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RESEARCH ARTICLE

Strength of Problematic Soil Stabilised with Gypsum and Palm Oil Fuel Ash

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ABSTRACT - Soil stabilisation technique becomes one of the techniques for solutions to problematic methods of soil improvement. This method is one of the techniques that are categorised as a new alternative to soil engineering problems as well as taking into account the impact of wasted materials and waste in the oil palm industry which is the industry that drives the country to the second largest producer in Asia. Palm oil fuel ash is used as a substitute for cement that reacts chemically to increase shear strength and problematic soil bearing ability. Kaolin is used as a problematic soil sample to study. To strengthen the mixture between kaolin and palm oil fuel ash, gypsum is also added as a catalyst during chemical reactions between mixed materials to be more effective. To determine the level of improvement in soil shear strength, laboratory tests, namely the Unconfined Compression Test (UCT) were implemented. Kaolin provides as control sample in addition to gypsum at the consumption level of 6% continuously mixed together with 4% of the palm oil fuel ash that are determined at the percentage level of 4%, 8% and 12 % separately that later been divided into four (4) different samples according to the respective mixture that has been determined for the research study. The highest improvement that was recorded is reaching to 192.40% increases on the 30th day of curing from the mixed samples which is the mixtures of Kaolin with 6% of gypsum and 12% palm oil fuel ash. This elucidates that both gypsum and POFA are the potential soil stabilisers.

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1. INTRODUCTION

Problematic soils pose significant challenges in geotechnical engineering due to their unpredictable behaviors and adverse effects on construction and infrastructure [1-2]. These soils, which include expansive clays, collapsible soils, organic soils, silty soils, saturated soils, and saline soils, exhibit issues such as excessive swelling, sudden settlement, low bearing capacity, and susceptibility to liquefaction. These characteristics can lead to structural instability, foundation damage, and costly maintenance [3-4]. Effective mitigation strategies, such as soil replacement, chemical and mechanical stabilization, drainage improvement, and the use of geosynthetics, are crucial to address these challenges [5-6].

Soil stabilization is a treatment that aims at improving soil geotechnical properties, soil strength and the need of increasing the resistance to plasticity by the present of water flow between the soil particles that bonding together, by applying precaution such as water proofing the particles or combining of the both methods stated [7-8]. Soil stabilization can be categorized into mechanical and chemical stabilisation. Mechanical soil stabilisation is one method of modification of the physical soil nature of the soil own particles either by applying vibration, compaction treatment or either by the addition of graded aggregates into the soil [9-11]. For chemical stabilisation, it affected mainly soil chemical reactions among cementitious material or soil stabiliser and pozzolanic soil minerals to obtain the desired effect [12-14].

Gypsum and palm oil fuel ash (POFA) are gaining recognition as effective soil stabilizing materials, offering sustainable solutions for improving soil properties. Gypsum, a naturally occurring mineral, enhances soil structure by reducing plasticity and swelling in expansive clays through cation exchange and flocculation processes [15-16]. This results in increased soil strength and stability, making it a valuable amendment for problematic soils. POFA, a byproduct of palm oil production, is rich in silica and alumina, contributing to pozzolanic reactions when mixed with soil [17-19]. These reactions enhance soil's compressive strength and durability by forming additional cementitious compounds. Utilizing gypsum and POFA not only improves soil performance but also promotes environmental sustainability by recycling industrial byproducts and reducing the reliance on conventional, non-renewable stabilizers. This approach aligns with sustainable development goals, particularly in resource management and sustainable urban infrastructure development. In this research, palm oil fuel ash (POFA) and gypsum are mixed into kaolnitic clay to enhance its strength properties.

2. METHODOLOGY

The experimental program was initially designed to characterize the materials used, which included gypsum, palm oil fuel ash (POFA), and kaolinitic clay soil. This was followed by conducting shear strength tests on soft kaolin clay

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stabilized with gypsum and POFA. A summary of the laboratory testing program and the standards used is presented in Table 1.

Table 1. Laboratory testing program

Material	Test Name	Standard
Kaolinitic Clay	Atterberg Limit Particle Size Distribution Unconfined Compression Test Compaction Test	[20] [20] [21] [22]
Gypsum	Particle Size Distribution	[20]
Palm Oil Fuel Ash (POFA)	Particle Size Distribution	[20]
Kaolinitic Clay Stabilized with Gypsum and POFA	Atterberg Limit Particle Size Distribution Unconfined Compression Test Compaction Test	[20] [20] [21] [22]

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 [10]. 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) [1], [4], [6]. Gypsum were purchased at V-city Sdn Bhd, located at Kuala Lumpur, Malaysia. The gypsum was in powder form, supplied by a local garden store. The gypsum used in this experiment are recycled gypsum (no impurities), white in colour, size of <63um. 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 focused on stabilizing kaolinitic clay with a combination of 6% lime and varying percentages of palm oil fuel ash (POFA) at 4%, 8%, and 12% to improve its cementitious properties. Consistency and particle size distribution tests were performed according to BS 1377: Part 2: 1990 [20]. Compaction tests, adhering to BS 1377: Part 4: 1990 [22], were conducted to ascertain the maximum dry density (MDD) and optimum moisture content (OMC) of the soil. Additionally, unconfined compression tests (UCT) were conducted on samples cured for 1, 7, 14, and 30 days, following ASTM D2166 [21] standards.

3. EXPERIMENTAL RESULTS

In the study, various laboratory tests were conducted as outlined in Table 1, focusing on the shear strength of kaolinitic clay stabilized with gypsum and palm oil fuel ash (POFA). Four types of laboratory tests were performed: Atterberg limits, particle size distribution, compaction, and unconfined compression tests.

3.1 Consistency Limit

Based on the different materials tested, Kaolin S300 is the only material show the expected to be tested smoothly thoroughly for requiring the parameters. Gypsum and POFA are classified in the category of non-plastic (NP) materials.

The results obtained are considered as based on the materials nature. For gypsum, the result also can be found similar to previous research Hasan et al. [1]. Based on Alhokabi et al. [3], the tested POFA also been categorized as non-plastic material. The summary of this laboratory testing data is presented in Table 3.

Table 3. Consistency limits of materials used in the study

Materials	Parameter	Value
Kaolin	Plastic Limit, *wp* (%)	26
	Liquid Limit, *wL* (%)	36
	Plastic Index, *Ip* (%)	10
Gypsum	Plastic Limit, *wp* (%)	NP
	Liquid Limit, *wL* (%)	
	Plastic Index, *Ip* (%)	
POFA	Plastic Limit, *wp* (%)	NP
	Liquid Limit, *wL* (%)	
	Plastic Index, *Ip* (%)	

3.2 Particle Size Distribution

Throughout laboratory testing by combining the mechanical sieve analysis (dry sieving) and hydrometer is done for determining the particle distribution for Kaolin, gypsum and POFA. Mechanical sieve analysis shows that almost 40 % from 500g of Kaolin passing through sieve size of 0.063 mm. Hydrometer test proving that Kaolin particle is finer with ranging from 0.0008 to 0.063 mm. The Liquid Limit (LL) of Kaolin which is 36 % with Plasticity Index (PI) of 10 %. According to ASTM D3283-93 [23], Kaolin used for this testing is classified in A-5 group which stated as fine silty soil with particle size ranging from 0.002 to 0.065 mm.

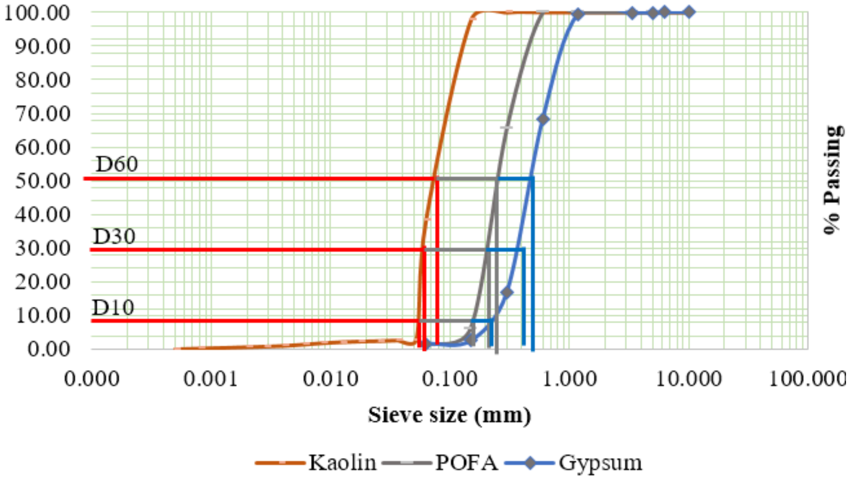

Figure 1. Particle size distribution of kaolinitic clay, POFA, and Gypsum

For POFA, the test that been conducted is only for mechanical sieving analysis (dry sieve) as the result projecting that most of the particle is likely to be sand that passing through more than 50 % than No.4 sieve size (425 µm) which is retained on sieve size 300 µm about 65.43 %. The wet sieve analysis (hydrometer test) could be ignored without testing. For plastic behaviour and liquid limit of POFA which being determined by Atterberg Limit test also cannot be done as the particle hard to mould into shape and considering that POFA is categorized as non-soil material. The classification should be done based on using the gradation coefficient, Cc (0.9680 and uniformity coefficient, Cu (1.792) from the obtained POFA passing percentage (%). The value of D_{60} (0.160), D_{30} (0.210) and D_{10} (0.286) could be estimated from the particle distribution graph. These values are used in determining listed coefficient above.

For Gypsum, the test that been conducted is only for mechanical sieving analysis (dry sieve). Gypsum dry sieving can be classified in similar condition with POFA. The gypsum particles which are considered sand as the particles only passing through at most 20 % through No.4 sieve size (425 µm) which is retained on sieve size 300 µm about 16.94 %. The hydrometer test could be ignored without testing as the percentage of gypsum particle on No.200 sieve size (75 µm) is not passing 50 %. For plastic behaviour and liquid limit of gypsum which being determined by Atterberg Limit test also cannot be done as the material is quickly react with water to solidify and gypsum is categorised as natural mineral (non-plastic. The classification should be done based on using the gradation coefficient, Cc (1.129) and uniformity coefficient, Cu (2.422) from the obtained POFA passing percentage (%). The value of D_{60} (0.551), D_{30} (0.376) and D_{10} (0.227) could be estimated from the particle distribution graph.

3.3 Compaction Behaviour

Figure 2 shows the compaction curve of kaolinitic clay sample, KG6, KG6P4, KG6P8, AND KG6P12 mixtures. Based on compaction curve presented, the maximum dry density (MDD) and optimum moisture content (OMC) is obtained in this laboratory testing. For Kaolin (K), the maximum dry density (MDD) is obtained at 1.55 (g/cm^3) and the optimum moisture content is 19.50 %. For KG6, the maximum dry density (MDD) is obtained at 1.69 (g/cm^3) with the optimum moisture content (OMC) of 18.5 %. For KG6P4, the maximum dry density (MDD) is found at 1.64 (g/cm^3) meanwhile the optimum moisture content (OMC) is found to be at 15.5 %. For KG6P8, the maximum dry density (MDD) is 1.63 (g/cm^3) and the optimum moisture content (OMC) is 16.00. While, for KG6P12, the maximum dry density (MDD) is recorded at 1.64 (g/cm^3) and the optimum moisture content (OMC) limiting at 16.5%.

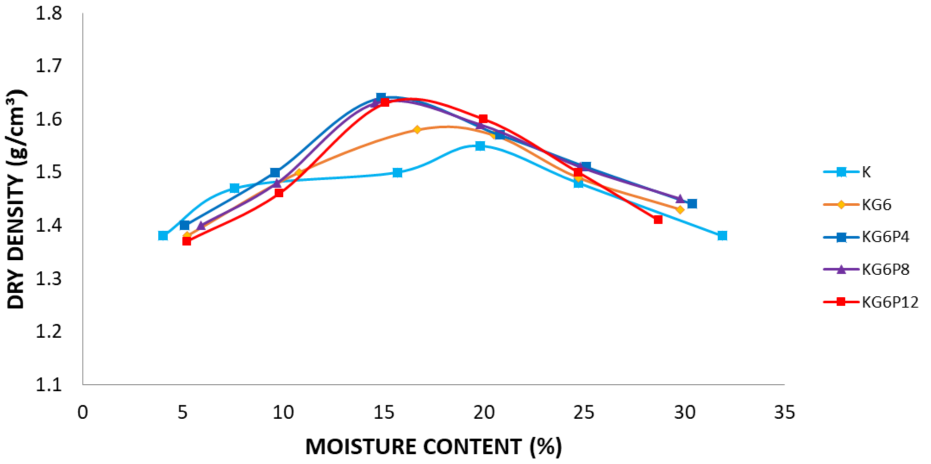

Figure 2. Compaction Curve of kaolinitic clay and stabilized kaolinitic clay with gypsum and POFA

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 3. The shear strength of the kaolinitic clay increased from 16.17 kN/m^2 to 18.32 kN/m^2, 23.62 kN/m^2, 24.59 kN/m^2 and 25.78 kN/m^2 with a strength improvement of 13.29%, 46.07%, 52.07% and 59.43% 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-gypsum-POFA mixture in this research is kaolin mixed with 6% gypsum and 12% POFA with the sample coding KG6P12. At 30 days of curing, the stabilized kaolinitic clay soil using 6% of gypsum and 12% of POFA recorded the highest improvement of shear strength with a value of 64.66 kN/m^2 (299.88% of strength improvement). Therefore, it can be concluded that, the utilization of gypsum at 6% and various proportion of POFA resulted to the significant improvement of the shear strength.

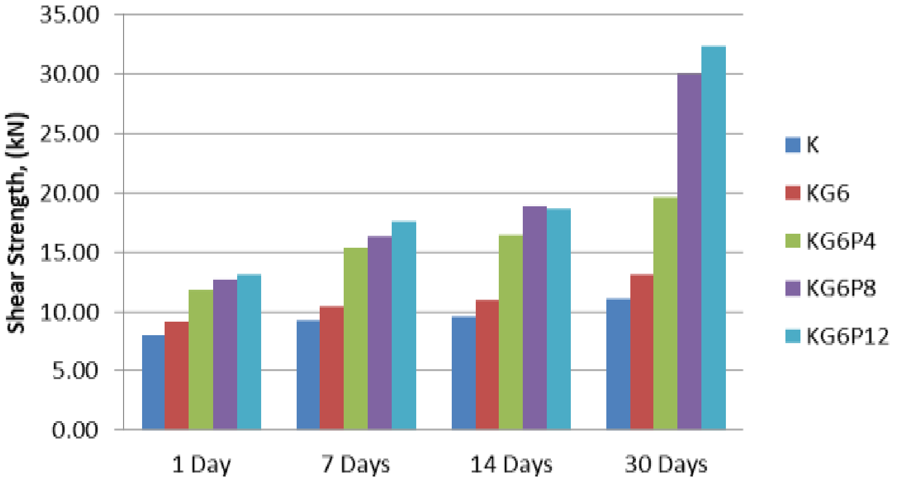

Figure 3. Undrained shear strength of kaolinitic clay soil stabilized with gypsum and POFA

4. CONCLUSION

The primary objective of this research is to investigate the stabilization of kaolinitic clay soil using lime and POFA as stabilizing agents. To accomplish this, the undrained shear strength of kaolin mixed with gypsum and POFA was measured and compared to that of untreated kaolin samples over four different curing periods: 1 day, 7 days, 14 days, and 30 days. From the series of laboratory tests performed, the study classified Kaolin S300 as A-4 by ASTM D3283-93 [23] and ML by USCS, with properties of clayey silts and slight plasticity (LL: 36%, PI: 10%), a specific gravity of 2.62, MDD of 1.55 g/cm³, and OMC of 19.80%. POFA and gypsum were non-plastic with specific gravities of 2.06 and 2.32, respectively. Compaction tests for various mixtures (KG6, KG6P4, KG6P8, KG6P12) showed MDDs ranging from 1.63 to 1.69 g/cm³ and OMCs from 15.50% to 18.50%. The undrained shear strength (USS) of kaolin stabilized with 6% lime and varying POFA improved significantly over curing periods, with KG6P12 achieving the highest improvements: 45.61% (1 day), 89.29% (7 days), 192.40% (30 days), and KG6P8 showing 97.15% (14 days). This stabilization method effectively enhances soil strength and aligns with environmental goals of reducing palm oil industry waste in Malaysia.

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AUTHOR CONTRIBUTIONS

Muhammad Syamsul Imran Zaini: Original draft preparation, Conceptualization, Methodology, Software
Muzamir Hasan: Supervision
Muhammad Khairul Faiz Jamal: Laboratoy works

DATA AVAILABILITY STATEMENT

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

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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