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SHEAR STRENGTH OF SOFT CLAY REINFORCED WITH SINGLE ENCASED STONE DUST COLUMNS

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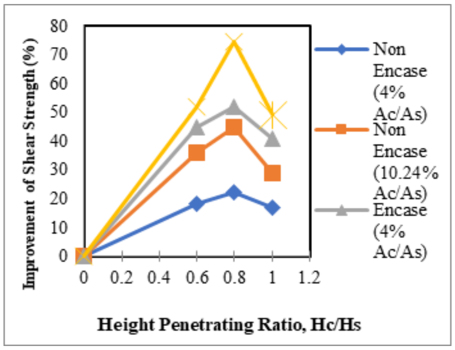
Graphical abstract



Abstract

The application of stone columns, which can improve the overall carrying capacity of soft clay as well as lessen the settlement of buildings built on it, is among the most widespread ground improvement techniques throughout the globe. The performance of foundation beds is enhanced by their stiffness values and higher strength, which could withstand more of the load applied. Therefore, the cost of construction can be decreased by using recycled stone dust as granular material in vertical granular columns, which can then be strengthened with a singular stone dust column that is covered in geotextile for enhancing soft clay's overall strength. A further unconfined compression test was performed on remolded specimens of soft kaolin clay measuring 50 mm in diameter and 100 mm in height and mounted with a single encapsulated stone dust column measuring 10 mm and 16 mm in diameter. Test results show that when kaolin is implanted with a single encased stone dust column that has an area replacement ratio of 10.24% and penetration ratios of 0.6, 0.8, and 1.0, the shear strength increases are 51.75%, 74.5%, and 49.20%, respectively. The equivalent shear strength increases are 48.50%, 68.50%, and 43.50% for soft soil treated with a 12.00% area replacement ratio and 0.6, 0.8, and 1.0 penetration ratios, respectively. The diameter and height of the column had an impact on the shear strength parameters, which significantly improved for both encased and non-encased stone dust columns.

Keywords: Soft Soil, Stone dust column, Shear strength, UCS

Abstrak

Penggunaan tiang batu, yang boleh meningkatkan kapasiti tampung keseluruhan tanah liat lembut serta mengurangkan penempatan bangunan yang dibina di atasnya, adalah antara teknik pembaikan tanah yang paling meluas di seluruh dunia. Prestasi katil asas dipertingkatkan dengan nilai kekukuhan dan kekuatan yang lebih tinggi, yang boleh menahan lebih banyak beban yang dikenakan. Oleh itu, kos pembinaan boleh dikurangkan dengan menggunakan habuk batu kitar semula sebagai bahan berbutir dalam lajur berbutir menegak, yang kemudiannya boleh diperkukuh dengan lajur habuk batu tunggal yang diliputi dalam geotekstil untuk meningkatkan kekuatan keseluruhan tanah liat lembut. Ujian mampatan tidak terkurung selanjutnya dilakukan pada spesimen yang dibentuk semula dari tanah liat kaolin lembut berukuran 50 mm diameter dan 100 mm tinggi dan dipasang dengan satu lajur habuk batu berkapsul berukuran 10 mm dan 16 mm diameter. Keputusan ujian menunjukkan bahawa apabila kaolin ditanam dengan tiang habuk batu bersalut tunggal yang mempunyai nisbah penggantian kawasan 10.24% dan nisbah penembusan 0.6, 0.8, dan 1.0, peningkatan kekuatan ricih adalah 51.75%,

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74.5%, dan 49.20%, masing-masing. Peningkatan kekuatan ricih setara ialah 48.50%, 68.50%, dan 43.50% untuk tanah lembut yang dirawat dengan nisbah penggantian kawasan 12.00% dan nisbah penembusan 0.6, 0.8, dan 1.0. Diameter dan ketinggian lajur mempunyai kesan ke atas parameter kekuatan ricih, yang bertambah baik dengan ketara untuk kedua-dua tiang habuk batu bersarung dan tidak bersarung.

Kata kunci: Tanah Lembut, Lajur debu batu, Kekuatan ricih, UCS

1.0 INTRODUCTION

Construction over unstable ground, like soft clay, can impact the stability and settlement of the structure. The qualities of soft clay can be improved using a variety of ground improvement techniques, including vibrated granular columns, preloading, sand columns, sand drains, stone columns, and piling.

The original foundational system design, geotextile-encased columns (GECs), has been widely used and is well-accepted throughout practical application [1-5]. Identical approaches focused on geogrid encasing as possibly stiffer and more resilient alternatives to geotextile have been developed and investigated lately in order to demonstrate the overall usefulness of geosynthetic encasement and also to enhance design processes [5-7].

The increment of the load-carrying capacity of soft soils as well as the reduction of the superstructure's settlement are two of the most widely employed soil improvement techniques in the world [8, 9]. Because of their greater stiffness and strength, stone columns behave substantially better than other types of columns, which can sustain more of the imposed weight [10].

Stone dust is a much darker and coarser version of sand. It is made in a quarry just like sand by putting stones through a crushing process, with the exception that it takes much less time. Whenever stone or gravel is artificially crushed to produce coarse aggregate, this is generated in crusher factories as waste. Such garbage is currently just thrown away in landfills and not repurposed in any way [11-13].

Stone dust is typically employed in the demineralization of soils, despite the fact that the idea of making stone dust may appear unusual. The majority of micro minerals in soils come from ground-up stone, particularly basalt, granite, volcanic rock, and similar rocks. Although it can be effective on virtually any soil, this substance is particularly excellent at rebuilding worn-out soils. One must first have the right stone on hand. Glacial till, as well as new or ancient andesite, lavas, or volcanic ash, are abundant. However, a variety of minerals must be present in the stones utilized. The production of rock dust also has additional drawbacks, such as the excessive expense of the equipment [14] and the energy needed during crushing [15]. The tumblers fueled by water that are employed to polish specific rocks for jeweler could serve as a substitute. Small water wheels are typically installed on massive, heavy plastic cylinders, including an axil, on a stream with a good fall. They are jam-packed with a wide variety of mineral-rich rocks. As they rotate and tumble, the encased rocks are reduced to rock dust. This benefits the soil it is applied to in a variety of ways. The individual or group that generates the dust may use it themselves or sell it to others. A few pieces of charcoal added to the drum will optimize the benefits to the treated soil because charcoal encourages the growth of soil microbes.

Recycling and the use of coal ash have drawn a lot of attention in the building industry in order to meet the present concern towards long-term as well as sustainable growth across Europe and to lower overall expenses associated with waste management. As per Kumar and Stewart [16], sand and stone dust have qualities that are almost comparable. As a result, bottom ash may be used in the vertical granular column in place of sand [17-20]. It reduces construction costs and can be used productively [21, 22].

2.0 METHODOLOGY

2.1 Reinforcing Through Singular Stone Dust Columns

2.1.1 Specimen Making

Stone Dust Columns (SDC) were placed into clay by employing a replacement method after the soft clay had been prepared using a customized compaction technique. After being air dried, the kaolin was mixed with 19.2% water, the appropriate water content for kaolin as measured by a compaction test in accordance with industry guidelines. The soil was thoroughly blended prior to being placed into a specifically designed metal mold having an inner diameter of 50 mm and a height of 100 mm, where it was subsequently compressed into 3 levels. Every layer had indeed been compressed using five free-falling strokes from an innovative metal extruder.

2.1.2 Stone Dust Column Installation

Two samples measuring 50 mm in diameter and 100 mm in height were included in one batch of the kaolin specimen. The sample contains no stone dust reinforcement as the 0 penetration, 60 mm of stone dust reinforcement as the 0.6 penetration, 80 mm of stone dust reinforcement as the 0.8 penetration, and 100 mm of stone dust reinforcement as the 1.0 penetration. The penetration ratios in each batch of kaolin specimens are 0, 0.6, 0.8, and 1.0, however the area replacement ratios vary. Every penetrating proportion was tested twice using the unconfined compression test to come up with an average result. For each batch of soft clay, the shear strength of the unreinforced sample, which has a penetration ratio of 0, was ascertained by using the sample with no stone dust reinforcement as the "controlled sample." Then, employing drill bits with the proper size, holes were created for the insertion of SDC reinforced samples whereas the samples were still within the mold for preventing this from spreading. Placement as well as compression of the stone dust proved to be exceedingly difficult because the specimen is delicate and mushy. According to the findings of numerous preliminary experiments, it was established that the raining technique constituted the most efficient way to create uniform SDC inside the clay samples. Before any experiment was performed on the samples, each sample was enclosed in geotextile fabric. The encasing material for the kaolin clay reinforced with stone dust columns have been selected as polyester non-woven geotextile needle punched fabric (MTS 130).

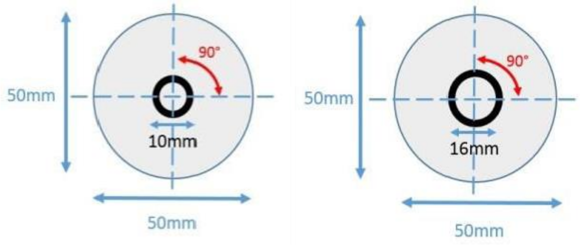

Figure 1 Complete column arrangements for the area replacement ratios of 4.00% and 10.24%

As a result, testing was performed on two (2) mixtures of samples, including two more sets of samples with inserted geotextile. The replacement approach was chosen for removing the clay and building the cavities needed to install the column in order to prevent heaving at the specimen's surface and cause the least amount of disturbance. The exact layout of the column(s) featuring different area replacement ratios is shown in Figure 1.

3.0 RESULTS AND DISCUSSION

3.1 Summary of Sample Properties

Table 1 provides an overview of the characteristics of stone dust, geotextile, and kaolin clay.

3.2 Shear Strength

Table 2 displays the overall proportion of shear strength gains including all specimens in the unconfined compression test (UCT). The shear strength of the latter was significantly enhanced when compared to specimens lacking reinforcements and single columns. The contained column of stone dust also increases the specimens' total shear strength in comparison to those with no geotextile. For the encapsulated stone dust columns, shear strength increases by 44.95%, 51.95%, and 40.90% for 10 mm dia. columns having the 4.00% area replacement ratio, and by 51%, 75%, 74.50%, and 49.20% for 10 mm dia. columns having the 10.24% area replacement ratio at Hc/Hs of 0.6, 0.8, and 1.0, respectively. The increases in shear strength for the stone dust columns that are not encased are 4.00% area replacement ratio, 18.00%, 22.20%, and 17.00%. The improvements in shear strength area for a 10.24% area replacement ratio are 36.00%, 45.00%, and 28.50%, respectively.

3.3 Area Replacement Ratio's Impact

Figure 2 displays shear force against the area replacement ratio, Ac/As. It can be observed that as the bottom ash columns' diameter increases, the shear stress rises. With an area replacement ratio of 4.00% and a height penetration ratio of 0, 0.6, 0.8, and 1.0, respectively, the figure indicates that the shear strength values are 12.75 kPa, 18.48 kPa, 19.22 kPa, and 17.97 kPa. The shear strength results for a 10.24% area replacement ratio while maintaining the same penetrating proportion as that of the prior experiment were 12.75 kPa, 19.54 kPa, 22.25 kPa, and 19.02 kPa. Overall shear strengths were improved significantly by 10.24% in area replacement ratio and by 4.00% for the soft clay strengthened with a single encapsulating stone dust column.

Table-1 Detailed characteristics of stone dust, kaolin clay and geotextile

Name	Experiment	Specification	Value
Stone Dust	Soil Categorization	AASHTO	A-1-a
	Standard Compaction	Maximum dry density, Ρd(max)	1.65 Mg/m^3
		Optimum moisture content,Wopt	21 %
	Shear Strength	Friction Angle	36.62 °
		Cohesion	7.28 kPa
	Specific Gravity	GS	2.27
	Constant Head	Permeability	1.59 x 10^{-3} m/sec
Kaolin	Soil Categorization	ASSHTO	A-4
		USCS	ML
	Atterberg Limits	Liquid limit, w_L	36.50 %
		Plastic limit, w_P	26.70
		Plasticity Index, I_p	9.80 %
	Specific Gravity	G_S	2.60
	Standard Compaction	Maximum dry density, $Ρ_d$(max)	1.65 Mg/m^3
		Optimum moisture content,W_{opt}	19.2%
	Falling Head	Permeability	8.89 x 10^{-12} m/sec
Geotextile	Material type	-	Polyster
	Basic Properties	Unit Weight	130g/m^2
		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

Table-2 The variations in Shear strength characteristics

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	12.75	0
Non-Encapsulated Column							
NE1060	1	10	4	60	0.6	15.05	18.00
NE1080				80	0.8	15.58	22.20
NE0100				100	1	14.91	17.00
NE1660		16	10.24	60	0.6	17.34	36.00
NE1680				80	0.8	18.49	45.00
NE16100				100	1	16.29	28.50
Encapsulated Column							
E1060	1	10	4	60	0.6	18.48	44.95
E1080				80	0.8	19.22	51.95
E10100				100	1	17.97	40.90
E1660		16	10.24	60	0.6	19.35	51.75
E1680				80	0.8	22.25	74.50
E16100				100	1	19.02	49.20

Where, C = Controlled Sample, NE = Non-Encapsulated Single SDC and E = Encapsulated Single SDC

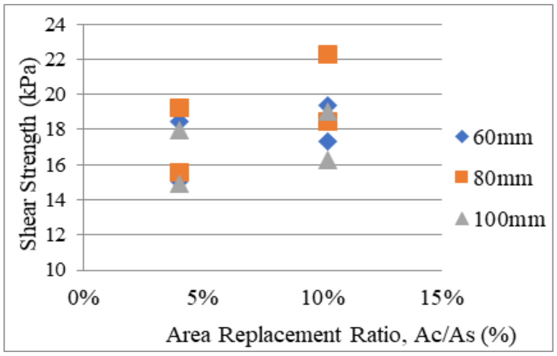

Figure 2 Shear strength versus area replacement ratio

According to the findings, the trend is consistent with earlier research by Tandel, *et al*. [23] and Murugesan and Rajagopal [24] in which how greater confining stress mobilize in smaller stone dust columns and what is responsible for the decline in performance was outlined. A higher stiffness of smaller diameter results from the columns' higher value of confining stresses.

The findings also support research conducted by Sivakumar and Black [25] and Maakaroun, *et al*. [26] who came up with the conclusion that soft clay improvement was impacted by the area replacement ratio as well as the proportion of column height over diameter.

3.4 The Effect of Height Penetrating Ratio

Figure 3 depicts, for single stone dust columns and single enclosed stone dust columns, the incremental shear strength and penetration ratio, respectively. The graph's outcome reveals that the area replacement ratios for the specimen strengthened using a stone dust column and the enclosed stone dust columns are respectively 4.00% and 10.24%. The shear strength will increase as the column length decreases. The percentage increase might be regarded as significant when the stone dust column's penetration ratio rises. The increase is caused by the replacement of some of the soft soil with stone dust, a harder substance. It demonstrates that an increase in shear strength depends not only on the penetrating proportion but also on the area replacement ratio of the stone dust column.

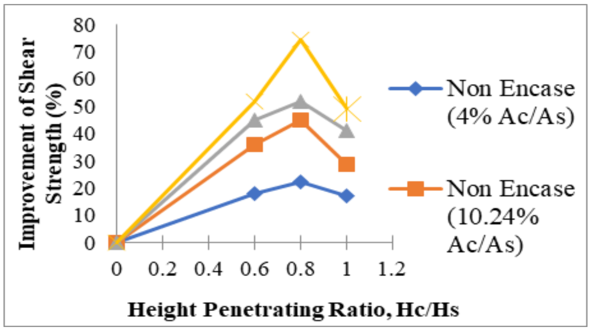

Figure 3 Shear strength against height of penetration ratio for single-stone-dust columns and single encased stone dust columns

As it can be observed that for stone dust column diameters greater than 10 mm, the shear strength falls as the column diameter grows. Regarding single encapsulated stone dust columns with 16 mm diameter, the improved shear strength for a height penetrating proportion of 0.8 is more than that of 0.6. The height penetrating proportion for a 16 mm diameter is higher than 0.6 mm at 1.0 mm. The results are analogous to those of a study on the encasement of a sand column conducted by Najjar, *et al*. [27], which discovered that the undrained shear strength was raised by encasing the sand column. As per the studies by Marto, *et al*. [28] and Najjar, *et al*. [29], the enhancement of soft clay's shear strength when paired with either stone dust columns or sand columns relies upon both the area replacement ratio and also the penetrating proportion.

3.5 The Effect of Height Over Diameter of Column

Figure 4 depicts the increase in undrained shear strength versus the height/diameter proportion for the purpose of examining any achievable impact of such a proportion on undrained shear strength. Marto, *et al*. [20] and Maakaroun, *et al*. [26] data were compared side by side. The "essential column length," as determined by earlier studies like Najjar, *et al*. [27], is 4–8 times the column diameter (Dc). The results from [20, 26] were represented by the blue area on a similar chart to compare.

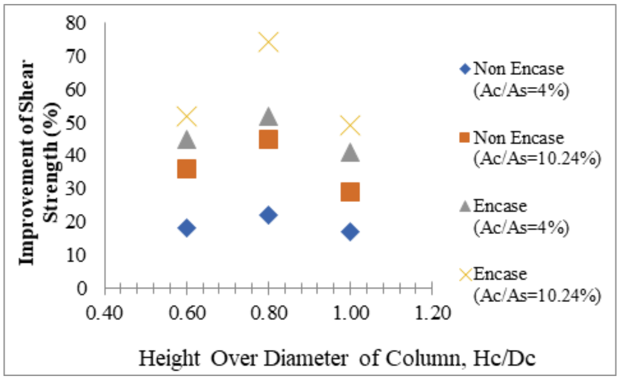

Figure 4 Effect of ratio column height to diameter on shear strength

The findings support the theory that undrained shear strength increases only slightly beyond a critical column length. In general, columns made of soft clay and stone dust increased in strength. For area replacement ratios of 4.00% and 10.24%, overall undrained shear strength rose more noticeably whenever it approached 80mm column height around 8Dc. Comparing specimens with and without the encasement, the soft clay supplemented with enclosed stone dust columns shows some appreciable enhancement.

Najjar, *et al*. [27] proposed that the enhancement in undrained shear strength could rely upon this column height to diameter ratio as well as the the column penetrating proportion (Hc/Hs). In their study of this relationship, Fernández-Ruiz, *et al.* [30] suggested critical column length, above which the columns is unlikely to have any favorable impacts upon efficiency gains.

3.6 Corelations

Figure 5 displays the contained specimens as well as the relationship line among specimen shear strength with area replacement ratio considering penetrating ratios of 4% and 10.24%. From the graph, the relationship formula may be inferred as follow:

$$S_U = -0.2026(A_C/A_S)^2+2.5927(A_C/A_S)+12.84 \quad (1)$$

Where $R^2 = 0.7304$

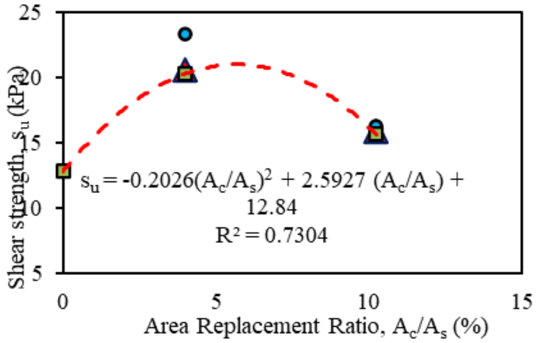

Figure 5 Shear strength and area replacement proportion relationship chart for soft clay reinforced with a single encased stone dust column

The relationship between height of penetrating proportion and the specimen shear strength of stone dust columns is shown in Figure 6 at 0.6, 0.8, and 1.0. A S_U vs Hs/Hc plane with the correlation projection plotted on it. The correlation equation is discovered to be as follows, as shown in the figure:

$$S_U = 7.5321(H_C/H_S) + 13.636 \quad (2)$$

Where $R^2 = 0.8366$

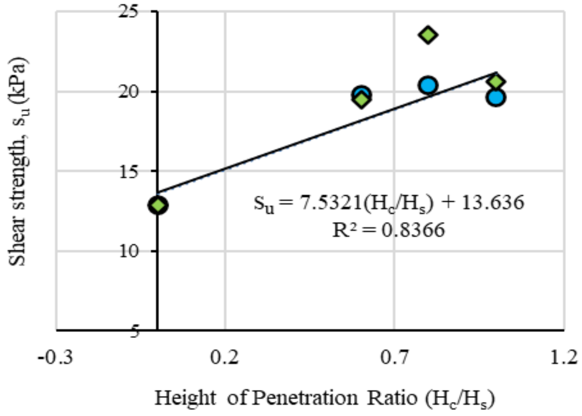

Figure 6 Shear strength against height of penetrating proportion diagram for soft clay strengthened with a single stone dust column

In Figure 7, the relationship curve for the shear strength vs height/diameter are displayed at 6, 8, and 10 mm. The formula for the relationship can be deduced from the illustration as follows:

$$S_U = 6.3143 (H_C/D_C) + 13.721 \quad (3)$$

Where $R^2 = 0.5039$

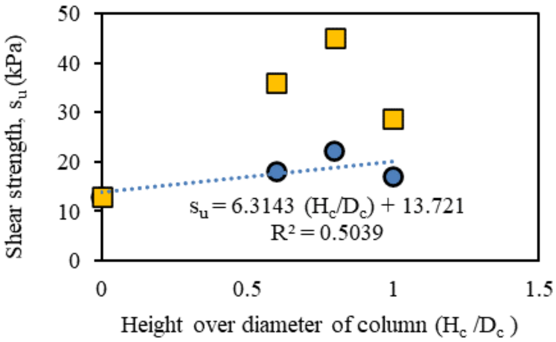

Figure 7 The shear strength vs the height over the column's diameter for soft clay reinforced with singular stone dust column

Figure 8 displays the specimens' relationship curve of deviator stress vs axial strain with area replacements of 4.00% and 10.24% for the single stone dust column. The correlated formula can be deduced from the figure as follows:

$$q_U = -6.3755\varepsilon + 36.441 \quad (4)$$

Where $R^2 = 0.8120$.

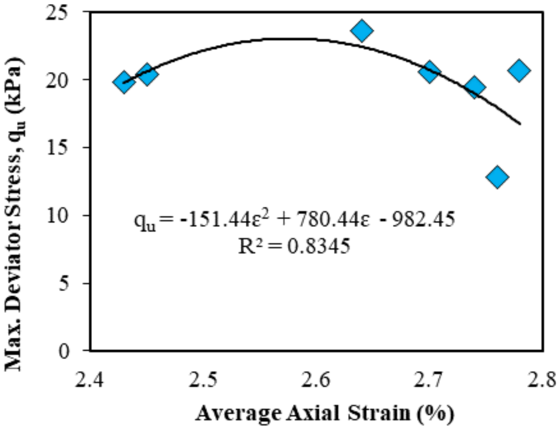

Figure 8 The relationship between deviator stress and axial strain at failure for stone dust columns placed in areas with varying penetration ratios (4.00% and 10.24% respectively)

The overview of relationships derived from the study is shown in Table 3.

Table 3 The correlations and R^2 value of different specimens

Specimen name	Formula of correlation	R^2
NE1060	$Su = -0.1496(Ac/As)^2 + 2.2933(Ac/As) + 12.84$	0.6906
E1060	$Su = -0.2026(Ac/As)^2 + 2.5927(Ac/As) + 12.84$	0.7304
NE1080	$\Delta S_u = -0.8512(Ac/As)^2 + 13.395(Ac/As) + 12.84$	0.5892
E1080	$\Delta Su = -1.677(Ac/As)^2 + 18.063(Ac/As) + 12.84$	0.6156
NE10100	$Su = 7.5321(Hc/Hs) + 13.636$	0.8366
E10100	$Su = 3.2214(Hc/Hs) + 13.232$	0.7891
NE1060	$\Delta Su = 58.657(Hc/Hs) + 6.1982$	0.8366
E1060	$\Delta Su = 25.086(Hc/Hs) + 3.0536$	0.7892
NE1080	$Su = 6.3143(Hc/Dc) + 13.721$	0.5039
E1080	$Su = 34.011(Hc/Dc) + 17.254$	0.7329
NE10100	$\Delta Su = 49.177(Hc/Dc) + 6.8647$	0.5039
E10100	$\Delta Su = -554.9(Hc/Dc)^2 + 788.07(Hc/Dc) - 2.091$	0.9705
NESDC	$q_u = -6.3755\varepsilon + 36.441$	0.8120
ESDC	$q_u = -151.44\varepsilon^2 + 780.44\varepsilon - 982.45$	0.8345

Note: NESDC – Non Encased Stone Dust Column
ESDC - Encased Stone Dust Column

4.0 CONCLUSION

The shear strength improvement of soft clay incorporating encapsulated stone dust columns was looked into in this study. The following are the conclusions that can be decided to make:

Along with the shear strength increment, the presence of a stone dust column has significantly boosted kaolin's shear strength. The specimens' overall shear strength was greatly increased by the inclusion of a stone dust column.

The test results show that when kaolin is implanted with a single encased stone dust column that has an area replacement ratio of 10.24% and penetration ratios of 0.6, 0.8, and 1.0, the shear strength increases are 51.75%, 74.5%, and 49.20%, respectively. The equivalent shear strength increases are 48.50%, 68.50%, and 43.50% for soft soil treated with a 12.00% area replacement ratio and 0.6, 0.8, and 1.0 penetration ratios, respectively.

Improvements in shear strength are influenced by both the stone dust column penetration ratio and the area replacement ratio. Whenever the stone dust column's penetration ratio rises, the percentage increase might be regarded as significant. The replacement of the soft soil with stone dust, a stiffer material, is the cause of the increase in increment. It's because the weight was applied to the stone dust column at both ends when penetration was higher; when penetration was lower, only the column's one side was exposed to the load while the remainder was partially obscured by soft clay.

The "critical column length" that was determined by the outcome ranges from 4 to 8 times the column's diameter. Due to the brittle nature of the stone dust, the column could no longer sustain extreme pressures, raising the risk of failure increased beyond this length.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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References

[1] M. Raithel and H.-G. Kempfert. 2000. Calculation Models for Dam Foundations with Geotextile Coated Sand Columns. *ISRM International Symposium*. OnePetro.
[2] N. Aarthi, A. Boominathan, and S. Gandhi. 2022. Experimental Study on the Behaviour of Sand Compaction Columns in Sandy Strata. *International Journal of Geotechnical Engineering*. 16(5): 641-654. Doi: https://doi.org/10.1080/19386362.2019.1710391.
[3] M. Raithel, A. Kirchner, C. Schade, and E. Leusink. 2005. Foundation of Constructions on Very Soft Soils with Geotextile Encased Columns-state of the Art. *Innovations in Grouting and Soil Improvement*. 1-11. Doi: https://doi.org/10.1061/40783(162)20.
[4] D. Alexiew, D. Brokemper, and S. Lothspeich. 2005. Geotextile Encased Columns (GEC): Load Capacity, Geotextile Selection and Pre-design Graphs. *Contemporary Issues in Foundation Engineering*. 1-14. Doi: https://doi.org/10.1061/40777(156)12.
[5] C. Yoo and S.-B. Kim. 2009. Numerical Modeling of Geosynthetic-encased Stone Column-reinforced Ground. *Geosynthetics International*. 16(3): 116-126. Doi: https://doi.org/10.1680/gein.2009.16.3.116.
[6] V. Sivakumar, D. McKelvey, J. Graham, and D. Hughes. 2004. Triaxial Tests on Model Sand Columns in Clay. *Canadian Geotechnical Journal*. 41(2): 299-312. Doi: https://doi.org/10.1139/t03-097.
[7] S. K. Dash and M. C. Bora. 2013. Influence of Geosynthetic Encasement on the Performance of Stone Columns Floating in Soft Clay. *Canadian Geotechnical Journal*. 50(7): 754-765. Doi: https://doi.org/10.1139/cgj-2012-0437.
[8] M. Dheerendra Babu, S. Nayak, and R. Shivashankar. 2013. A Critical Review of Construction, Analysis and Behaviour of Stone Columns. *Geotechnical and Geological Engineering*. 31: 1-22. Doi: https://doi.org/10.1007/s10706-012-9555-9.
[9] S. Murugesan and K. Rajagopal. 2007. Model Tests on Geosynthetic-encased Stone Columns. *Geosynthetics International*. 14(6): 346-354. Doi: https://doi.org/10.1680/gein.2007.14.6.346.

[10] J. Hughes, N. Withers, and D. Greenwood. 1975. A Field Trial of the Reinforcing Effect of a Stone Column in Soil. *Geotechnique*. 25(1): 31-44. Doi: https://doi.org/10.1680/geot.1975.25.1.31.

[11] B. O. Ahmed, M. Inoue, and S. Moritani. 2010. Effect of Saline Water Irrigation and Manure Application on the Available Water Content, Soil Salinity, and Growth of Wheat. *Agricultural Water Management*. 97(1): 165-170. Doi: https://doi.org/10.1016/j.agwat.2009.09.001.

[12] S. Cheik, P. Jouquet, J. L. Maeght, Y. Capowiez, T. Tran, and N. Bottinelli. 2021. X-ray Tomography Analysis of Soil Biopores Structure under Wetting and Drying Cycles. *European Journal of Soil Science*. 72(5): 2128-2132. Doi: https://doi.org/10.1111/ejss.13119.

[13] M. I. Hoque, M. H. Kabir, and T. Rahman. 2018. Engineering Properties and Cost Comparison among Sylhet Sand, Khustia Sand and Local Sand in the Context of Foundation Engineering. *Journal of Advance in Geotechnical Engineering*. 1(2).

[14] R. Ilangovana, N. Mahendrana, and K. Nagamanib. 2008. Strength and Durability Properties of Concrete Containing Quarry Rock Dust as Fine Aggregate. *ARPN Journal of Engineering and Applied Sciences*. 3(5): 20-26, Doi: 10.21275/24041805.

[15] P. Van Straaten. 2006. Farming with Rocks and Minerals: Challenges and Opportunities. *Anais da Academia Brasileira de Ciências*. 78: 731-747. Doi: https://doi.org/10.1590/S0001-37652006000400009.

[16] S. Kumar and J. Stewart. 2003. Utilization of Illinois PCC Dry Bottom Ash for Compacted Landfill Barriers. *Soil and Sediment Contamination*. 12(3): 401-415. Doi: https://doi.org/10.1080/713610980.

[17] M. Hasan, K. H. Yee, M. F.-h. A. J. Pahrol, and M. Hyodo. 2019. Shear Strength of Soft Clay Reinforced with Encased Lime Bottom Ash Column (ELBAC). *GEOMATE Journal*. 16(57): 62-66. Doi: https://doi.org/10.21660/2019.57.4644.

[18] R. Moradi. 2016. Physical and Numerical Modelling of Bottom Ash Columns Installed in Soft Soil. Universiti Teknologi Malaysia.

[19] M. Hasan, W. N. W. Jusoh, W. S. Chee, and M. Hyodo. 2018. The Undrained Shear Strength of Soft Clay Reinforced with Group Encapsulated Lime Bottom Ash Columns. *GEOMATE Journal*. 14(46): 46-50. Doi: https://doi.org/10.21660/2018.46.45208.

[20] A. Marto, M. Hasan, M. Hyodo, and A. M. Makhtar. 2014. Shear Strength Parameters and Consolidation of Clay Reinforced with Single and Group Bottom Ash Columns. *Arabian Journal for Science and Engineering*. 39: 2641-2654. Doi: https://doi.org/10.1007/s13369-013-0933-2.

[21] P. Das and S. K. Pal. 2013. A Study of the Behavior of Stone Column in Local Soft and Loose Layered Soil. *EJGE*. 18: 1777-17786.

[22] M. Mokhtari and B. Kalantari. 2012. Soft Soil Stabilization using Stone Column--A Review. *Electronic Journal of Geotechnical Engineering*. 17: 1459-1466.

[23] Y. Tandel, C. Solanki, and A. Desai. 2013. Laboratory Experimental Analysis on Encapsulated Stone Column. *Archives of Civil Engineering*. 359-379. Doi: https://doi.org/10.2478/ace-2013-0020.

[24] S. Murugesan and K. Rajagopal. 2006. Geosynthetic-encased Stone Columns: Numerical Evaluation. *Geotextiles and Geomembranes*. 24(6): 349-358. Doi: https://doi.org/10.1016/j.geotexmem.2006.05.001.

[25] V. Sivakumar and J. Black. 2007. A Laboratory Model Study of the Performance of Vibrated Stone Columns in Soft Clay.

[26] T. Maakaroun, S. S. Najjar, and S. Sadek. 2009. Effect of Sand Columns on the Load Response of Soft Clays. *Contemporary Topics in Ground Modification, Problem Soils, and Geo-Support*. 217-224. Doi: https://doi.org/10.1061/41023(337)28.

[27] S. S. Najjar, S. Sadek, and T. Maakaroun. 2010. Effect of Sand Columns on the Undrained Load Response of Soft Clays. *Journal of Geotechnical and Geoenvironmental Engineering*. 136(9): 1263-1277. Doi: https://doi.org/10.1061/(ASCE)GT.1943-5606.0000328.

[28] A. Marto, N. Latifi, and H. Sohaei. 2013. Stabilization of Laterite Soil using GKS Soil Stabilizer. *Electronic Journal of Geotechnical Engineering*. 18(18): 521-532.

[29] M. Najjar, A. M. Soliman, and M. L. Nehdi. 2014. Critical Overview of Two-stage Concrete: Properties and Applications. *Construction and Building Materials*. 62: 47-58. Doi: https://doi.org/10.1016/j.conbuildmat.2014.03.021.

[30] J. Fernández-Ruiz, M. Miranda, J. Castro, and L. M. Rodríguez. 2021. Improvement of the Critical Speed in High-speed Ballasted Railway Tracks with Stone Columns: A Numerical Study on Critical Length. *Transportation Geotechnics*. 30: 100628. Doi: https://doi.org/10.1016/j.trgeo.2021.100628.