_c/H_s of 0.6, 0.8, and 1.0, showing the shear strength increased to 12.12 kPa, 12.47 kPa, and 12.88 kPa respectively.

6. Critical column length occurred between 4 and 8 times the diameter of the column. The strength generally increased within the range of 4 to 8 of height over the diameter of column ratio, H_c/D_c. For column diameter of 10 mm, the highest shear strength achieved at H_c/D_c of 8, whereas for column diameter of 16 mm, the highest shear strength achieved at H_c/D_c of 6. The increasing the length of the column beyond the 'critical column length' did not benefit the load-carrying capacity of the composite ground.

5. ACKNOWLEDGEMENTS

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