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Improving the Early Properties of Treated Soft Kaolin Clay with Palm Oil Fuel Ash and Gypsum

Abdulmajeed Al-hokabi [1,*], Muzamir Hasan [1], Mugahed Amran [2,3,*], Roman Fediuk [4], Nikolai Ivanovich Vatin [5] and Sergey Klyuev [6]

[1] Department of Civil Engineering, College of Engineering, Universiti Malaysia Pahang, Lebuhraya Tun Razak, Kuantan 26300, Pahang, Malaysia; muzamir@ump.edu.my
[2] Department of Civil Engineering, College of Engineering, Prince Sattam Bin Abdulaziz University, Alkharj 16273, Saudi Arabia
[3] Department of Civil Engineering, Faculty of Engineering and IT, Amran University, Amran 9677, Yemen
[4] Polytechnic Institute, Far Eastern Federal University, 690922 Vladivostok, Russia; roman44@yandex.ru
[5] Peter the Great St. Petersburg Polytechnic University, 195251 St. Petersburg, Russia; vatin@mail.ru
[6] Belgorod State Technological University named after V.G. Shukhov, 308012 Belgorod, Russia; klyuyev@yandex.ru
* Correspondence: alhokabi93@gmail.com (A.A.-h.); m.amran@psau.edu.sa or mugahed_amran@hotmail.com (M.A.)

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Abstract: Soft soil problems and increased production of fuel waste have emerged due to world population growth. These two problems are prompting engineers to introduce new methods of using waste fuel to stabilize the soil. Previous research has shown clear sustained improvements in soil properties using palm oil fuel ash (POFA) when mixed with a calcium-based binder such as NaCl, lime or cement. The use of such a stabilizing agent can reduce the economic problems associated with reducing the cost of waste disposal and create a sustainable ecological system. It is an alternative method of replacing part of the soil to ensure a balance between economic growth and ecological privilege, leading to the achievement of green technology goals. However, this research is aimed at improving the properties of processed soft kaolin clay with a combination of POFA and gypsum. The physical and mechanical properties of all samples were tested. The results showed a decrease in the specific gravity with the addition of POFA and an increase with gypsum alone, as well as a decrease with a mixture of POFA and gypsum and a decrease in the soil plasticity index due to a better increase in the plasticity limit compared to the liquid limit. This is considered a sign of improved geotechnical properties and reduced linear shrinkage. It was also shown that the treated clay showed an increase in the optimal water content and a drop in the maximum dry density. Nevertheless, it can be concluded that the initial properties of the processed soft kaolin clay with the addition of POFA can be significantly improved.

Keywords: Soft Soil; palm oil fuel ash; gypsum; soft kaolin clay; concrete; properties

1. Introduction

Global water presence in clay affects the behavior of it to either shrink or swell [1]. The swelling of expansive clay soil is a result of water content variation, which leads to significant destruction of overlying structures; thus, civil engineering researchers consider this issue [2]. Soil stabilization is the most economical way to improve the properties of the problematic soil; generally, soil stabilization is a method of modifying and enhancing soil properties by blending other materials. Improvements include increasing the compressive and shear strength and bearing capabilities to strengthen geotechnical properties and other applications [3]. When a stabilizer is mixed with soil, the action of change takes four stages. The first two stages are defined as soil modification and the last two stages are classified as stabilization. The first stage is cation exchange, followed by flocculation and agglomeration as a result of water reduction in the second stage. The third stage is known as a pozzolanic reaction, and lastly, the fourth stage is an autogenous healing process [4]. During the stabilization process, two main factors affect the mix design (stabilizer proportions) and the curing period (the curing period is one of the most significant parameters that has an impact on the extent of soil stabilization [5]). There are different ways of soil stabilization [6–9]. Researchers found that some of the byproduct waste materials, which contain a high amount of silica, alumina and lime, might enhance soil characteristics to minimize the issue. Engineers adopted a method of utilizing by-product waste to tackle both issues of problematic soil and massive daily production of biomass solid waste.

By-product materials are produced in massive quantities daily worldwide. They have a negative impact on sustainability and the environment due to the cost of disposal and potential contamination of land and groundwater caused by heavy metals which are part of their chemical composition contents [10,11]. Palm oil production has risen by more than four times in the past 25 years [12]. Biomass of the oil palm industry productions ranked the largest in Malaysia, where a large amount is useless, with 143 million tons of solid and liquid waste in 2012 [13]. Malaysia and Indonesia are the primary palm oil fuel ash (POFA) producers, manufacturing 86% of global supplies, according to [14]. It is also reported that Malaysia's annual production of raw palm oil is about 7 million tones, and it is increasing annually [15]. It is stated that Malaysia produces about 5 million tons of POFA only [16]. Given that open burning is no longer permitted [17], this residue is disposed of in landfills and consequently causes environmental problems such as air pollution and groundwater quality issues because of the leaching of different metals from the ash [18]. POFA contains a large amount of silica and has a high potential to be used as a pozzolanic material [19]. The chemical properties of POFA depend on the burning process, the raw materials used and the burning temperature [20,21]. Treatment of POFA to improve the chemical compositions properties and physical properties by grinding and thermal treatment to increase the fluidity, fineness and effectiveness leads to enhanced strength properties [22]. It is found that utilizing POFA to treat soft clays increased the plastic limit, and overall, utilizing POFA in soft clay treatment reduces the plasticity and improves the consistency of the treated soil, which can be attributed to the agglomeration and flocculation that occurred in the particles of the stabilized soil, as found by [23,24].

Gypsum is mined and has applications in many products such as drywall used in construction, agriculture and industry [25,26]. Gypsum itself is a non-plastic material [27–29]. During the production, construction and demolition of gypsum plasterboards, about fifteen million tons of waste are generated yearly in the world [27,30]. It can be used as a soil amendment that can improve soil characteristics to allow for improved crop yields and soil structure [1]. However, we should consider that the high amount of gypsum in the soil increases the internal sulphate attack [31]. Gypsum is one of the materials used as an alternative in chemical improvement techniques by many researchers [32,33]. It is also found that gypsum partially applied in soil enhanced its physical and chemical properties. It absorbs more water and decreases soil loss, and this is known as the ionic strength effect [34]. The chemical properties of gypsum include a high amount of CaO, which is one of the key factors of enhancing bonding between clay soil particles, as mentioned by [35]. An experimental study was conducted of soil mixed with different percentages of gypsum and it was found that 4% gypsum marked the optimum dosage of gypsum [36]. The optimum moisture content and maximum dry density at 4% gypsum are 11.76% and 19.16 KN/m^3, respectively. It is stated that the unconfined compressive strength increased with the addition of percentages of gypsum to the soft soil, but the UCS values reduced after 6% of gypsum [37].

Kaolin S300 is commonly treated before use because of its low strength and high settlement in the presence of water [38]. Kaolin is easily dispersed in water, having poor geotechnical properties, high plasticity and low workability [39,40]. POFA was used as a means of waste management and it has the potential to be used as a stabilizing agent due to the chemical compositions of POFA as alumina and silica [41,42]. On the other hand, gypsum also was added as a pozzolanic activator and stabilizer [43]. Further, soft soil issues and the increment in palm oil waste productions are in correspondence with the increment in global demand for oil because of world population growth. Malaysia is facing the two main issues that encourage engineers to adopt new methods of using palm oil waste in soil stabilization. Previous investigations have shown an apparent means of sustainable enhancement in soil properties by using POFA when mixed with a calcium-based binder such as NaCl, lime or cement. Utilizing POFA as the stabilizing agent can reduce economic issues by reducing the cost of waste landfill and help attain a sustainable ecological system. To stabilize the soft soil, the addition of POFA and gypsum is required to investigate their effect on modifying the properties of the soil. This is an alternative method to replace some of the soil so that it balances between economic growth and environmental privilege that leads to achieving green technology goals.

The novelty of this study is focused on the use of both POFA as pozzolanic waste, and gypsum as binder as well as the inclusion of pozzolan activator to achieve better properties modification and soil stabilization to sustain a higher load. POFA is abundant and cost-effective, and it is a better method to dispose of it in the engineering field than in landfills. Gypsum is more economical than cement or lime; it can be produced in soil, mined and has no negative impact on environment. However, this study aims to improve the early properties of soft kaolin clay with the combination of POFA and gypsum. This study is presents the materials and methodology used, results, discussion and conclusions to explain the investigation and the effectiveness of POFA and gypsum in the stabilization of soft kaolin clay in terms of physical properties, compaction properties of optimum moisture content and maximum dry density.

2. Materials and Methodology

This research was basically planned to determine the physical properties and the variation of compaction characteristics of the original soft clay and clay treated with POFA and gypsum. The soft clay utilized in this experiment was kaolin; it was substituted and replaced with different percentages of gypsum and POFA. The flow of works followed standard laboratory test procedures and data analysis methods, according to British Standards (BS) and the American Society for Testing and Materials (ASTM). The specific gravity test was conducted according to BS 1377: Part 2: 1990: 8.3 [44]. The liquid limit was conducted according to BS 1377: Part 2: 1990: 4.3 [44], whereas the plastic limit test was conducted according to BS 1377: Part 2: 1990: 5.3 [44]. The linear shrinkage test was conducted according to BS 1377: Part 2: 1990: 6.5 [44]. A standard proctor test was carried out according to BS 1377: Part 4: 1990: 3.3 to determine compaction parameters (optimum moisture content and maximum dry unit weight) [44]. Figure 1 shows the experimental study workflow.

Figure 1. Experimental study workflow.

Table 1 POFA and gypsum. Gypsum and kaolin were imported, whereas POFA was collected from LKPP Corporation Sdn.Bhd, Lepar Hilir Palm Oil Mill, Gambang, Kuantan, Pahang, Malaysia. The amount required of gypsum and POFA was added based on the dry weight of the kaolin S300. All materials were dried in the oven at 105 °C for 24 h. After that, the materials were sieved based on the specific sieve size per test in accordance with British Standard (BS). The mixture prepared was carefully mixed by using a soil mixer until the mixture looked homogenous before testing was carried out. The 4% and 6% gypsum were selected based on the literature review, whereas the POFA (5%, 10%, 15%) percentages were randomly selected to test POFA usage in different amounts with gypsum to treat soil and investigate the enhancement of geotechnical physical and mechanical properties. All the tests were conducted with a minimum of three to five repeated times per sample per test to ensure the consistency and accuracy of the obtained results. Table 1 shows the twelve samples prepared and tested per test.

Table 1. Proportions of the used stabilizing agents.

Kaolin (%)	POFA (%)	Gyp (%)	Code
100	0	0	K
96	0	4	K4G
94	0	6	K6G
95	5	0	K5P
90	10	0	K10P
85	15	0	K15P
91	5	4	K4GP5
86	10	4	K4GP10
81	15	4	K4GP15
89	5	6	K6GP5
84	10	6	K6GP10
79	15	6	K6GP15

2.1. Test Setup and Procedures

The specific gravity (SG) is the ratio between the mass of soil to its volume. It is essential in relation to other tests, especially for calculating porosity and voids. Kaolin, POFA and gypsum were sieved through a 2 mm sieve size and a small pycnometer test was used. Pycnometer bottles maximum capacity is 100 mL [45]. The specific gravity values of kaolin and POFA were obtained with distilled water, whereas gypsum's specific gravity was obtained using kerosene as dissolving material for gypsum because gypsum hardened when utilizing water to obtain specific gravity; the same method was used by [46,47].

The liquid limits of kaolin, POFA and gypsum are determined by using the cone penetrometer method as it is more accurate and less liable to personal and experimental errors. The liquid limit is determined by obtaining a minimum of four points for plotting the curve. The consistency of the soil specimens is adjusted so the cone penetration ranges between 15 mm and 25 mm. The plastic limits of kaolin, POFA and gypsum are determined from the rolling thread method. Liquid limit and plastic limit are very critical indicators corresponding to undrained shear strengths [48]. The liquid limit was conducted after taking a weight of the sample, 300 g (kaolin or kaolin+ POFA, kaolin+ gypsum or kaolin+ POFA+ gypsum), which passed a 425 µm sieve. Then, distilled water was added to the soil specimen after it was mixed for at least 10 min to be homogenous and mixed with two spatulas. The well-mixed soil specimen was then put into the metal cup. The soil's liquid limit is obtained as moisture content at penetration at 20 mm. The plastic limit represents the moisture content at which soil changes to dry to plastic where it is considered the upper strength limit of consistency. The method of rolling a thread is suggested by Casagrande [49]. The sample was rolled on a glass plate until it crumbled at a diameter of 3 mm, weighed and then put in the oven for 24 h; then, the dry samples were weighed. The plasticity index is a workability indicator defined by the difference between the liquid and plastic limit of soil. The most challenging aspects in the soil are shrinkage and swelling, relying on the study of soil plasticity.

Linear shrinkage is defined as the change in the length of the soil bar when dried in the range below the liquid limit [50], which can be calculated as a percentage of the oven-dried soil length to the initial length of the soil bar according to BS 1377: Part 2: 1990: 6.4. Samples were sieved and passed a 425 µm sieve. The mold used was about 140 ± 1 mm and had an internal radius of 12.5 ± 0.5. To establish consistent results, after obtaining the liquid limit per sample, water used for mixing was equal to the percentage of water obtained at 20 mm from liquid limit results [44]. The linear shrinkage test determines the shrinkage strain of elongated specimens placed in a mold and subjected to drying in an oven for 24 h [50]. Linear shrinkage is when the contained water content reduced from a specific range reaches the maximum loss of moisture content and there is no more volume change. Linear shrinkage is a sign that indicates the soil reactivity but not necessarily the particular clay present in the soil [51].

The procedure for conducting this test is described in BS 1377: Part 4 1990: 3.3 [44] and ASTM D 698 [52]. The test is conducted to obtain relationships between compacted dry density and soil moisture content, where the measurement of the degree of compaction can be identified in these terms. The materials were sieved and passed through 4.75 mm. When water is mixed with soil, added in a sequent way of 5% until the mass of mold and mixture showed a drop in weight, water plays the role of a softening agent for the soil particles. In this situation, the soil particles near closer to each other. They are forced to move into a dense position. The sample was compacted in three layers with equal thickness into a metal of about 105 mm internal diameter and about 985 cm^3 volume by a metal rammer with a 50 mm diameter circular face, weighing 2.5 kg and dropping from a height of 300 mm with 25 blows in the mold. The obtained samples were collected during the experiment to attain a representative graph on the variation of dry density with the addition of 5% of water. The effective compaction is determined by four dependents: dry density, water content, compaction type (heavy or light) and soil type. When water content added to the soil sample is plotted against dry densities for each cycle, the highest value in the curves is the most important point, as it highlights optimum moisture content (OMC) and the maximum dry density (MMD).

2.2. Materials

The kaolin powder grade S300 was used in this project. The used kaolin in our experiments is hydrous alumina silicate with the general chemical of formula $Al_2(Si_2O_5)(OH)_4$. Kaolin is considered as one of the huge natural resource deposits in Malaysia, which has around 112 million tones [53]. Kaolin is one of the tropical problematic soils that is exposed to volumetric change due to the seasonal water inconsistency [39]. It is selected to be treated due to its poor and expansive geotechnical properties, as it shows lows shear strength, high plasticity and low workability [39,40,54].

POFA is a by-product material obtained by burning shells and empty fruit bunches in palm oil mill boilers heated at the rated temperature of 800–1000 °C to generate steam. The obtained steam avails as a source of energy utilized in turbines to supply electricity during the milling operation [55,56]. Raw POFA is unusable because of its unknown moisture content. The POFA is shown in Figure 2; it is a pozzolanic waste material from the palm oil industry. A large amount of amorphous silica in POFA potentially contributes to the pozzolanic reaction during hydration, which results in cementation compounds called calcium aluminate hydrates (CAH) and calcium silicate hydrates (CSH). These compounds are responsible for improving engineering characteristics of soil that increase over time as a pozzolanic reaction. POFA is generated in huge quantities, mainly in developing countries. Indonesia and Malaysia are the primary POFA producers, manufacturing 86% of global supplies according to [10].

Figure 2. Kaolin, Gypsum and POFA used in Laboratory work.

Gypsum is a soft white mineral consisting of hydrated calcium sulphate, as shown in Figure 2; the chemical formula is calcium sulphate dihydrate ($CaSO_4$. $2(H_2O)$). It is a naturally occurring mineral that is comprised of calcium sulphate and water, and it is sometimes called hydrous calcium sulphate. Gypsum has better properties than organic additives because it does not cause air pollution and it is cheaper than cement, fire-resistant and resistant to deterioration by biological factors and chemicals [29,57]. It is also a by-product of many industrial processes. It is suggested that both coagulation and cementation in soil may be achieved by the addition of gypsum and cement or lime, with significant improvements in soil structure [25]. Malaysia still considers the by-product of gypsum or red gypsum as scheduled waste [58].

Gypsum, POFA and kaolin samples are shown in Figure 2, which exhibits that the color of any material is influenced by the mineralogy property of the material. Gypsum is appeared to be white; while POFA had a black color, but the finer the POFA, the more greyish than black; and kaolin has a creamy to a whitish color. In terms of texture, kaolin is very fine, smooth and soft; POFA has a gritty sandy texture, but it seems to be wet and smooth in particles smaller than 0.425 mm; and gypsum has a gritty, silty sand texture. Table 2 shows the chemical properties.

Table 2. Chemical Compositions of Kaolin, POFA, and Gypsum.

Material/Chemical Name	Component Formula	Kaolin	POFA	Gypsum
Alumina	Al_2O_3	17.1	1.33	1.25
Ferrite	Fe_2O_3	0.626	8.71	0.422
Silica	SiO_2	73.5	35.9	4.97
Lime	CaO	-	13.2	47
Potassium Oxide	K_2O	7.23	35.4	0.756
Magnesia	MgO	0.79	1.24	0.816
Sulfur trioxide	SO_3	0.102	1.39	44.6
Titanium dioxide	TiO_2	0.343	-	-
Phosphorus Pentoxide	P_2O_5	-	1.91	0.164
Manganese(II) oxide	MnO	-	0.257	-
Chlorine	Cl	-	0.256	-

3. Results and Discussions

3.1. Physical Properties

3.1.1. Particle Size Distribution

The analysis of particle size curves for representing samples are displayed in Figures 3 and 4. From the graph, approximately 76% of kaolin passed through sieve 0.075 mm; further, 43% passed sieve #270 (0.053 mm) with uniformity coefficient Cu = 1.6 and curvature coefficient CC = 0.87, which meant that the average size of the kaolin particles analysis was in the range of 0.001 mm to 0.2 mm (clay to fine silt). Therefore, with the corresponding results obtained from consistency limits tests, kaolin is classified as a fine-grained clayey silt (ML), according to USCS and classified under Group A-6 under AASHTO. POFA was classified as (SM) a poorly graded silty sand, corresponding to USCS, as 95% passed #4 (4.75 mm), only 19% passed through sieve #200 (0.075 mm) and 10% passed sieve #270 (0.053 mm) with uniformity coefficient Cu = 4 and curvature coefficient CC = 1. The sieve analysis of gypsum showed that only 4% passed through sieve 0.075 mm; therefore, it is also classified as poorly graded sand and (SP) according to USCS, with Cu = 2.2.

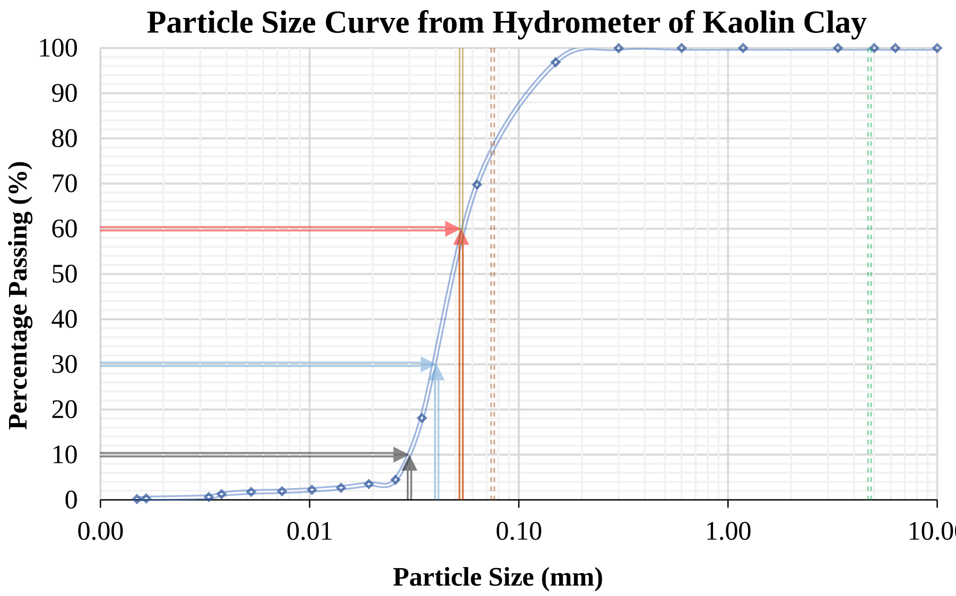

Figure 3. Particle size distribution of original kaolin clay.

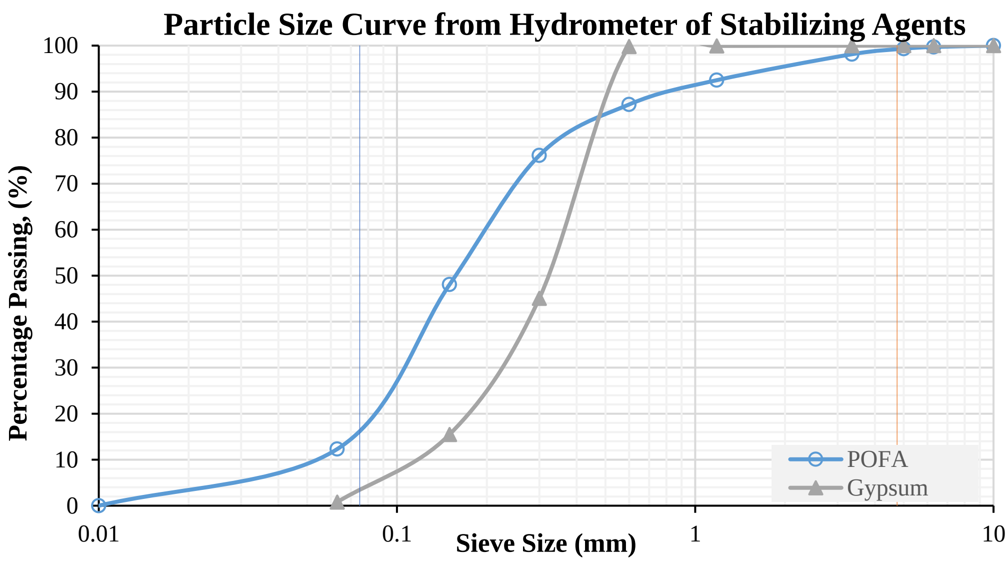

Figure 4. Particle size distribution of stabilizing agents (POFA and gypsum).

3.1.2. Natural Water Content and Specific Gravity

The kaolin, POFA and gypsum were analyzed for natural moisture content directly after being imported and collected. Table 3 illustrates the particle density and natural water content of kaolin, POFA and gypsum. As POFA was collected from an open area, the natural moisture content was the highest, whereas it had the lowest specific gravity. Kaolin marked the highest specific gravity, followed by gypsum. The reason behind the low specific gravity of POFA is because it contains some fibers, and previous researchers found that the specific gravity of POFA can be increased with burning, grinding and treatment, and results confirmed that the finer the POFA, the higher the value of specific gravity [21,59]. Various factors affect the specific gravity, one of them being the fineness of the material, where a higher proportion of silt corresponds to higher specific gravity [60]. The POFA, as an example, is affected by the treatment processes and the burning temperature. The m finer it is, the higher the specific gravity [21,59].

Table 3. Summary of particle density and natural water content of materials.

Sample	Specific Gravity, SG (g/cm^3)	Natural Moisture Content (%)
Kaolin	2.71	0.457
POFA	2.25	4.494
Gypsum	2.66	1.093

From Figure 5, K4GP10 showed the lowest specific gravity of 2.59 g/cm^3, followed by K6GP15, with specific gravity of 2.60 g/cm^3; in contrast, the highest specific gravity is of K6G, which reached a value of 2.78 g/cm^3, followed by K4G, with a value 2.74 g/cm^3. The specific gravity of kaolin was decreased when POFA was applied alone—it dropped from 2.69 g/cm^3 to 2.61 g/cm^3 compared to the specific gravity of original kaolin, which is 2.70 g/cm^3. On the other hand, it was increased with the addition of gypsum alone. The overall mixture of both POFA and gypsum demonstrated a reduction in the specific gravity lower than the original soil. One reason behind the specific gravity reduction is due to the low specific gravity of POFA compared to kaolin. Another reason might be the high amount of lightweight buoyant fibrous material in POFA, which float on water. The chemical reactions of POFA and gypsum also play a role in the reduction, where gypsum alone with clay showed an opposite result. An overall investigation of treated clay showed a clear decrement in its specific gravity with the addition of POFA and gypsum.

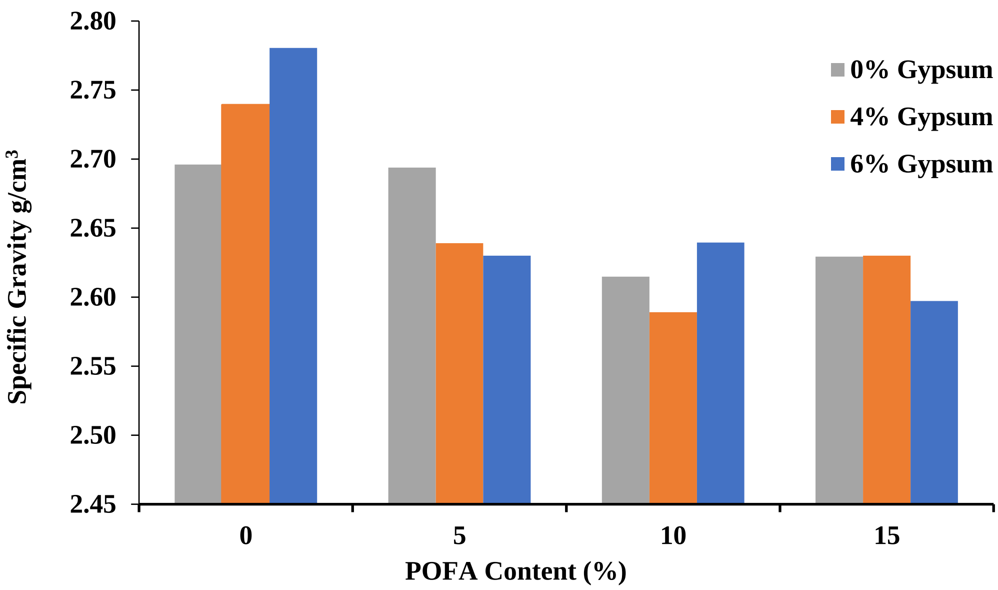

Figure 5. Specific gravity of kaolin and treated kaolin with POFA and gypsum.

3.1.3. Liquid Limit

Figure 6 illustrates the liquid limit results of both untreated and treated kaolin. The addition of POFA and gypsum mixed with kaolin increased its liquid limit. K4GP15 showed the highest value of 43.11% water content, followed by K6GP15 with 42.60%. Gypsum alone at 4% and 6% also showed a slight increment in the liquid limit value, from 40.18% for original soil to 40.30% and 41.19%, respectively. POFA alone mixed with kaolin absorbed much water and showed higher liquid limit in samples K5P, K10P and K15P. One reason for the increment may be the high amount of fiber in POFA, which absorbs a significant amount of water, or it might be the increase in CaO content in POFA and gypsum, which usually absorb more water; these results agree with those of [10,37]. Another reason for the increment in the liquid limit might be due to an elongation of the diffuse double layer as a result of the increment in the specific surface area, which assisted in the soft soil's capacity to hold more water; the results showed agreement with soft clay treated with high calcium fly ash investigated by [61]. It was also found that by adding a small amount of ultrafine POFA, the liquid limit increased [24], whereas by adding more than 10%, the liquid limit decreased as along with the plastic limit, which agrees with the results found in this work. In general, the drop in soil plasticity due to using of POFA and POFA-blended gypsum is a sign of enhancement. It was also reported that the high porosity of binder materials with an agglomerated morphology could lead to a reduction in the workability due to the increase in the water absorbed by the large open areas of high porosity POFA [61]. Table 4 shows the standard deviation and variance per sample for the liquid limit tests.

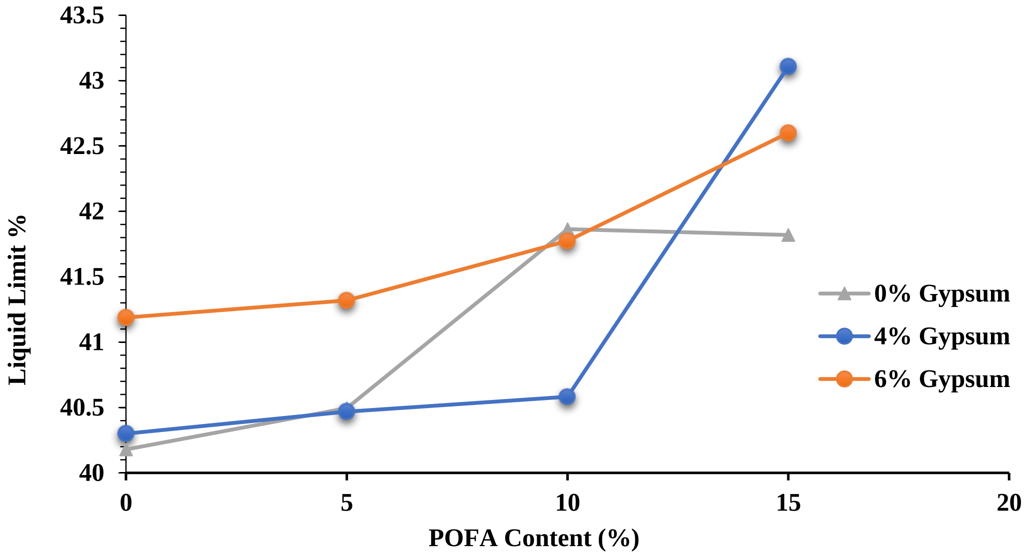

Figure 6. Liquid limit of kaolin treated with various dosages of POFA.

Table 4. Summary of standard deviation and variance of the specimen of liquid limit.

Sample	Standard Deviation	Variance	Sample	Standard Deviation	Variance
K	0.874	0.022	K4GP5	0.454	0.011
KG4	0.252	0.006	K4GP10	1.302	0.031
KG6	0.234	0.006	K4GP15	0.248	0.006
KP5	0.671	0.017	K6GP5	0.124	0.003
KP10	0.374	0.009	K6GP10	0.438	0.011
KP15	0.060	0.0014	K6GP15	0.033	0.0008

3.1.4. Plastic Limit

The plastic limit of the control sample is 30.72%, as shown in Figure 7. It is apparent that the plastic limit was increased, save for a reduction with the addition of sole gypsum to kaolin in KG4 and KG6. It then showed a drop to 29.85% and 29.24% in K5P and K6GP5, respectively. On the other hand, overall increments were detected in all other samples, especially with the addition of POFA. K4GP15 marked the highest plastic limit of 35.27% followed by K6GP15 with a plastic limit of 35.16%. The previous reasons described as affecting the increment in the liquid limit also affected the plastic limit. It is also interpreted that a constant increment might be attributed to the agglomeration and flocculation that occurred in the particles of the POFA-treated soil, similar to a study on clay treated with

POFA and calcium carbide conducted by [23,61]. The enhancement of the plastic limit referred to the change in the index of plasticity from silt with medium plasticity to low plasticity because of the addition of POFA and gypsum, which have a higher particle size than kaolin [62]. Table 5 shows the standard deviation and variance per sample for plastic limit tests.

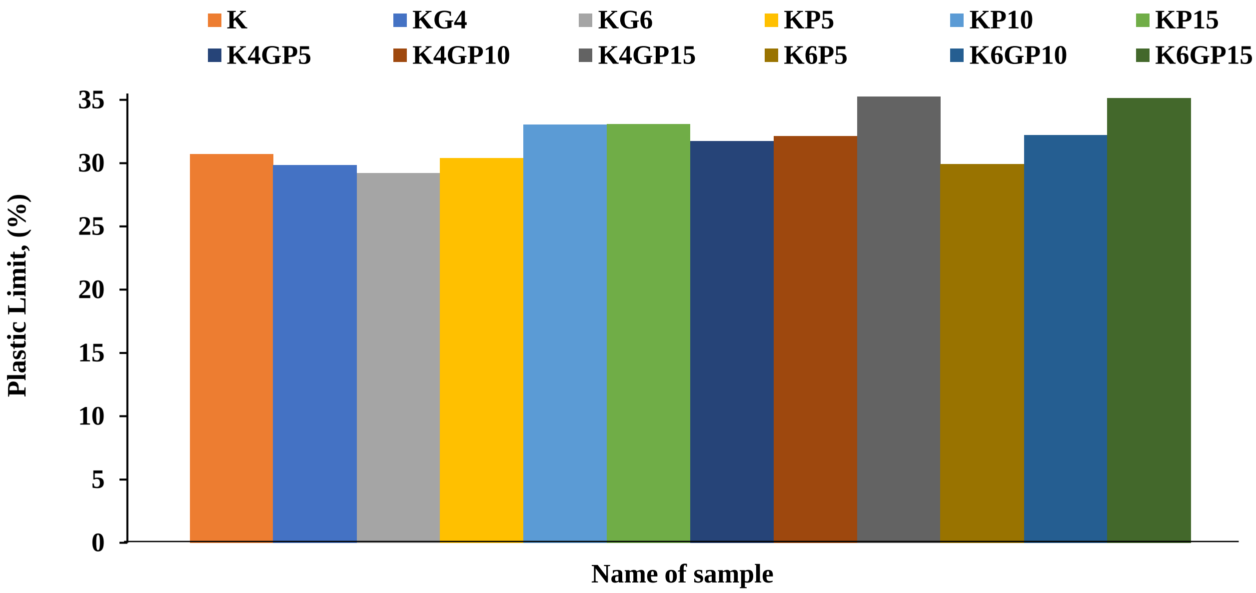

Figure 7. Plastic limit of kaolin treated with various dosages of POFA.

Table 5. Summary of standard deviation and variance of the specimen of plastic limit.

Sample	Standard Deviation	Variance	Sample	Standard Deviation	Variance
K	0.737	0.024	K4GP5	0.677	0.022
KG4	0.058	0.0019	K4GP10	1.684	0.050
KG6	0.492	0.0166	K4GP15	0.187	0.006
KP5	1.442	0.048	K6GP5	0.323	0.011
KP10	1.526	0.045	K6GP10	0.175	0.005
KP15	1.135	0.0335	K6GP15	0.325	0.0092

3.1.5. Plasticity Index

From Figure 8, it can be seen that even though the plasticity index is reduced by adding POFA, more POFA corresponds to more deduction in plasticity index value. The plasticity index was slightly increased with the addition of gypsum because of the clear raise in soil plastic limit to a tendency higher than the increment in the liquid limit with the addition of both POFA and gypsum. K4G, K6G and K6GP5 showed a small increment due to the chemical reaction of soil with gypsum. K4GP15 was marked by the lowest plasticity index, with 7.84%. Consistency limits of treated soil with gypsum found that the decrement of the PI is controlled by shearing resistance and the double-layered diffusion of clay [25]. Table 6 demonstrates the standard deviation and variance per sample for plasticity index.

Table 6. Summary of standard deviation and variance of the specimen of plasticity index.

Sample	Standard Deviation	Variance	Sample	Standard Deviation	Variance
K	1.30	0.145	K4GP5	0.956	0.098
KG4	0.310	0.030	K4GP10	0.382	0.047
KG6	0.258	0.017	K4GP15	0.435	0.058
KP5	1.949	0.198	K6GP5	0.447	0.038
KP10	1.899	0.235	K6GP10	0.263	0.028
KP15	1.075	0.135	K6GP15	0.293	0.040

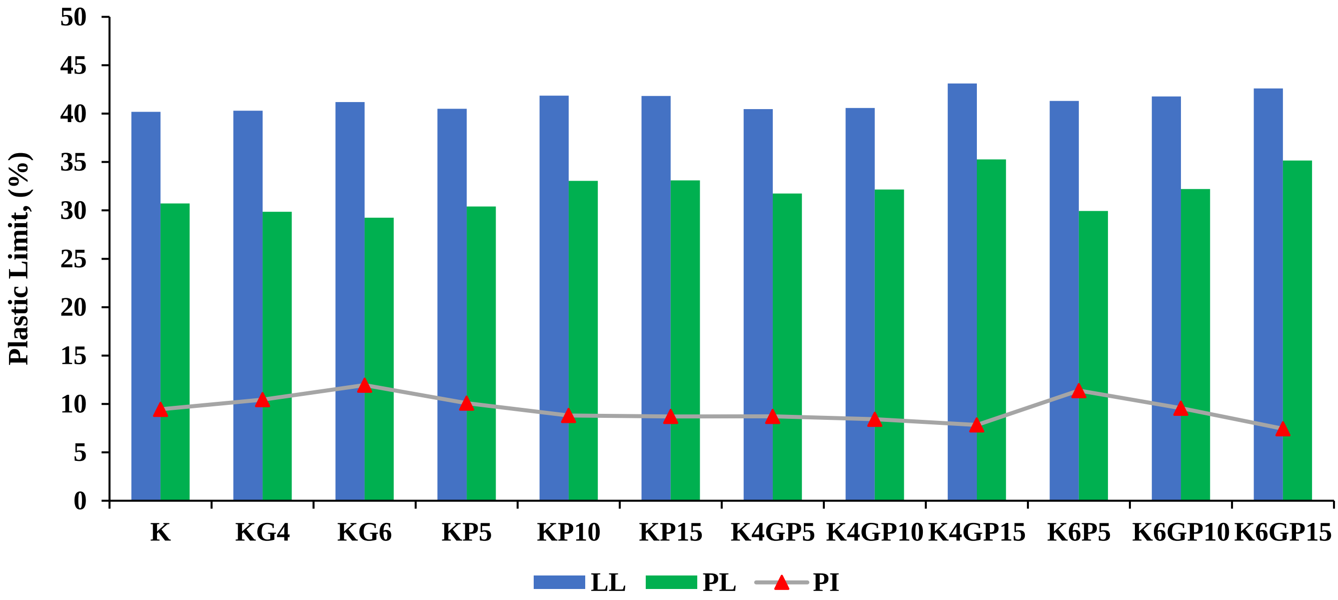

Figure 8. Plasticity index of kaolin treated with gypsum and POFA.

3.1.6. Linear Shrinkage

The results of linear shrinkage in Figure 9 show that kaolin does not have a high tendency to shrink, as only a 1.55% reduction in the mold length occurred. The results show that linear shrinkage was generally reduced with the addition of POFA or gypsum, where KG6 illustrated the lowest value of linear shrinkage with only 0.5%, followed by KP15 with 0.77%. The linear shrinkage showed a different reaction with the mixture of both POFA and gypsum. The value increased to 2.13% for K6GP10, which marked the highest overall value among all samples. The slight reduction that occurred is predictable due to the chemical reactions between gypsum with POFA and clay, which lead to the reduction in plasticity properties and related linear shrinkage [50].

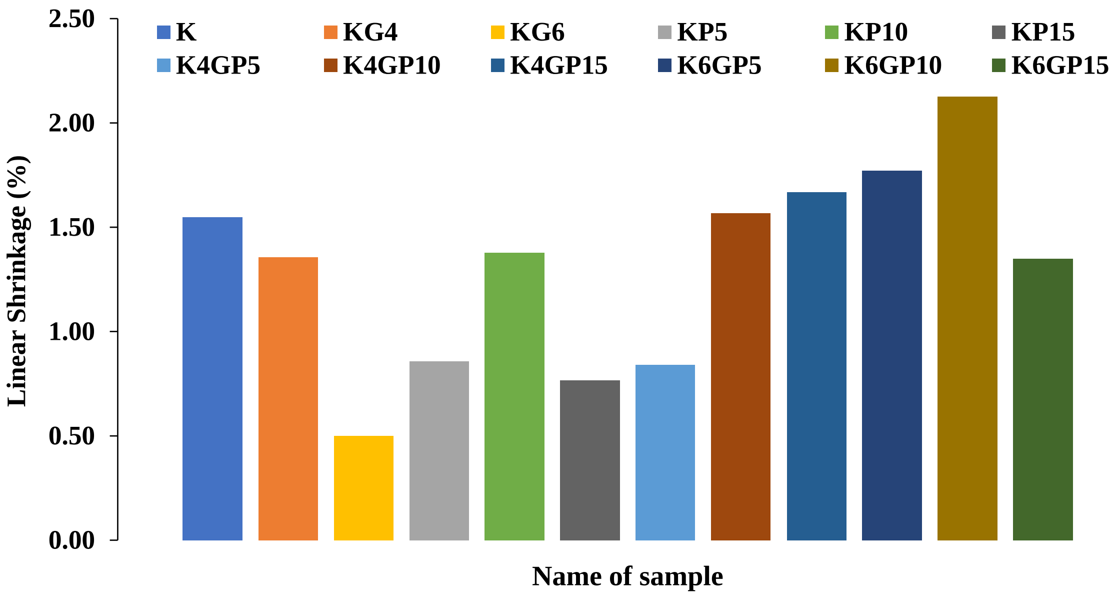

Figure 9. Linear shrinkage of kaolin and treated kaolin with POFA and gypsum.

3.2. Mechanical Properties

3.2.1. Variation of Dry Density with Addition of Water

The compaction curves were plotted, as shown in Figures 10–13. From Figure 10, water absorption was increased by adding POFA dosage; it is apparent that with more POFA, higher water content is needed to obtain the optimum moisture content and maximum dry density. With the addition of more POFA content to kaolin, the maximum dry density achieved was decreasing accordingly. It can be interpreted as the POFA having lower specific gravity compared to kaolin and gypsum. The results showed an increase in OMC of the treated kaolin with POFA, results which are in line with previous work [63–66]. The referred increment can be explained as a result of crowding out of calcium ions released from POFA during ionic dissociation of hydrolyzed calcium oxide of POFA and pozzolanic reaction between calcium ions of POFA and SiO_2 in kaolin, where both are considered as a factor of soil chemical stabilization.

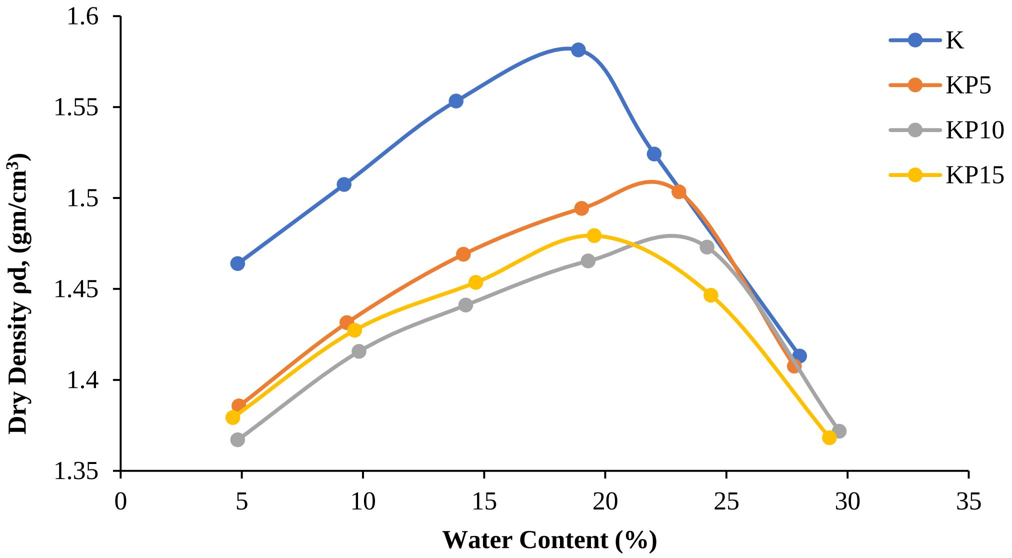

Figure 10. Variation of MDD and OMC of treated kaolin with various POFA content.

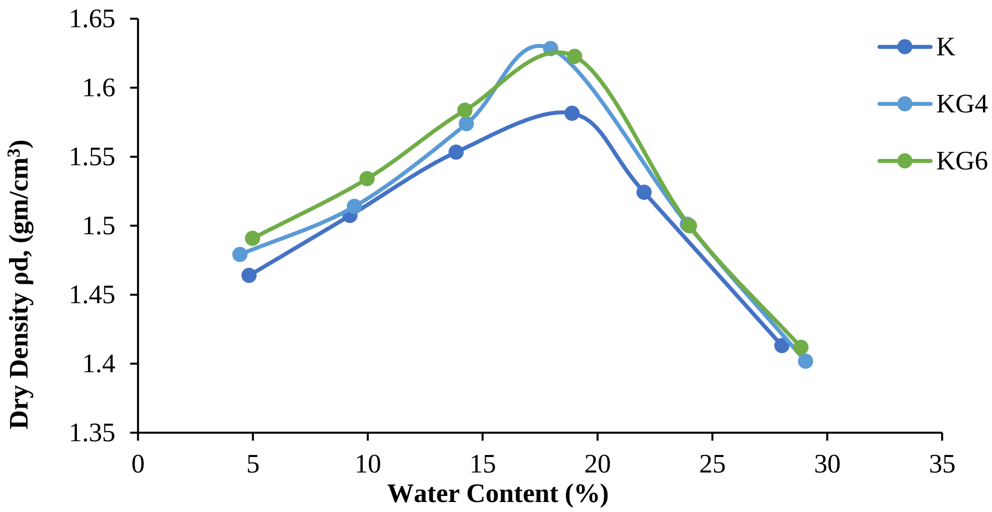

Figure 11. Variation of MDD and OMC of treated kaolin with gypsum content.

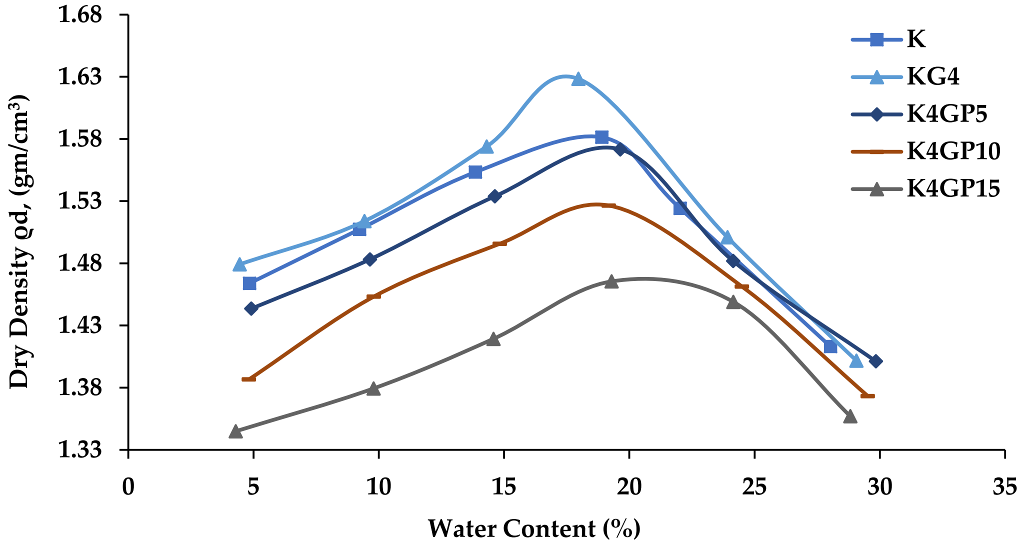

Figure 12. Variation of MDD and OMC of treated kaolin with 4% gypsum and various POFA content.

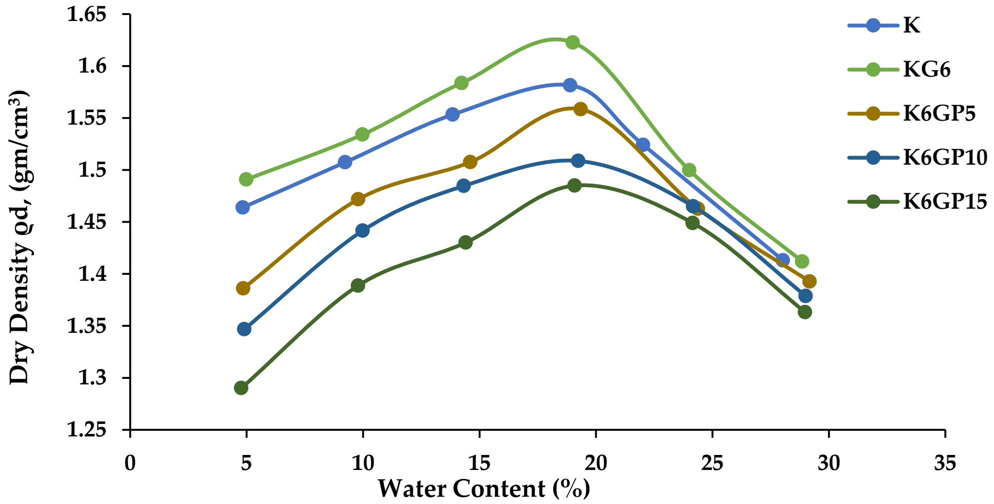

Figure 13. Variation of MDD and OMC of treated kaolin with 4% gypsum and various POFA content.

As seen in Figure 11, there was a slight reduction in maximum dry density and increment in the optimum water content of the treated samples with the addition of gypsum. The change in standard compaction test results was not high with the addition of gypsum only, compared to the control sample. These results agree with previous research works that reported that the addition of gypsum to clay soil can increase the absorption of water content needed for the chemical reaction [34].

The addition of different percentages of POFA with 4% and 6% of gypsum content is shown in Figure 12. The maximum dry density of KG4 and KG6, 1.63 gm/cm^3 and 1.62 gm/cm^3, respectively, was higher than the control sample, but it slightly dropped to reach the lowest at K4GP15 with 1.46 gm/cm^3 compared to 1.58 gm/cm^3 as MDD of kaolin. This can be explained as a result of higher water absorption required by porous POFA, which conquers the pore space of POFA soil and leads to particle buoyancy [65]. The higher amount of fiber in the added POFA also affected the reduction in maximum dry density and the specific gravity of treated clay [19,67]. The reduction in maximum dry density might be due to the resistance of compaction as a result of the flocculation of soil particles during soil stabilization [5].

3.2.2. Maximum Dry Density (MDD)

The maximum dry density increased from 1.59 gm/cm^3 for kaolin alone to 1.63 g/cm^3 and 1.62 g/cm^3 for K4G and K6G, respectively, as the gypsum absorbs more water during compaction, as shown in Figure 15; these results are in line with those presented by [32,35,68,69]. However, when adding up 5%, 10% and 15% of POFA with gypsum, the MDD continued to drop until reaching 1.465 g/cm^3 for K6GP15 as the lowest. On the other hand, POFA alone mixed with kaolin of 15% started to increase, as the maximum dry density of K10P is 1.475 g/cm^3 whereas K15P reached 1.482 g/cm^3. A drop in the maximum dry density value by adding POFA is predicted due to the too low specific gravity of POFA (2.25) [67]. Previous results on POFA used as a stabilizer with lime conducted by [19] found that the density of soil is affected by lime content—predicted to be present in our gypsum—where the lime tends to absorb the water and hence, decrease the maximum dry density of treated soil. The maximum dry densities of kaolin and treated kaolin are shown in Figure 14. Table 7 displays the standard deviation and variance per sample for the liquid limit tests.

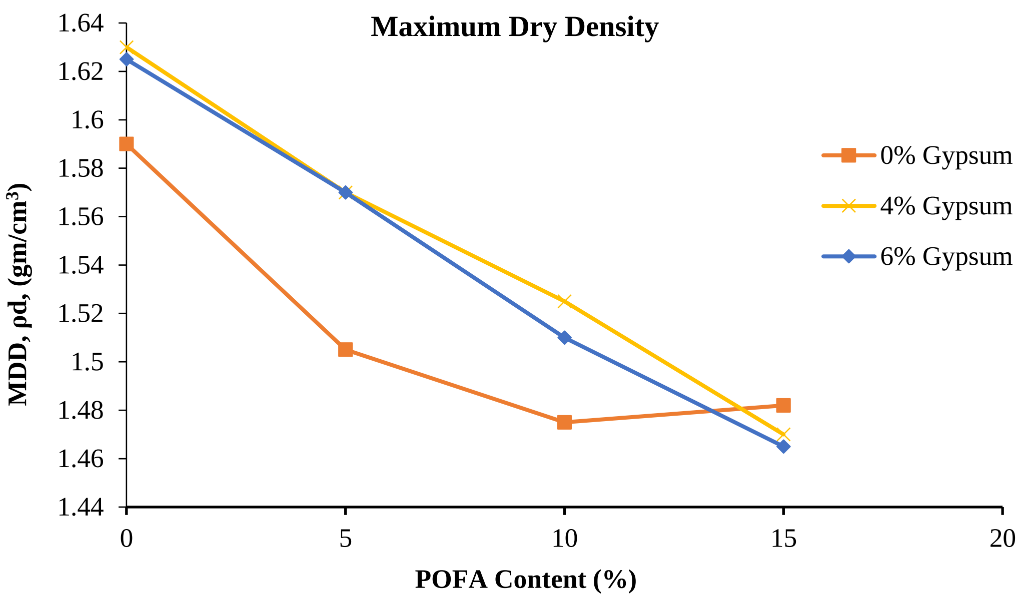

Figure 14. MDD of treated kaolin with various POFA content and gypsum.

Table 7. Summary of standard deviation and variance of MDD.

Sample	Standard Deviation	Variance	Sample	Standard Deviation	Variance
K	0.007	0.004	K4GP5	0.035	0.022
KG4	0.021	0.013	K4GP10	0.028	0.019
KG6	0	0	K4GP15	0.006	0.004
KP5	0.0035	0.0024	K6GP5	0.007	0.005
KP10	0.007	0.005	K6GP10	0.007	0.005
KP15	0.014	0.0095	K6GP15	0.021	0.014

3.2.3. Optimum Moisture Content (OMC)

The optimum water content of kaolin and POFA–gypsum-treated kaolin is shown in Figure 15. The optimum water content increased because the tendency of POFA for water absorption is high. This tendency is clearly explained by OMC, which increased from 18% for the control sample to 24% for KP10, but when adding more POFA, the water content drops until reaching 19.2% for KP15. The water content is slowly increased when gypsum is added compared to the values of POFA, therefore, with kaolin soil, the more POFA added, the higher the optimum moisture content achieved, similar to results published by [30,65,67,70]. The high amount of CaO in gypsum can be one of the reasons behind the increment in water absorption by treated soil; [3] mentioned that lime is known to decrease the plasticity index and maximum dry density of the soil and increase its optimum water content. Table 8 summaries the standard deviation and variance of OMC values.

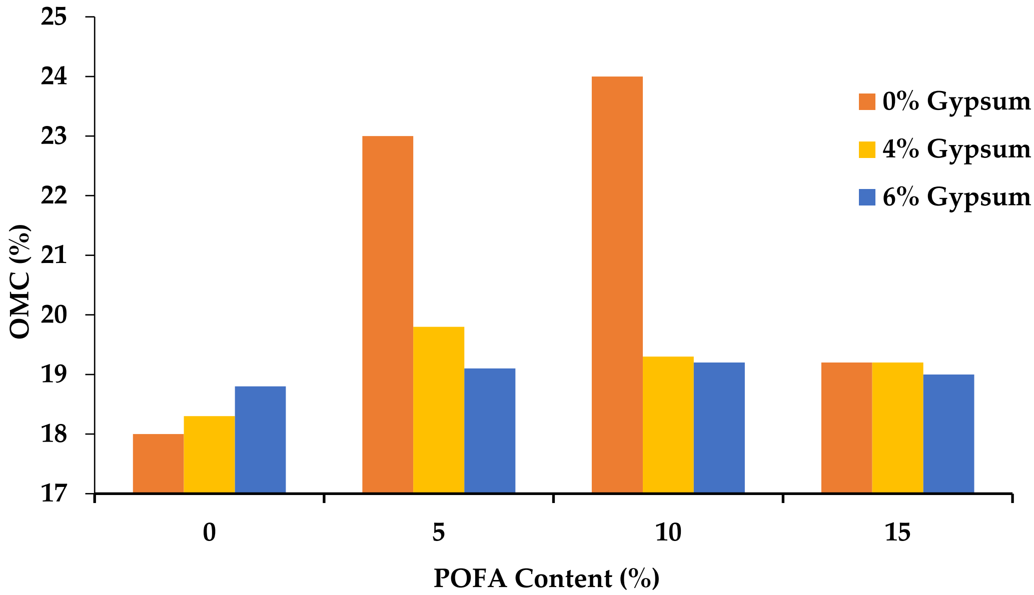

Figure 15. Optimum water content of treated kaolin with various POFA content.

Table 8. Summary of standard deviation and variance of OMC.

Sample	Standard Deviation	Variance	Sample	Standard Deviation	Variance
K	0.353	0.0199	K4GP5	0.156	0.008
KG4	1.103	0.059	K4GP10	0.509	0.026
KG6	0.127	0.007	K4GP15	0.100	0.0052
KP5	1.414	0.643	K6GP5	0.311	0.016
KP10	0.495	0.021	K6GP10	0.382	0.0196
KP15	0.127	0.0066	K6GP15	0.063	0.003

4. Conclusions

This research is aimed at improving the properties of processed soft kaolin clay with a combination of POFA and gypsum. POFA and gypsum were separately utilized to treat kaolin to evaluate the singular effect per material. POFA alone exhibited low effectiveness in enhancing soil properties; it is better to be mixed with gypsum. The changes in compressive and shear strength capabilities provided with SEM and EDX can highlight a greater effect of pozzolanic reaction with 0 days, (24 h) 1 day, 7 days and 28 days of curing. Over the course of the studies carried out, the following main results were obtained:

- In general, kaolin had the highest specific gravity of 2.70 compared to gypsum (2.66) and POFA (2.25). The result also showed a reduction in specific gravity of kaolin when mixed with POFA; however, specific gravity of kaolin is increased when mixed with gypsum, likely due to the type of chemical composition generated and the degree of decomposition or dissolution with water.
- The liquid limit increased with the addition of gypsum and POFA, as they absorb more water. The plastic limit increased due to the sand properties of POFA and gypsum, and thus, the plasticity index marked a clear decrement that can be a sign of the improvement of soil properties when treated with POFA and gypsum. The effect of sandy POFA and gypsum also decreased the linear shrinkage of kaolin.
- The compaction test is considered an important geotechnical indicator in this research, as other tests such as unconfined compression tests and falling head permeability tests

depend on the results obtained from this test. The result of this test demonstrated an overall increment in optimum water content by adding more POFA and a decrement in maximum dry density, related to the porosity and low specific gravity of POFA as well as the tendency of water absorption by both POFA and gypsum. Meanwhile, the results did not show a remarkable increment in water content when kaolin was mixed with gypsum alone.

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