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SHEAR STRENGTH OF SOFT CLAY REINFORCED WITH SINGLE ENCASED BOTTOM ASH COLUMNS

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ABSTRACT

Stone column is one of the most commonly used in soil improvement technique around the world which capable to increase the bearing capacity of soft clay and reduce settlement of structure constructed on them. Due to its higher value of strength and stiffness, it can sustain larger proportion of the applied load which improves the performance of foundation beds. Meanwhile, the substantial amount of bottom ash disposed in the landfills have causes a serious environment pollution. As the bottom ash is part of the residue of combustion of coal and also the by-product produced in a furnace of the power plant. Hence, by reutilize the bottom ash as granular material in vertical granular column, the cost of construction can be reduced and able to achieve more strength of soft clay after being reinforced with a single bottom ash column which been encased with geotextile. Remolded specimens of 50 mm in diameter and 100 mm in height soft kaolin clay installed with single encapsulated bottom ash columns with 10 mm and 16 mm diameter was subsequently tested under Unconfined Compression Test. It can be concluded that the shear strength parameters shows some significant improvement on encased and non-encased bottom ash columns and were affected by the diameter and height of the column.

Keywords: bottom ash, shear strength, encased bottom ash columns.

INTRODUCTION

Constructing structure on poor ground such as soft clay will affect the stability and settlement of the structure. There are numbers of ground improvement methods that can be used to improve the soft clay properties such as preloading, sand drains, piling, vibrated granular columns, stone column and sand column.

The initial design of foundation system introduced as a geotextile encased columns (GECs) which has been successfully adopted and is well established in engineering practice [Raithel and Kempfert, (2000); Raithel *et al*., (2002)]. Similar concepts based on geogrid encasement as a more robust and perhaps stiffer alternative to geotextile have more recently been introduced and investigated (Sivakumar *et al.*, 2004) to demonstrate the effectiveness of geosynthetic encasement and to improve design methods.

Stone column is one of the most commonly used of soil improvement technique around the world which can increase the bearing capacity of soft soils and able to reduce the settlement of superstructures constructed on them. Due to its higher value of strength and stiffness, it can sustain larger proportion of the applied load which improves significant the performance foundation beds (Hughes *et al*., 1974).

Bottom ash is produced as a result of burning coal in a dry bottom pulverized coal boiler. The unburned material was from a dry bottom boiler that consists of about 20 percent bottom ash. The basic properties of bottom ash are a porous, glassy and dark gray material with a grain size similar to the sand or gravelly sand (Steam, 1974). Although similar to natural fine aggregate, bottom ash is lighter and more brittle and has a greater resemblance to cement clinker (Rogbeck and Knutz, 1996).

The recycling and utilization of coal ash have attracted great attention in construction field to fulfil the current interest in long term and sustainable development in Europe, as well as to reduce the cost of managing the landfill. According to Kumar and Stewart (2003), the properties of sand and bottom ash are almost similar. Hence, the bottom ash has the potential to be used as a substitution to replace sand in the vertical granular column. It reduced the costs of construction and can be put to profitable use.

REINFORCING SOFT CLAY WITH A SINGLE ENCAPSULATED BOTTOM ASH COLUMNS

Preparation of samples

The soft clay was prepared using customised compaction method and the Bottom Ash Columns (BAC) had been installed in the soft clay using the replacement method. The kaolin was air dried and then mixed with 18.2 % of water which is the optimum moisture content of the kaolin obtained from standard compaction test. After uniform mixing of the soil, it was poured into the customized steel mould of 100 mm height and 50 mm internal diameter, and compacted in three layers. Each layer had been compacted with five free fall blows of a customized steel extruder.

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Installation of bottom ash columns

One batch of the kaolin specimen had 2 samples with 50 mm in diameter and 100 mm in height. Each batch of kaolin specimen contains the same penetration ratio, which is 0, 0.6, 0.8 and 1.0, but different number of area replacement ratio. Unconfined Compression Test was applied to test every same penetration ratio for two (2) times to obtain an average value. The sample without any reinforcement of bottom ash, which is of 0 penetration ratio, was considered as the 'controlled sample' to determine the shear strength of unreinforced sample, for each batch of soft clay. Next, in order to prepare for the installation of BAC for the reinforced specimens, the holes for the installation of BAC were drilled using drill bit of respective diameter with the specimens still inside the mould to prevent it from expanding. Since the specimen is soft and sensitive, the process of installation and densification of the bottom ash was very challenging. Through the results of several pilot tests, it was decided that the raining method was the best way to create homogeneous BAC in the clay specimens. Then, all the sample has been encased with geotextile fabric before any experiment conducted on the samples. The Polyester Non-woven Geotextile Needlepunched Fabric (MTS 130) has been chosen to encase the kaolin clay reinforced with bottom ash columns.

There were two (2) different batches of specimens tested as tabulated in with another two batch of specimens installed with geotextile. In order to prevent heave at the surface of the specimen and also to minimize disturbance, replacement method was selected to remove clay and created hole(s) for the bottom ash column to be installed. Figure-1 shows the detailed arrangement of the column(s) with different area replacement ratio.

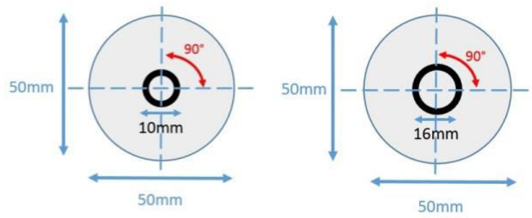

Figure-1. Detailed column(s) arrangement for 4.00 % and 10.24 % of area replacement ratio.

SUMMARY OF KAOLIN, BOTTOM ASH AND GEOTEXTILE

Preparation of samples

A summary of the properties of kaolin clay, bottom ash and geotextile was shown in Table-1.

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Table-1. Summary of kaolin clay properties.

Material	Test	Parameter	Value
Bottom Ash	Soil Classification	AASHTO	A-1-a
	Specific Gravity	Specific Gravity, G_S	2.27
	Standard Compaction	Maximum dry density, $\rho_{d(max)}$	1.65 Mg/m^3
		Optimum moisture content, w_{opt}	21 %
	Shear Strength	Friction Angle	38.83 º
		Cohesion	7.28 kPa
	Constant Head	Permeability	1.59 x 10^{-3} m/sec
Kaolin	Soil Classification	ASSHTO	A-4
		USCS	ML
	Atterberg Limits	Liquid limit, w_L	36.47 %
		Plastic limit, w_P	27.70
		Plasticity Index, I_p	8.3 %
	Specific Gravity	Specific Gravity, GS	2.68
	Standard Compaction	Maximum dry density, $\rho_{d(max)}$	1.65 Mg/m^3
		Optimum moisture content, w_{opt}	18.2%
	Falling Head	Permeability	8.89 x 10^{-12} m/sec
Geotextile	Material	Material	Polyster
	Basic Properties	Unit Weight	130g/m2
		Thickness	1.08mm
	Mechanical Properties	Max. Tensile Strength, MD	10.0 kN/m
		Max. Tensile Strength, CD	9.3 kN/m
		Elongation at Max. Tensile Strength, MD	56.0%
		Elongation at Max. Tensile Strength, CD	84.0%
		CBR puncture strength	2.2 kN/m
		Trapezoid Tearing Strength, MD	350 N
		Trapezoid Tearing Strength, CD	280 N
		Index puncture strength, MD	310.3 N
		Apparent opening size	140 µm
		Vertical permeability	0.27 cm/s
		Grab tensile strength, MD	620.2 N
		Grab tensile strength, CD	668.0 N

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SHEAR STRENGTH

Percentage of shear strength improvement by Unconfined Compression Test (UCT) of all the samples is tabulated in Table-2. The shear strength of singular columns was increased compared to the samples without reinforcement. Besides that, the encapsulated bottom ash column increases the overall shear strength of the samples compared to the samples that without geotextile. For the encapsulated bottom ash columns, the 4.00 % area replacement ratio (10 mm columns diameter), the increase in shear strength are 31.91 %, 65.17 % and 41.66 % while for 10.24 % area replacement ratio (16 mm columns diameter), the increase in shear strength are 26.43 %, 62.15 % and 48.60 % at sample penetration ratio, Hc/Hs of 0.6, 0.8 and 1.0 respectively. For the non-encapsulated bottom ash columns, the 4.00 % area replacement ratio, the increase of shear strength are 19.04 %, 41.21 % and 30.68 %. For 10.24 % area replacement ratio, the improvements in shear strength area are 15.34 %, 31.58 % and 26.54 %, respectively.

Table-2. Shear strength improvement.

Sample	Number of Columns	Column Diameters (mm)	Area Ratio, A_c/A_s (%)	Column Height (mm)	Height Penetrating Ratio, H_c/H_s	Shear Strength, s_u (kPa)	Shear Strength Improvement, Δs_u (%)
Controlled Sample							
C	0	0	0	0	0	8.93	0
Non-Encapsulated Column							
S1060	1	10	4	60	0.6	10.63	19.03
S1080				80	0.8	12.61	41.20
S10100				100	1	11.67	30.68
S1660		16	10.24	60	0.6	10.3	15.34
S1680				80	0.8	11.75	31.58
S16100				100	1	11.3	26.53
Encapsulated Column							
SE1060	1	10	4	60	0.6	11.78	31.91
SE1080				80	0.8	14.75	65.17
SE10100				100	1	12.65	41.66
SE1660		16	10.24	60	0.6	11.29	26.43
SE1680				80	0.8	14.48	62.15
SE16100				100	1	13.27	48.60

*C denotes Controlled Sample
**S denotes Non-Encapsulated Single BAC
***SE denoted Encapsulted Single BAC

The effect of area replacement ratio

Figure-2 shows the graph of shear strength versus area replacement ratio, A_c/A_s. The results show that as the shear strength increases, the diameter of the bottom ash columns increase. The graph shows that the values of the shear strength for area replacement ratio 4.00 % with height penetration ratio (0, 0.6, 0.8, and 1.0) are 8.93 kPa, 10.63 kPa, 12.61 kPa, and 11.67 kPa respectively. Meanwhile, values of the shear strength for area replacement ratio 10.24 % with the same height penetration ratio as previous test are 8.93 kPa, 10.30 kPa, 11.75 kPa, and 11.30 kPa respectively. For the soft clay reinforced with single encapsulated bottom ash columns, the performance of 10.24% for the area replacement ratio in shear strength is greater compare to 4.00% area replacement value thus increased both of the shear strength.

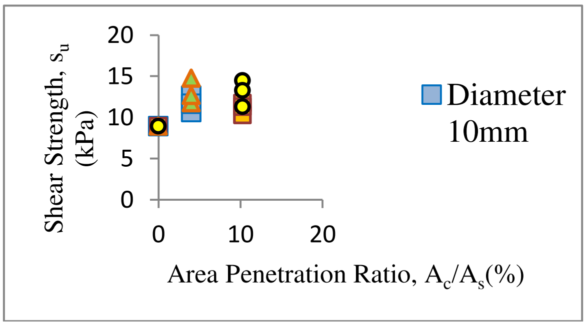

Figure-2. Shear strength versus area replacement ratio.

Based on the result, the trend is similar with the previous study conducted by Tandel *et al.* (2012) and Murugesan *et al.* (2006). They explained that the decrease of the performance is caused by the mobilization of higher confining stress in smaller bottom ash columns. The higher value of confining stresses in the columns causes a higher stiffness of smaller diameter.

Besides that, the results is also similar with the study done by Black *et al.* (2007) and Maakaroun *et al.* (2009) using the sand column had concluded that the degree of improvement of soft clay was influenced by the area of replacement ratio and the height of column over column diameter ratio.

The effect of height penetrating ratio

Figure-3 shows the increment of shear strength at penetration ratio for single bottom ash columns and the single encapsulated bottom ash columns respectively. The result from the graph shows that the sample reinforced with bottom ash column and the encapsulated bottom ash columns is at 0, 0.6, 0.8 and 1.0 for 4.00 % and 10.24% area replacement ratio. As the column length is decreased, the shear strength will increase. The percentage of increment can be considered substantial as the penetration ratio of bottom ash column is increased. The reason of the increase of increment is because of certain portion of soft soil is replaced by stiffer material which is bottom ash. It shows that the improvement of shear strength does not depend on the area replacement ratio but also depend on the penetration ratio of the bottom ash column as well.

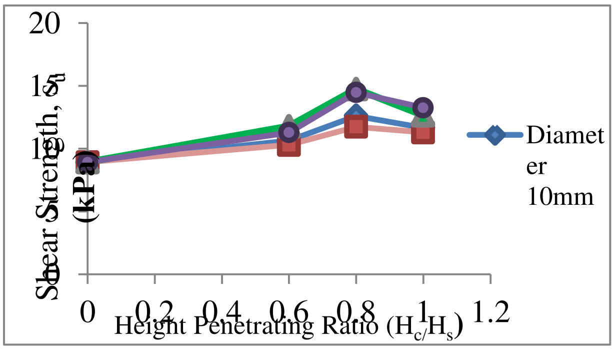

Figure-3. Shear strength versus height of penetration ratio for singular bottom ash columns and singular encased bottom ash columns.

The results shows that the shear strength decrease as the diameter of the bottom ash column decrease for the early after that increase for diameter 10 mm. For the single encapsulated bottom ash columns, the improvement shear strength for height penetration ratio for 0.8 is higher compared to 0.6 for diameter 16 mm. For diameter 16 mm, height penetration ratio for 1.0 mm is greater than 0.6 mm. The result is similar to the study done by Najjar *et al.* (2010) on the encasement of sand column, where the encasement of the sand column does improved the undrained shear strength. According to the study by Marto *et al.* (2013) and Najjar *et al.* (2010), the improvement of shear strength of soft clay installed either bottom ash column and sand column does not merely depends on area replacement ratio, but the penetration ratio as well.

The effect of height over diameter of column

To investigate the possible influence of height over diameter of column ratio to undrained shear strength, a graph of improvement of undrained shear strength was plotted versus the height over diameter of column ratio in Figure-4. For comparison, data by Maakaroun *et al.* (2009) and Marto *et al.* (2014) was plotted on the same figure. As proposed by past researcher like Maakaroun *et al.* (2009), "the critical column length" which is between 4 to 8 times the diameters of column (D_c). The result of Maakaroun *et al.* (2009) and Marto *et al.* (2013) was also plotted on the same graph was marked as the blue area in the Figure for a comparison.

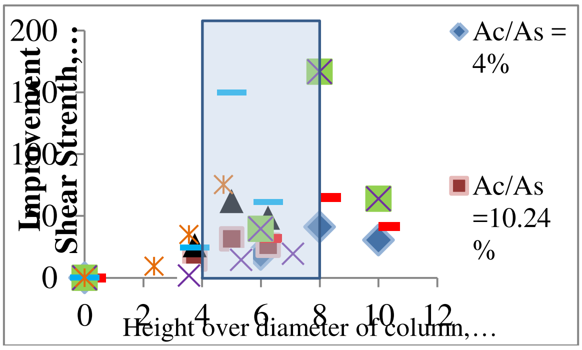

Figure-4. Effect of ratio column height to diameter on shear strength.

The result is in accordance with the hypothesis of a critical column length beyond which the increase in undrained shear strength becomes relatively negligible. Generally, there were higher increases in strength that were spotted for soft clay reinforced with bottom ash column. For area ratio of 4.00 % and 10.24 % the highest improvement of undrained shear strength were when it reached 80mm column height at $8D_c$. The soft clay reinforced with encapsulated bottom ash columns shows some significant improvement compared with the samples that without the encasement. Najjar *et al.* (2010) reported that on his study on encasement of sand column, some disproportionate increase in strength indicates that the improvement in undrained shear strength may not only be a function of the column penetration ratio (H_c/H_s), but also of the ratio of the column height to the column diameter. This dependence studied by other researchers Narasimha Rao *et al.* (1992) who proposed the idea of the critical column length beyond which the column will not have any positive effect on improvements in capacity.

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CORRELATIONS

Figure-5 shows the samples that been encapsulated which the correlation line for sample shear strength versus area replacement ratio of penetration ratio at 4 % and 10.24 %. From the figure, the equation of the correlation is found to be:

$$s_u = -0.0901(A_s/A_c)^2 + 1.3928(A_s/A_c) + 8.93 \quad (1)$$

with the coefficient of determination, $R^2 = 0.7648$.

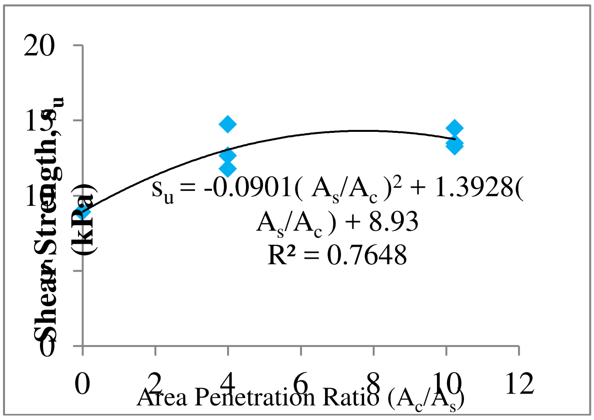

Figure-5. Correlation graph of shear strength with area replacement ratio for soft clay reinforced with single encapsulated bottom ash column.

The correlation line for sample shear strength of bottom ash columns against the height of penetration ratio at 0.6, 0.8 and 1.0 are shown in Figure-6. The projection of correlation plotted on a Δs_u versus H_s/H_c plane. According to the figure, the equation of the correlation is found to be:

$$s_u = 2.9435(H_c/H_s) + 9.0087 \quad (2)$$

with the coefficient of determination, $R^2 = 0.7139$.

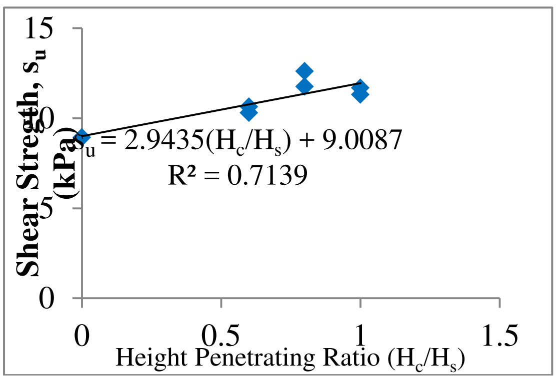

Figure-6. Graph correlation of shear strength versus height of penetration ratio for soft clay reinforced with single bottom ash column.

The value of the correlation line for shear strength of bottom ash columns versus height over diameter of column are shown in Figure-7 at 6, 8 and 10 mm. From the figure, the equation of the correlation is found to be:

$$s_u = 0.2944(H_c/D_c) + 9.0087 \quad (3)$$

with the coefficient of determination, $R^2 = 0.7139$.

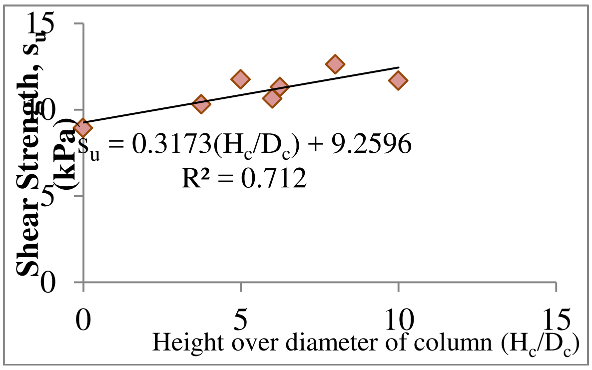

Figure-7. Graph correlation of shear strength versus height over diameter of column for soft clay reinforced with single bottom ash column.

The correlation lines of the samples for deviator stress versus axial strain of the single bottom ash column are shown in Figure-8 at 4.00 % and 10.24 % area replacement. From the figure, the equation of the correlation is found to be:

$$q_u = -6.5733(\varepsilon) + 38.785 \quad (4)$$

with the coefficient of determination, $R^2 = 0.7517$.

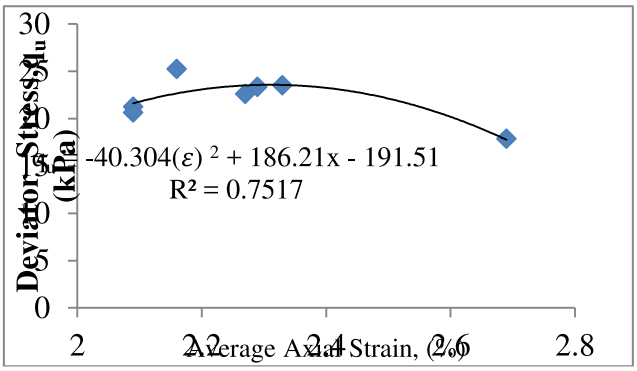

Figure-8. Graph correlation of deviator stress versus axial strain at failure for 4.00% and 10.24% area placement of bottom ash column at different penetration ratio.

Table-3 shows the summary of correlations generated from the study.

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Table-3. Correlations and R^2 value.

Sample	List of correlation equation	Value of R^2
S1060	$s_u = -0.0742(A_s/A_c)^2 + 0.9735(A_s/A_c) + 8.93$	0.6438
SE1060	$s_u = -0.0901(A_s/A_c)^2 +1.3928(A_s/A_c) + 8.93$	0.7648
S1080	$\Delta s_u = 1.6103(A_s/A_c)^2 - 23.864(A_s/A_c) + 100$	0.9224
SE1080	$\Delta s_u = 1.3042(A_s/A_c)^2 - 18.655(A_s/A_c) + 100$	0.6694
S10100	$s_u = 2.9435(H_c/H_s) + 9.0087$	0.7139
SE10100	$s_u = 4.7786(H_c/H_s) + 9.1732$	0.6656
S1060	$\Delta s_u = -63.813(H_c/H_s) + 81.527$	0.5825
SE1060	$\Delta s_u = -43.261(H_c/H_s) + 83.368$	0.3549
S1080	$s_u = 0.4779(H_c/D_c) + 9.1732$	0.6656
SE1080	$s_u = 0.4779(H_c/D_c) + 9.1732$	0.6656
S10100	$\Delta s_u = -6.3813(H_c/D_c) + 81.527$	0.5825
SE10100	$\Delta s_u = 1.2168(H_c/D_c)^2 - 17.91 (H_c/D_c) + 97.880$	0.6746
NEBAC	$q_u= -6.5733(\varepsilon) + 38.785$	0.7517
EBAC	$q_u = -41.406(\varepsilon)^2 + 182.61(\varepsilon) - 172.59$	0.5989

Note: NEBAC - Non Encased Bottom Ash Column
EBAC - Encased Bottom Ash Column

CONCLUSIONS

This paper examined the shear strength improvement of soft clay specimens reinforced with encapsulated single BAC. The conclusions that can be drawn are as follows:

- The presence of BAC has greatly increased shear strength of kaolin together with the increment in shear strength. The encasement of BAC significantly improved the overall shear strength of the specimens.

- The improvement of the shear strength is not only depends on the area replacement ratio, but the penetration ratio of the bottom ash column as well. The percentage of increment can be considered substantial as the penetration ratio of BAC is increased. The reason of the increase of increment is because of certain portion of soft soil is replaced by stiffer material which is bottom ash. It is because for higher penetration, the load was very near imposed on the BAC at both ends while for partially penetration column only one end of BAC is exposed directly to the load and for the other one is cover partly by the soft clay.

- The “critical column length” that obtained from the result is in range of between 4 to 8 times of the diameter of the column. The column could not sustained excessive loads beyond the critical column length, attributed to the brittle nature of the bottom ash, thus the probability of failure would be higher beyond this critical length.

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