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RESEARCH ARTICLE

Bearing Capacity of Footing on Soft Clay Strengthened by Lightweight Expanded Clay Aggregate Raft

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ABSTRACT - This research represents an investigation into the effectiveness of replacement methods to increase the bearing capacity of soft clays under footing load, where Light Expanded Clay aggregates (LECA) were used as a substitute for common aggregate fillers. The soil replacement technique is the easiest and cheapest way to improve soft soil compared to installing a raft footing or using a deep foundation such as piles. LECA is known to be light, strong and environmentally sustainable and is widely used in Geotechnical applications where weight is an issue. The bearing capacity of the footing on soft soil reinforced by LECA was analysed through finite element analysis using commercial software PLAXIS 3D (2020). The soft ground is represented by Hardening Soil (HS) constitutive model, while LECA has been modelled as Mohr-Coulomb (MC). Parametric studies were conducted to assess the effect of LECA raft thickness to bearing capacity improvement for various friction angles of LECA. The research found that the bearing capacity is directly proportional to the internal friction angle of LECA and the LECA raft thickness. Nevertheless, the bearing capacity appears to be almost linear when 2.5 m and 3.5 m thick LECA rafts are used, indicating that the depth of replacement ratio more than 25% give insignificant effect towards improvement ratio.

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1.0 INTRODUCTION

Development on soft ground has become one of the construction industry's most significant issues, particularly in the field of geotechnical engineering. Due to soft soil's poor shear resistance and high compressibility, various technical issues such as slope instability, bearing capacity failure or excessive settlement may occur during or after construction. The bearing capacity of soil refers to its ability to withstand the loads applied to the land above. It is mostly determined by the type of soil, its shear strength, and density. Additionally, it is dependent on the load's embedment depth where the deeper the load is embedded, the larger the bearing capacity. Where the carrying capacity of the ground is insufficient, the ground can be upgraded or the load can be dispersed over a larger area, reducing the applied stress on the soil to a level that is acceptable but less than the bearing capacity

Several ground improvement methods have been used in practice. In the case of clay deposits, accelerating consolidation through installation of sand drains or PWD and chemical means have gained acceptance. In the case of loose sand deposits, densification through the installation of compaction sand piles or stone columns is a widely adopted technique. The traditional approach to soil improvement is to replace poor soil with better soil. However, replacing the entire weak zone is impractical due to high costs and environmental restrictions on recent mining and reclamation. Considering the above factors, selective replacement in the most desired zones is a realistic solution. The idea is replacing poor soil (e.g., medium to heavy clay and fertile soil) with more qualified materials such as sand, gravel, or other appropriate granular materials. In general, the assessment of soil thickness is based on experience, which is not certain. However, the thickness of the replaced zone should be deeper than 0.5 meters, with the size of the replacement zone depending on the problem to be mitigated [1].

Lawton [2] suggested replacement zone length and/or breadth of 1 to 3 footing widths and a thickness of 0.5 to 1.5 footing widths to improve the bearing capacity and reduce settlement of a footing on a soft soil. This troublesome soil behaviour can be remedied by completely or partially replacing the insufficient soils with layers of compacted granular fill. The complete replacement is performed to raise the bearing capacity and minimise settlement, whereas the partial replacement is performed primarily to improve the side slope's stability [3]. As seen in Figure 1, [4] recommended full and partial repair of soft soil beneath an embankment constructed on soft soil.

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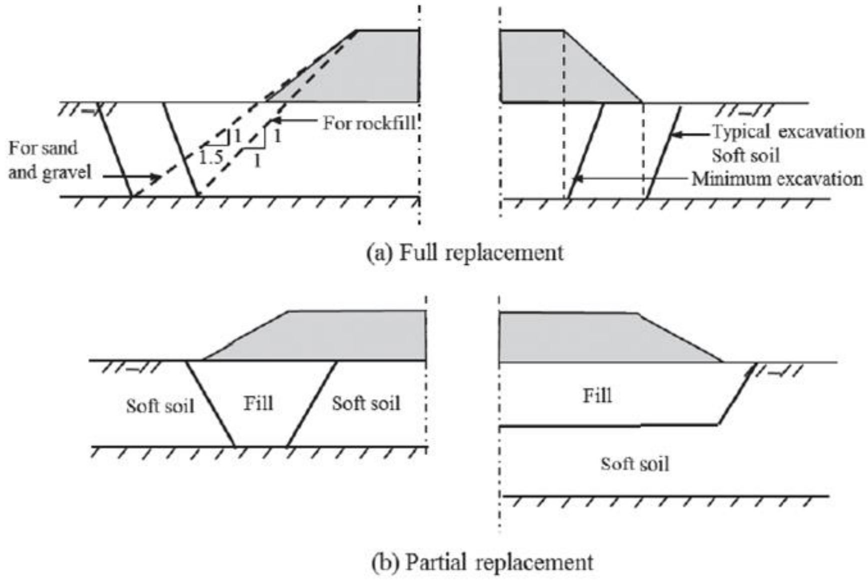

Figure 1. (a) Full and (b) Partial replacement under an embankment [4]

2.0 RELATED WORK

There are several researchers study on the soft soils problems and the properties of material that commonly used as replacement materials such as gravels, sand, Expanded Clay and Shale (ECS), tyre chips, stone aggregates, and lightweight aggregates and recycle materials. Some study does focus on the bearing capacity, settlement issue and/or improved properties either by using laboratory testing, physical modelling or numerical approaches. Very few studies have been conducted to evaluate the capability of Lightweight Expanded Clay Aggregate (LECA) in soft soil rehabilitation works such as replacement works as discussed in this research paper. Usually, lightweight aggregates are used in concrete structures to reduce their own weight without neglecting the strength and durability of the building structure.

The reinforcement of the problematic soils with granular fill layers is one of the soil improvement techniques that are widely used. Problematic soil behaviour can be improved by totally or partially replacing the inadequate soils with layers of compacted granular fill [5]. An artificial neural network (ANN), and a multiple linear regression (MLR) model have been used to predict the bearing capacity of a circular shallow footing supported by a layer of compacted granular fill on top of natural clay. The results of the study show that the use of granular fill layers over natural clay soil has a significant effect on the bearing capacity characteristics and that the ANN model serves as a simple and reliable tool for predicting the bearing capacity of circular footings in stabilized natural clay soil [6]. Meanwhile, the authors predicted scale effects for a circular footing supported by a replaced layer, dense, on natural clay deposits through 2-dimensional numerical modelling and then verified by field tests. The soft soil and replaced layer were modelled with Mohr-Coulomb. The scale effect phenomenon was analysed according to the footing sizes. Based on numerical and field-test results, the Bearing Capacity ratio (BCR) of the partially replaced, natural clay deposits increased with an increase in the footing diameter and there was no significant scale effect of the circular footing resting on natural clay deposits [7].

Al-Waily [6] has studied the effect of partial replacement by using crushed concrete as a recycled material to increase the bearing capacity and reduce the settling of soft clay. The experimental work carried out showed a significant decrease in settlement and an increase in the bearing capacity of treated soil by increasing the depth of the partial replacement layer for both square and strip sites compared to untreated soil [8]. Apart from that, Fattah & Al-Waily [7] utilised the reclaimed asphalt pavement (RAP) as a replacement material underneath a footing resting on soft clay. A trench of replaced soil will be extended to different depths to investigate the suitable dimensions of the trench. It was concluded that there is increase in the bearing capacity ratio when a trench of RAP material is constructed underneath the footing depends on the width and depth of the trench [9]. All these studies have used natural granular materials and recycled materials as replacement materials to increase the bearing capacity of the soil.

Lightweight Expanded Clay Aggregate (LECA) exhibit considerable differences in particle shape and texture depending on the source and the method of production. Shapes may be cubical, rounded, angular, or irregular, while the textures may range from fine pore, relatively smooth skins to highly irregular surfaces with large, exposed pores. LECA is utilised to substitute conventional aggregate in this study to improve soft soil bearing capacity under footing load. A. Zukri was evaluated ultimate bearing capacity under footing load through three-dimensional numerical modelling and then verified using physical modelling developed in laboratory. The study concluded that bearing capacity improved when soft soils were replaced with LECA aggregates. Generally, the numerical analysis with Hardening Soil constitutive model was well predicted in corresponding to the physical testing, where the discrepancy of the values is less than 12% [10].

In conclusion, the employment of replacement methods is advantageous for resolving geotechnical concerns associated with soft soils. The use of replacement soil can significantly boost bearing capacity, since the result exhibits no evidence of failure throughout a wide range of loads and soil replacement thicknesses. Meanwhile, this study was conducted to evaluate the ability of lightweight aggregate to be used as a replacement material.

2.1 Objective of the study

The purpose of this research is to evaluate the ultimate bearing capacity of soft soil treated with LECA raft under footing load. The bearing capacity of LECA replacement installed in soft clay was evaluated through three-dimensional numerical modelling. Relationships in the bearing capacity behaviour of soft soils related to LECA replacement were then developed.

3.0 RESEARCH METHODOLOGY

PLAXIS 3D is adopted in this research to simulate the behaviour of LECA raft under square footing load. The soft ground is represented by Hardening Soil (HS) constitutive model with undrained (B) type while LECA represented by Mohr-Coulomb (MC) model with drained type. Since soil is a complex body consisting of soil particles and spaces filled with water and/or air, it is difficult to choose a constitutive model that accurately describes the true soft soil process. Therefore, the selection of the appropriate constitutive model was done by comparing the bearing capacity value of the untreated state. The values obtained are confirmed using analytical methods. The untreated bearing capacity value calculated using the Terzaghi equation was found to be 44kN/m^2, while the PLAXIS value was 43kN/m^2, given an error of 2% and considered acceptable. The bearing capacity for three different LECA replacement thicknesses from the numerical modelling is then compared with the physical modelling that has been made by [10] for the same situation. The bearing capacity for the 1.5m, 2.5m and 3.5m LECA rafts installed under the footing load is 52kN/m^2, 60kN/m^2 and 68kN/m^2, respectively, which is comparable to the physical modelling result of 55.87kN/m^2 , 60.64kN/m^2, and 67.19kN/m^2 that have been carried out [10]. Therefore, HS was chosen as the constitutive model for soft soil in this study.

Meanwhile, fine mesh was selected in the analysis to increase the accuracy of the numerical result. Elements must be tight enough to minimise the discretization error but not so close as to allow additional computing memory or execution time [11]. Many numerical studies performed with PLAXIS software use fine mesh analysis to verify the accuracy of the findings.

It is also necessary to allocate the boundary at a sufficient distance from centre of foundation so that boundary conditions do not influence the numerical results, Azizi [12] suggested that the minimum distance to boundary should be five times the greater foundation dimension (Width of pad or length of strip). However, Killeen [13] suggested that a foundation width of eight times the breadth for a foundation of 3 meters neglect the influence of the outer boundary. The sensitive analysis conducted by Stuart Law [14] proved that this suggestion obtained valid results.

In order to fulfil the first objectives of this study, physical and mechanical properties of LECA is needed to evaluate. Laboratory testing is used to examine the physical and mechanical properties of LECA aggregate. The properties of these materials are important for conducting finite element analysis through numerical modelling. The laboratory tests conducted for LECA aggregates were particle size distribution test, relative density test, compaction test, specific gravity test, permeability test and consolidated undrained triaxial test. However, this research adopts the LECA properties from previously published papers, where laboratory work has been successfully carried out at the Geotechnical Laboratory of Universiti Teknologi Malaysia [15].

Two stages of calculation involved; initial and loading phase as shows in Table 1 below. Finite element analysis was conducted on LECA raft to determine the ultimate bearing capacity (qu) of treated soft clay.

Table 1. Finite element analysis phases

Behaviour	Phase	Calculation type	Loading input
Ultimate bearing capacity under footing load	Initial phase	K_0 procedure	Stage construction
	Loading phase	Consolidation analysis	Stage construction

3.1 Parametric study

From the review made, there are numerous of LECA manufacturer all around the world and the properties of the LECA are varies accordingly to their manufacturer's production. The friction angle value of LECA was found to vary from 35˚ to 53˚ and the unit weight of LECA varied between 3 kN/m^3 to 8kN/m^3, which is lower than the density of water [15]. LECA rafts with variable thickness (1.5m, 2.5m and 3.5m) and four (4) different LECA friction angles namely 35˚, 37˚, 40˚ and 45˚ were selected in this study. The value of the friction angle used in this study was predicted based on the density and particle density of the LECA material with reference to the correlation plot proposed by Zukri [16]. Then, the Young Modulus, E of LECA aggregates is calculated using Equation 1 proposed by Shafigh *et al.* [17]. In addition, dilatation angle of LECA is determined using Equation 2 proposed by Kowalska [18] which ϕ is the friction angles of LECA. Table 2 tabulates the properties used in the numerical analysis. Figure 1 represents the schematic diagram of LECA replacement model.

$$E_{Gpa} = 8.96\ \rho_{ton/m^3} - 3.78 \tag{1}$$

$$\psi = \phi - 30° \tag{2}$$

Table 2. Materials properties used in numerical modelling

Parameters	Kaolin Clay	LECA			
Constitutive model	Hardening soil	Mohr Coulomb			
Type of analysis	Undrained (B)	Drained			
Unit weight, γ (kN/m³)	16	4.5	5.5	6.0	8.0
Young's Modulus, E (kN/m²)	3807	5353	6543	7050	8497
Cohesion, c' (kN/m³)	7	0	0	0	0
Friction angle, ϕ' (°)		40	42	43	45
Dilatation angle, φ (°)		10	12	13	15
Permeability, k (m/day)	2.229 x10^{-5}				2185.92
Poisson's ratio, v					0.30

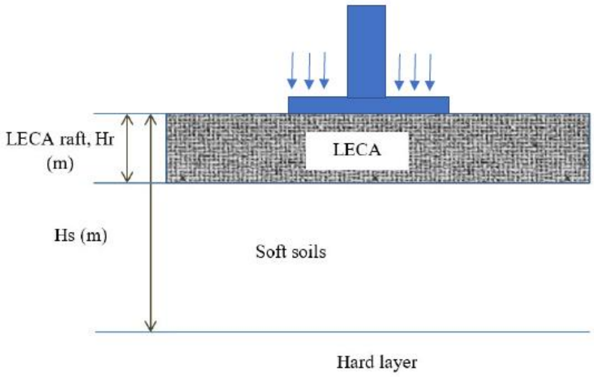

Figure 2. LECA replacement model

Many procedures have been developed to estimate bearing capacity under footing load tests. In this study, the Tangent Intersection Method is used to evaluate the value of the bearing capacity from the load-settlement plot which is withdrawn from the numerical analysis, where choosing the footing stress corresponding to a distinctive marked change in the settlement (that is, the intersection of the initial and final tangent slope of the stress versus settlement curve) [19].

4.0 RESULTS AND DISCUSSION

The analysis of bearing capacity of treated soft soil under footing load was examined under three different thickness of LECA replacement. Four different LECAs were used in this study that differed in terms of unit weight, friction angle and modulus. Thirteen (13) numerical models were analysed based on different parameters to evaluate the bearing capacity of LECA replacement under footing. Figure 2, Figure 3 and Figure 4 show the bearing capacity against settlement with respect to the thickness of 1.5m, 2.5m and 3.5m, respectively. Increasing the LECA replacement thickness and its angle of internal friction increases the ultimate bearing capacity 'q_u' and decreases the soil settlement. The findings are in good agreement with previous study conducted. However, Fattah *et. al.* [20] concluded that soil replacement method is more effective in improving the bearing capacity in case of the increasing the width of replacement compared with the increasing of the depth of replacement. Meanwhile, others study demonstrated that the ultimate bearing capacity is directly proportional to the angle of internal friction of granular soil, the granular layer thickness, and the foundation depth, while at the same time it is inversely proportional to the footing diameter [21].

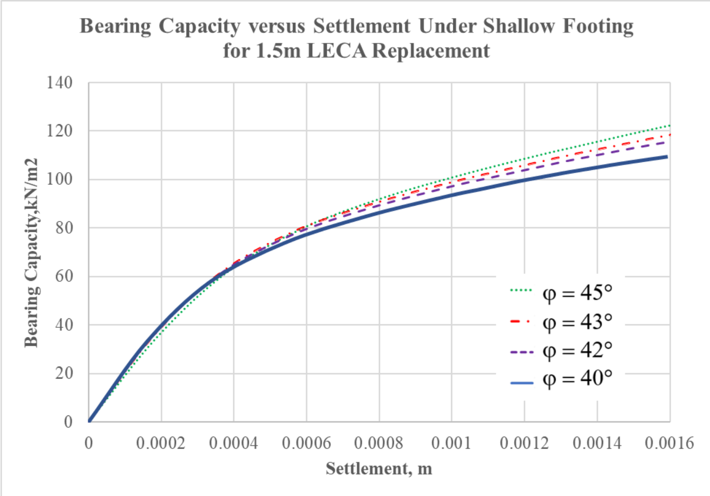

Figure 2. Bearing capacity of soft soil reinforced with 1.5m LECA raft

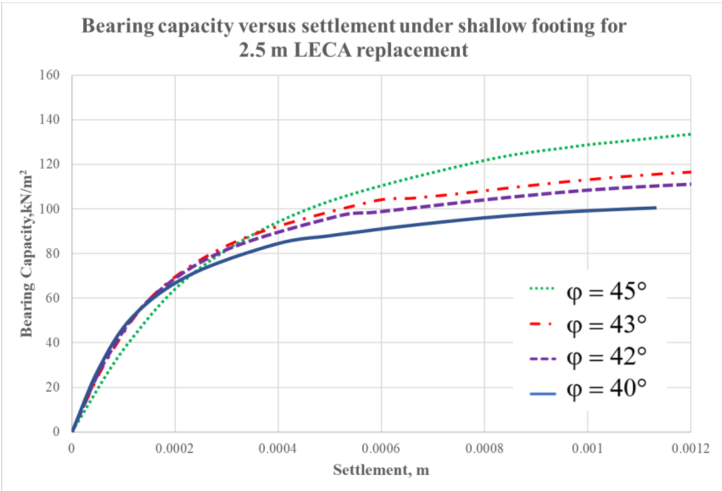

Figure 3. Bearing capacity of soft soil reinforced with 2.5m LECA raft

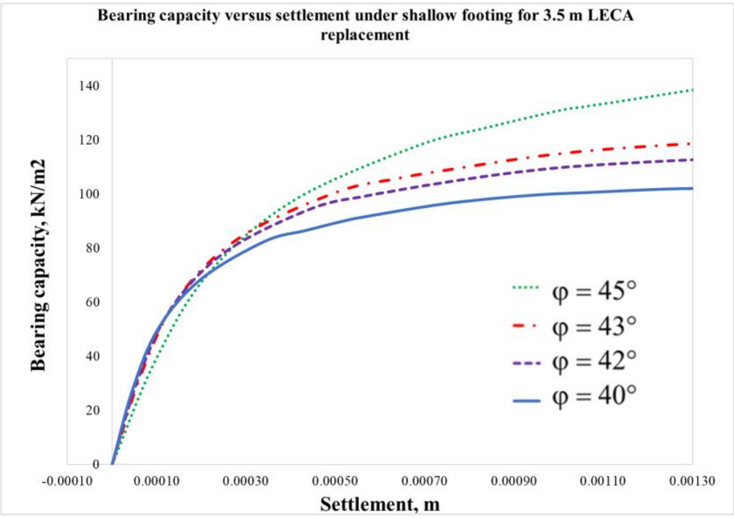

Figure 4. Bearing capacity of soft soil reinforced with 3.5m LECA raft

4.1 Influence of LECA replacement thickness on bearing capacity

Bearing capacity for various LECA replacement thicknesses as shown in Figure 5. It was noticed that the bearing capacity increased with increase in replacement thickness of LECA with φ = 42° from 44 kN/m^2 (untreated soil) to 69 kN/m^2, 78 kN/m^2 and 80 kN/m^2 for 1.5m 2.5m and 3.5m thick raft, respectively. The result is similar with other LECA replacement where the bearing capacity increased up to 88 kN/m^2 and 94 kN/m^2 when φ = 42° and 43°, respectively. The bearing capacity appears to increase with the increase of the LECA friction angle up to 166%, especially when φ = 45° LECA with 3.5 meters replacement has been applied. Table 3 tabulates the percentage of bearing capacity improvement for various friction angles of LECA and replacement thickness.

The results proved the ability of soft soil replacement with LECA materials can improve the bearing capacity under shallow foundation. Moreover, LECA with the highest angle of friction and deepest replacement leads to the highest bearing capacity values. Moreover, the LECA with the highest friction angle and the deepest replacement leads to the highest bearing capacity values. The reason behind this is that LECA with a higher friction angle is denser and has a high modulus value which contributes to the high durability of the material, further increasing the bearing capacity value. The findings are in good agreement with previous study conducted, where the thickness of replacement contributed to better bearing capacity improvement [1], [22]–[24]. This has proven that lightweight materials such as LECA are as good as normal aggregates that can be used as replacement materials to strengthen soft soils with limited depth.

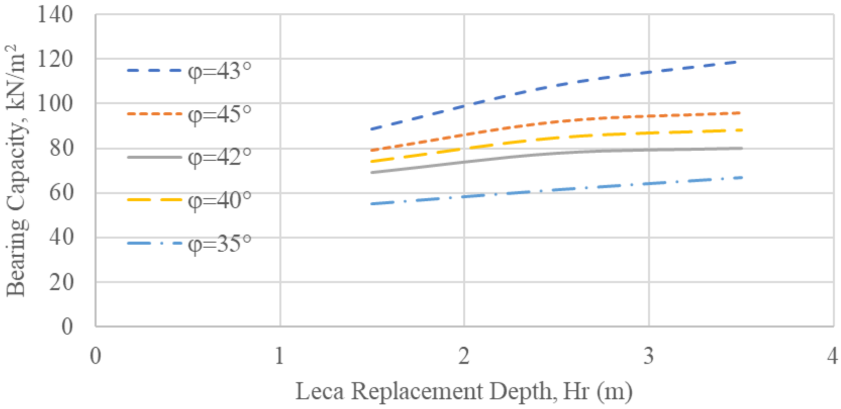

Figure 5. Bearing capacity for various LECA replacement depth

Table 3. Percentage of bearing capacity improvement

Hr (m)	LECA friction angle, φ°				
	35°	40°	42°	43°	45°
1.5	26.98%	56.82%	65.91%	72.73%	90.91%
2.5	37.82%	77.27%	95.45%	115.91%	159.09%
3.5	52.70%	81.82%	100.00%	113.64%	165.91%

4.2 Prediction of bearing capacity of soft soil treated with LECA replacement

The bearing improvement ratio (ultimate bearing capacity of treated-to-untreated soil) increased with increasing of LECA replacement as plotted in the graph in Figure 6. This figure can be considered as the reference plot to predict the bearing capacity of treated soil according to specified LECA replacement thickness. The result indicated that the most controlling parameter is Hr, where *qu* increases considerably with increase of Hr. The properties of LECA material also play important role to improve the soft soil bearing capacity. However, the bearing capacity values appear to be almost linear when 2.5 m and 3.5 m of LECA replacements are used, indicating that the replacement thickness is not necessary to obtain a better improvement in term of bearing capacity. That is, the 2.5m thickness of LECA replacement even though the LECA friction angle is different is the most economical and optimal thickness to use. Reference plot in Figure 6 can be referred to predict the bearing capacity value of soft soil treated with LECA replacement under footing load according to the following procedure.

Step 1	Calculate the untreated bearing capacity (BC_u) under footing load using analytical method, for example Terzeghi Equation. The properties of origin soil and footing size are needed in order to calculate the bearing capacity.
Step 2	Based on LECA used in constrcution site (LECA friction angle value) and designed thickness of replacement, the value of Bearing capacity ratio (η) can be predicted by refer to plot in Figure 6. The LECA properties used are required to use this proposed plot. The optimum or economic thickness for LECA replacement is 2.5 meters, exceeding this depth, the bearing capacity value will not be much different.
Step 3	Treated bearing capacity (BC) can be estimated using Equation 3 below.

$$\eta = BC/BC_u \tag{3}$$

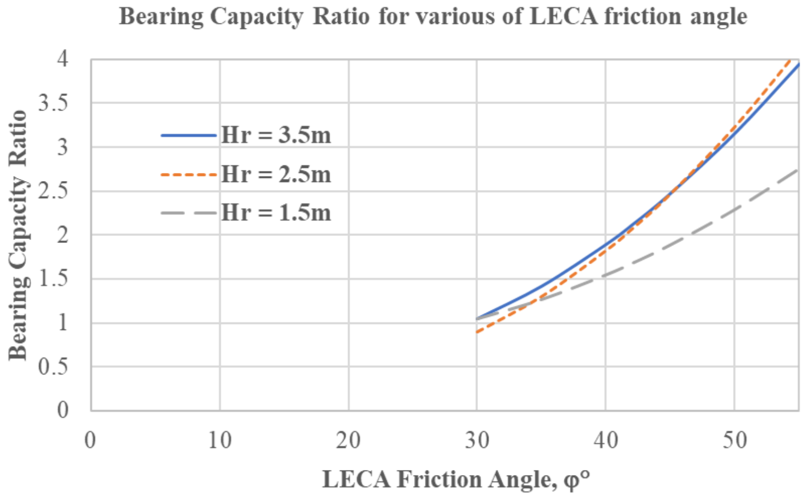

Figure 6. Bearing capacity prediction chart for various LECA replacement depth

4.3 Procedures limitations

The procedure proposed above has some shortcomings that need to be fixed so that it can be used in all situations when LECA is used as a replacement material under shallow foundations. These forecast charts are suggested to be verified using physical modeling to make them more reliable. Moreover, this procedure does not take into account the footing size, whereas the Terzaghi and Meyerhof equation considers the footing size to estimate the bearing capacity.

5.0 CONCLUSION

Based on the results of physical and mechanical tests, LECA can be characterized as well-graded coarse grains with particles that are acceptable for usage as a substitute material for soil replacement work. From the study conducted, it was observed that the replacement of soft soil with LECA aggregates improved the bearing capacity of footing on soft soil. The load carried by the LECA raft increase by increasing the angle friction of LECA and increasing the raft thickness. The result indicated that the most controlling parameter is *Hr*, where *qu* increases considerably with increase of *Hr*.

The properties of LECA material also play important role to improve the soft soil bearing capacity. However, the bearing capacity values appear to be almost linear when 2.5 m and 3.5 m of LECA replacements are used, indicating that the replacement thickness is not necessary in order to obtain a better improvement in term of bearing capacity. That is, the 2.5m thickness of LECA replacement even though the LECA friction angle is different is the most economical and optimal thickness to use.

To forecast the bearing capacity under the footing load, the design plot as shows in Figure 6 was developed. However, full-scale testing is necessary to compare the results of this study to actual fieldwork or a large-scale model so that the proposed plot can be referred with confidence.

As the LECA particles are lighter than water, it is recommended that future research include the application of geotextiles as the interfaces between the LECA and soft soils layer in order to increase the effectiveness of the LECA and reduce the possibility of buoyancy effect due to the rising ground water table. Additionally, geotextiles can serve as a separator between soil and LECA material.

6.0 AUTHOR CONTRIBUTIONS

Azhani Zukri.: Conceptualization, Methodology, Writing- Original draft preparation, Investigation.

Author have read and agreed to the published version of the manuscript.

7.0 FUNDING

Not applicable.

8.0 DATA AVAILABILITY STATEMENT

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

9.0 ACKNOWLEDGEMENT

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10.0 CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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