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RESEARCH ARTICLE

Strength of Kaolinitic Clay Soil Stabilized with Lime and Palm Oil Fuel Ash

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ABSTRACT - The use of palm oil fuel ash (POFA) mixed with lime as a catalyst in soil stabilization can significantly improve the stability of problematic soils and improve their engineering properties. Problematic soils can obstruct the construction process due to its low strength and low bearing capacity. In this study, various laboratory tests were carried out to determine the engineering properties of the soil's mixture which includes Atterberg limit, particle size distribution, compaction, and unconfined compression test. 4%, 8% and 12% POFA were mixed with 6% hydrated lime to stabilized the kaolinitic clay soil at different curing days (1, 7, 14, and 30 days). Compared to untreated kaolin, the addition of POFA plus lime resulted in higher undrained shear strength. The maximum undrained shear strength (USS) is 32.68kN/m^2, which was obtained on the 30th day of curing with the optimal mixture of stabilized kaolin which is kaolin mixed 6% of lime and 12% of POFA. The unconfined compressive strength increased by 185.04% compared to the unconfined compressive strength of untreated kaolinitic clay with a value of 65.36 kN/m^2. This proves that kaolin stabilized with lime and POFA can increase the strength parameters of clay, thus reducing construction costs for soil stabilization and reducing environmental issues.

ARTICLE HISTORY

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1.0 INTRODUCTION

Soft clay soil is a type of soil containing clay minerals and natural materials, which has a significant amount of moisture and loose sand deposits, which are the result of weathering [1-3]. When clay is dry, it tends to shrink, but when wet, it expands and becomes sticky. The existence of water in the soil affects those conditions. Soft clay is also known for having high permeability and compressibility, and low bearing capacity [4-6]. The swelling of soft clay can lead to the destruction of building structures, which has become one of the biggest concerns in the field of geotechnical engineering.

In Malaysia, soft clay is found scattered in the coastal areas of the country, including both East Malaysia and the Peninsula, where most of the social and economic development is developed along these areas [7-9]. So, construction projects are inevitable to be built on this type of problematic soil, for which many problems related to soil swelling occur during the construction process. These problems can cause projects to be delayed and will affect the quality of construction work. One of the effects of soil swelling is settlement.

Therefore, the problematic soil needs to be improved to be suitable for use in building construction projects, namely by using soil stabilization techniques. According to Zaini et al. [10] and Hasan et al. [11], soil stabilization is a method of enhancing the engineering characteristics of soft clay by mixing soil stabilizers with the soil. The purpose of this technique is to improve soil compressibility, compressive strength, plasticity, durability and soil permeability. Soil stabilization can be executed in two ways, which are in-situ, which is done at the place where the sample was taken or ex-situ, which is done at the soil laboratory [12-15].

Palm oil is a vital contributor to Malaysia's gross national income, ranking fourth, and is the leading sustainable vegetable production globally. The largest production of Palm Oil Fuel Ash (POFA) is recorded in East Asian countries like Indonesia, Malaysia, and Thailand, as well as West African nations such as Ghana, Nigeria, and Benin Republic. However, the rapid growth of the palm oil industry has led to significant environmental impacts, emphasizing the need for proper utilization of the resulting ash, which has become a national priority. Engineers are addressing these challenges with urgency to minimize environmental and financial burdens. New methods are being adopted to utilize waste in line with the principles of sustainable development, focusing on the Reduce, Recycle, and Reuse (3Rs) approach. Additionally, POFA's high pozzolanic characteristics make it a suitable and reliable option for treating soft soil [4].

Soil stabilization can be done using chemical and mechanical methods. According to Zaini et al. [16-18], mechanical stabilization is the process of compacting and mixing clay soil with other soil with different type of gradation to achieve a dense soil. This process can be implemented using various mechanical machines such as rollers, vibrators, and rammers. This method aims to meet the specific needs of well-graded soil, which ultimately improves the properties of the soil [19], [20-22]. Chemical stabilization of soil is the process of adding soil stabilizer admixture such as cement, lime or industrial

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wastes with the clay soil to improve the characteristics of soft clay, which its durability and shear strength [4], [23-25]. In this research, palm oil fuel ash (POFA) and lime are mixed into soft clay to enhance its strength properties.

2.0 METHODOLOGY

The experimental program was designed first to characterize the material used which was lime, palm oil fuel ash (POFA) and kaolinitic clay soil, followed by the shear strength tests on soft kaolin clay stabilized with lime and POFA. The summary of laboratory testing program and the standard used are as shown in Table 1.

Table 1. Laboratory Testing Program

Material	Test Name	Standard
Kaolinitic Clay	Atterberg Limit	BS 1377- Part 2: 1990: 4, 5 & 6.5
	Particle Size Distribution	BS 1377- Part 2: 1990: 9.5
	Unconfined Compression Test	ASTM D 2166
	Compaction Test	BS 1377: Part 4: 1990
Lime	Particle Size Distribution	BS 1377- Part 2: 1990: 9.3
Palm Oil Fuel Ash (POFA)	Particle Size Distribution	BS 1377- Part 2: 1990: 9.3
Kaolinitic Clay Stabilized with Lime and POFA	Atterberg Limit	BS 1377- Part 2: 1990: 4, 5 & 6.5
	Particle Size Distribution	BS 1377- Part 2: 1990: 9.5
	Unconfined Compression Test	ASTM D 2166
	Compaction Test	BS 1377: Part 4: 1990

2.1 Soil and Soil Stabilizers

Kaolinitic clay possesses a mineral structure resistant to water penetration, forming a uniform mixture when in contact with water, owing to its plate-like configuration consolidated by hydrogen bonds and secondary valence forces. The study incorporated various stabilizing agents, including lime and POFA. POFA, a by-product of palm oil processing, is produced by burning palm oil shells and empty fruit bunches in boilers at temperatures ranging from 800 to 1000 °C to generate steam for energy production. This steam is used to power turbines and supply electricity during the milling process. However, raw POFA is not usable due to its uncertain moisture content. POFA is considered a pozzolanic waste material originating from the palm oil industry. Its significant content of amorphous silica makes it conducive to pozzolanic reactions during hydration, leading to the formation of cementitious compounds known as calcium aluminate hydrates (CAH) and calcium silicate hydrates (CSH) [4], [25-26]. Laboratory-grade hydrated lime (L) was utilized. Geotechnical characteristics of kaolinite clay are outlined in Table 2.

Table 2. Geotechnical characteristics of kaolinitic clay

Characteristics	Unit	Data
Gravel	%	0
Sand	%	48
Clay and Silt	%	52
Liquid Limit	%	41.19
Plastic Limit	%	30.81
Plasticity Index	%	10.38
Maximum Dry Density	g/cm^3	1.53
Optimum Moisture Content	%	19.80
Unconfined Compression Strength	kPa	16.18

2.2 Preparation of Kaolinitic Clay

The laboratory experiments aimed to stabilize kaolinitic clay using 6% of lime and 4%, 8%, and 12% of POFA to enhance its cementitious properties. The consistency tests and particle distribution test were conducted in accordance with BS 1377: Part 2: 1990. Compaction tests was conducted following BS 1377: Part 4: 1990 standards to determine the maximum dry unit weight (MDD) and optimum water content (OMC) of the soil. Unconfined compression tests (UCT) were carried out on soil specimens cured for different durations (1, 7, 14, and 30 days), following ASTM D2166 protocols. Kaolinitic clay sample was remoulded in a 76 mm x 38 mm sample dimensions for the UCT test.

3.0 EXPERIMENTAL RESULTS

In the study, a series of laboratory testing was conducted according to the standard as mentioned in Table 1 and the shear strength of the stabilized kaolinitic clay with SF and lime was tested. There are four (4) types of laboratory testing conducted in the study which includes Atterberg limit, particle size distribution, compaction, and unconfined compression test.

3.1 Consistency Limit

The liquid limit for kaolinitic clay sample is 41.19%, while the plastic limit for kaolinitic clay sample is 30.81%. By subtracting liquid limit with plastic limit, the plasticity index for kaolinitic clay sample is 10.38%. According to USCS plasticity index in Figure 1, kaolinitic clay soil belongs to the ML (low-plastic inorganic silt) because its LL has less than 50% value and kaolinitic clay soil is considered to have a low degree of plasticity and PI value is more than 7%. The consistency limits of the kaolinitic clay is coherent to the results obtained by Ishak et al. [27], Zaini et al. [28], and Goh et al. [29]. Besides, the liquid limit for hydrated lime sample is 51.43%, while the plastic limit for hydrated lime sample is 40.31%. The plasticity index for hydrated lime is 11.12%. According to USCS plasticity chart in Figure 2, the hydrated lime belongs to the MH (high-plastic inorganic silty clay) because its LL has is more than 50% which hydrated lime is considered to have a high degree of plasticity. On the other hand, in research from Al-Hokabi et al. [4], POFA is a non-plastic material. It is an oil-based material and its soil behaviour type is sandy soil type. Atterberg limit test cannot be conducted on POFA sample as result of its soil behaviour, which high in porosity which led to low workability of the sample. According to AASHTO soil classification, non-plastic material is classified as class A-3.

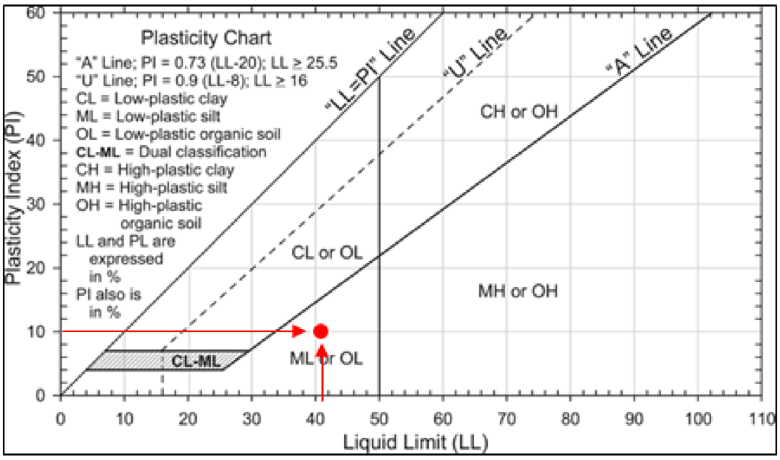

Figure 1. USCS Plasticity chart of kaolinitic clay

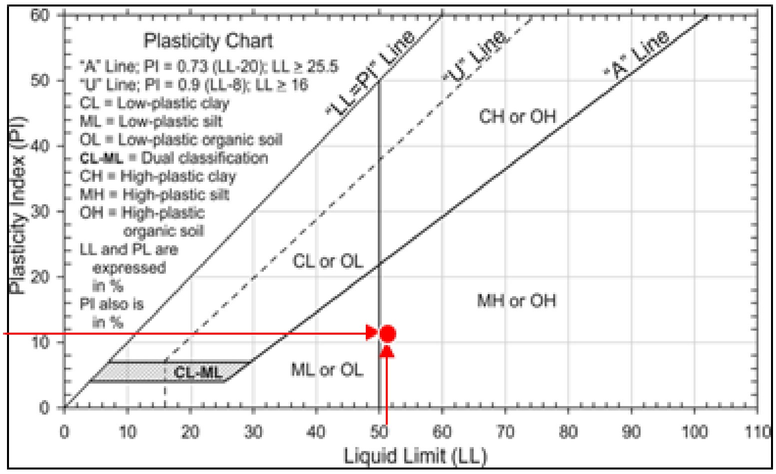

Figure 2. USCS Plasticity chart of hydrated lime

3.2 Particle Size Distribution

The result of particle size distribution of kaolinitic clay sample is shown in Figure 3. From the curve, there is approximately 52% of kaolinitic clay particles passing 0.075 mm sieve size. It can be concluded that kaolinitic clay is classified as clayey or silty soil which according to AASHTO soil classification system. Next, the result of particle size distribution of hydrated lime sample was plotted in a as shown in Figure 4. From the graph, according to USCS, sandy soil is in the range of 0.06 mm to 1 mm sieve size, which the hydrated lime particle has passing more than 50% of No. 4 (4.75mm) sieve size.

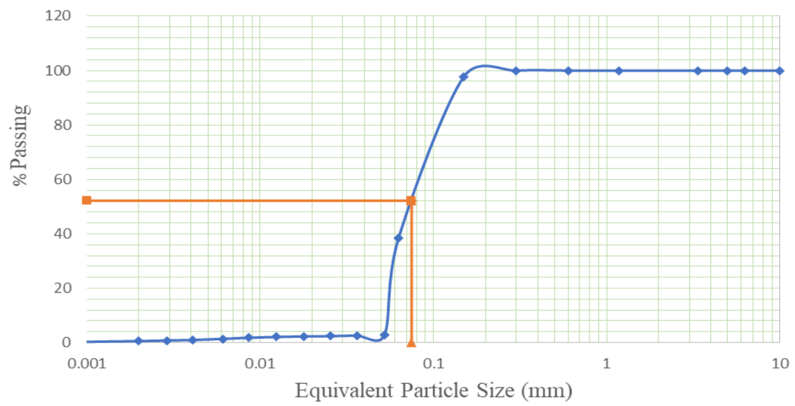

Figure 3. Particle size distribution of kaolinitic clay sample

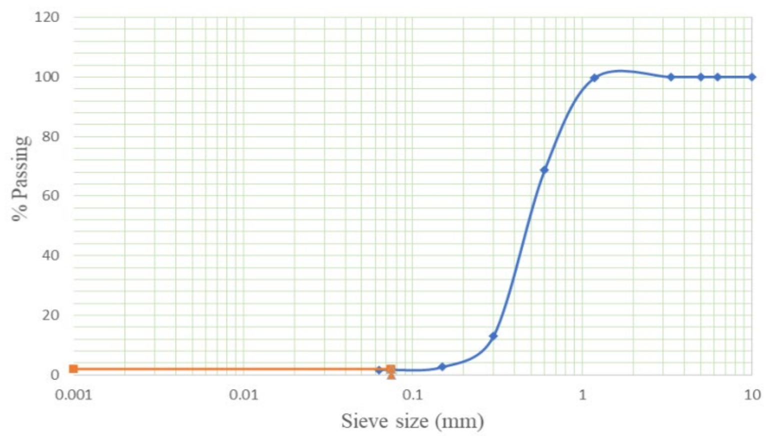

Figure 4. Particle size distribution of hydrated lime

Figure 5 shows the sieve analysis for POFA. From the analysis, the particle size distribution graph was obtained and from the graph, the value of D60 is 0.29, D30 is 0.21 and D10 is 0.16. These values can be used to calculate the value of Coefficient of Uniformity, Cu which is 1.792 and the Coefficient of Gradation, Cc which is 0.968. According to Unified Soil Classification System (USCS), in laboratory classification criteria, a type of soil is considered well-graded if its Cu value is between 4 and 6. Poorly graded soil is defined as having a Cu value less than 4. Whereas, the Cc value must fall between 1 and 3 for the soil to be considered as well-graded. Therefore, POFA can be categorized as SP, poorly graded sand. According to USCS, sandy soil is in the range of 0.06mm to 1 mm sieve size, which the POFA particle has passing more than 50% of No. 4 (4.75mm) sieve size.

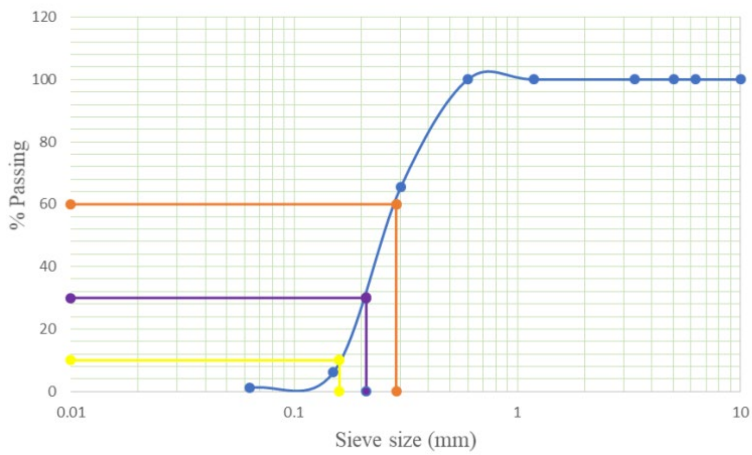

Figure 5. Particle size distribution of POFA

3.3 Compaction Behaviour

Figure 6 shows the compaction curve of kaolinitic clay sample, K6L4POFA, K6L8POFA and K6L12POFA mixtures. The MDD values for the addition of 4%, 8% and 12% POFA have a decreasing trend from 1.67g/cm^3 to 1.64g/cm^3. On the contrary, the OMC of 4%, 8% and 12% POFA has an increasing trend from 15% to 18.5%. The changing in curve of different kaolin-lime-POFA mixtures shows that the addition of POFA content with a high silica content has changed the arrangement of the sample particles causing a change in the specific area of the sample. This results in more water being needed to trigger the stabilization process by causing a chemical reaction between the small particles, thus resulted in increasing value of OMC [30-31]. As more water is added to the mixture, the MDD value of the mixture becomes lower [32-34].

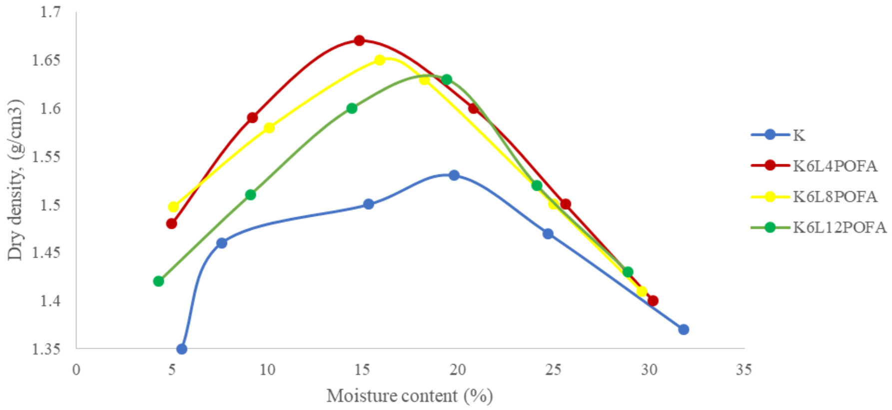

Figure 6. Compaction Curve of kaolinitic clay and stabilized kaolinitic clay with lime and POFA

3.4 Unconfined Compression Test

From the series of UCT results obtained, the undrained shear strength, USS were calculated and the average USS of each sample for each curing day were plotted in Figure 7. The shear strength of the kaolinitic clay increased from 16.18 kN/m^2 to 19.03 kN/m^2, 19.94 kN/m^2, and 25.21 kN/m^2 with a strength improvement of 17.64%, 23.26%, and 25.21% during 1 day of curing when the kaolinitic clay was stabilized with 4%, 8%, and 12% of POFA, respectively. When the curing days increased, the shear strength of the stabilized kaolinitic clay were also increased. From the graph, it was found that the optimal percentage of kaolin-lime-POFA mixture in this research is kaolin mixed with 6% lime and 12% POFA with the sample coding K6L12POFA. At 30 days of curing, the stabilized kaolinitic clay soil using 6% of lime and 12% of POFA recorded the highest improvement of shear strength with a value of 65.36 kN/m^2 (185.04% of strength improvement). Therefore, it can be concluded that, the utilization of lime at 6% and various proportion of POFA resulted to the significant improvement of the shear strength.

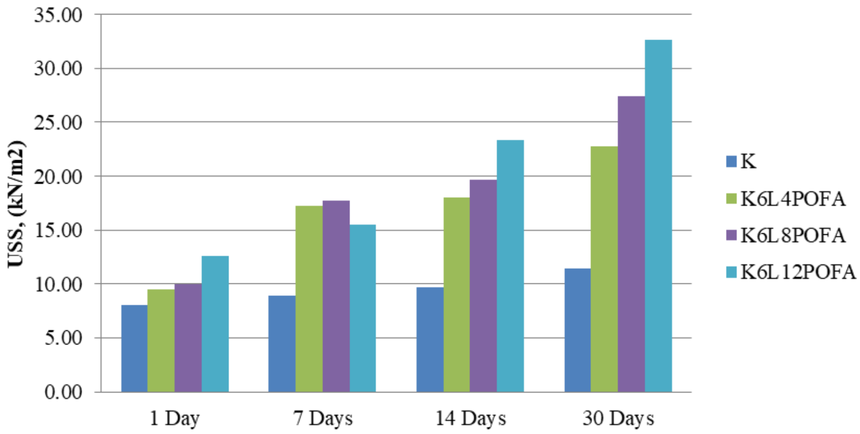

Figure 7. Undrained shear strength of kaolinitic clay soil stabilized with lime and POFA

4.0 CONCLUSION

The main purpose of this research is to examine the stabilization of kaolinitic clay soil using lime and POFA for soil stabilization method. Based on the numbers of laboratory tests conducted, the following outcomes can be made:

a) The Unified Soil Classification System (USCS) indicates that kaolinitic clay soil is categorized as ML which is a low-plastic inorganic silt, while from American Association of Highway and Transportation Officials (AASHTO), kaolinitic clay soil is categorized as class A-5 because its liquid limit is 41.19% and plasticity index is 10.38%. kaolinitic clay soil has a maximum dry density of 1.53g/cm^3 and optimum moisture content of 19.8%.

b) The Unified Soil Classification System (USCS) indicates that hydrated lime is categorized as MH which is a high-plastic inorganic silt, while from American Association of Highway and Transportation Officials (AASHTO), hydrated lime is categorized as class A-7-5 because its liquid limit is 51.43% and plasticity index is 11.12%. Hydrated lime has a maximum dry density of 1.11g/cm^3 and optimum moisture content of 43%.

c) The Unified Soil Classification System (USCS) indicates that palm oil fuel ash (POFA) is categorized as SP which is a poorly-graded sand because poorly graded is defined as having a C_u value less than 4, which its C_u value is 1.792. The American Association of Highway and Transportation Officials (AASHTO), palm oil fuel ash is categorized as class A-3 because it is a non- plastic material.

d) Kaolinitic clay soil mixed with 6% of lime and various percentage of POFA i.e., 4%, 8% and 12%, shows enhancement of the mixtures in terms of undrained shear strength (USS). According to this research, the optimal mixture of kaolinitic clay soil-lime- POFA mixture is kaolin mixed with 6% of lime and 12% of POFA, with a coding code of K6L12POFA. The mixture has the majority of maximum USS among other mixtures for curing days. On curing day 30, K6L12POFA mixture achieved the maximum USS of 32.68kN/m^2 compared to untreated kaolin sample's USS of 11.47kN/m^2 with an improvement rate of 184.92%.

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6.0 AUTHOR CONTRIBUTIONS

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

Muzamir Hasan: Supervision

Wafiyuddin Md Jariman: Data collection

7.0 FUNDING

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8.0 CONFLICTS OF INTEREST

The authors declare no conflict of interest.

9.0 DATA AVAILABILITY STATEMENT

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

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