Compaction Characteristics of Kaolin Reinforced with Raw and Rubberized Oil Palm Shell

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Abstract: This paper presents an attempt to evaluate the suitability of oil palm shell (OPS) and rubberized OPS (ROPS), an alternative bio-material, as reinforcement in kaolin. OPS was surface coated with rubber, and its water absorption potential was studied in 5 media involving water and kaolin samples (with different water contents). The water absorption data measured in the laboratory was used as an indirect measure to verify the degradability of ROPS samples when used as reinforcements in kaolin. The surface treatment of OPS with rubber was found to perform well, with around a fivefold decrease in water absorption, thus making it an ideal treatment procedure to this end. Kaolin-ROPS mixtures with different OPS and ROPS proportions (0, 5%, 10%, 20%, and 30% by weight) were prepared in laboratory to evaluate their compaction behaviors. Both standard proctor compaction and mini-compaction procedures were adopted in this study to ensure applicability of the findings across a wide range of compaction methods adopted in the laboratory. Compaction curves obtained for both kaolin-OPS and kaolin-ROPS mixes showed a decreasing trend in the maximum dry density values with increasing proportions of OPS and ROPS. Optimum water content of kaolin-OPS mixtures did not show a significant variation, while kaolin-ROPS mixture showed a downward trend with increasing ROPS contents, thereby signifying improvement in the compaction characteristics after OPS reinforcement in kaolin.

Keywords: surface coating; synthetic rubber; standard proctor compaction test; mini-compaction test

1. Introduction

Recent decades have witnessed the transition of research and industry towards sustainable developments. Solid wastes or biomass have seen increased utilization/reuse for reinforcement and stabilization of problematic soils. Reduction in greenhouse gas emission and a greater use environmentally friendly materials are the key reasons for this development. Biomass predominantly used for soil reinforcement typically involves fibrous and shell-type materials, which prove to be a cost-effective and eco-friendly alternative to synthetic grids and strip-type geotextiles. Among the various locally available bio-wastes, jute, bamboo, coir, and oil palm-based fiber are the frequently studied materials [1], and have demonstrated notable efficiency in improving the strength, ductility, and stiffness in clayey soils. Oil palm-derived fibers have displayed inherent ability to interlock the soil particles together, resulting in a high-strength coherent matrix [2]. Oil palm shell (OPS) is one such bio-mass or by-product commonly obtained from palm oil mills. OPS, also known as palm kernel shell, is derived from the palm oil extraction process, mostly in the form of raw shell fractions. OPS is
well known for its properties such as low specific gravity (typically 1.14 to 1.62) and low bulk density (typically 4.9 to 5.9 kN/m$^3$) depending on its age and species [3].

OPS, an agricultural solid waste, inevitably undergoes biodegradation. Its decomposition rate is subjective and varies depending on the presence of moisture and air [4]. As expected in a wide range of natural materials, water absorption most likely initiates the degradation process in OPS as well. The cause of OPS’s high-water absorption is partly attributed to the presence of fibers and pores on the surface of the shell [5,6]. Moreover, water absorption of OPS is highly influenced by the species of palm tree [3]. Studies estimate 14% to 33% water absorption when OPS are water soaked for 24 h [6,7], while another study shows that the average period of decomposition for untreated oil palm residues, including empty fruit bunches, leaflets, rachis, eco-mat, and palm fronds, is around eight months [8]. However, with a low nutrient content, which is optimum for decomposition as compared to other oil palm residues [9], OPS is likely to decompose at a much faster rate. For this reason, processing OPS into a less biodegradable form is crucial before utilizing and exposing it to moist soil environments. Various treatment methods have been tried to improve and reduce the water absorption of OPS and natural fibers. Studies involving OPS in concrete applications show pre-treatment of OPS using preservatives such as sodium dichromate solution, ferrous sulphate solution, and polyvinyl alcohol solutions [4]; in which studies polyvinyl alcohol (PVA) showed promising results by reducing movement of water into OPS. A recent study demonstrates heat treatment as another promising approach to reduce water absorption [10]. While these studies use advanced methods, traditional rubber-based coating, which has demonstrated its effectiveness in corrosion and chemical resistivity for steel items [11], is likely an eco-friendly approach. Notwithstanding this, rubber-based liquid sealants are resistant to water and moist air; moreover the physical treatment of OPS with synthetic liquid rubber can help decelerate the biodegradation process, while generating the least disturbance to the chemical and structural properties of the OPS.

Soil compaction is one of the commonly used soil improvement methods to enhance structural and mechanical properties by reducing the air-phase volume in the soil mass without changing the water volume within the pore space. Soil compaction typically aims to increase the bearing capacity and shear strength of soil, while reducing permeability and settlement of the soil mass by reducing its porosity [12,13]. The compaction characteristic in terms of optimum moisture content ($w_{\text{opt}}$) and maximum dry unit weight ($\gamma_{\text{dmax}}$) is rather important to ensure preparation of the soil base-layer with sufficient bearing for almost all construction works. Nonetheless, it is also crucial to identify the effect of varying compaction efforts, as this can play an important role in applicability of the results. Most of the published research bases its discussions mainly on compaction efforts using standard proctor and modified proctor compaction tests. The mini-compaction procedure [14] is another method which is highly preferred for fine grained soils. It should be noted that very limited studies have reported the compaction characteristic of natural fibers and shell-like material reinforced soil using the mini-compaction method. In addition, the difference in results between the standard proctor compaction and mini-compaction methods, due to variation in energy transmission during the compaction process, raises concern [15], which has led to a research gap requiring comparison of results from both these test procedures to arrive at reliable conclusions.

The main aim of this study is to evaluate the suitability of the ROPS samples as another effective reinforcement material for kaolin in improving the compaction characteristics and behavior of the ROPS-kaolin samples, using laboratory compaction tests. Effectiveness and performance of coating layer(s) of rubber sealant on the OPS’s surface is evaluated against resistance to water absorption. The compaction characteristics and behavior of thus prepared OPS-kaolin and ROPS-kaolin samples are evaluated in the laboratory. In this process, a comparative study between standard proctor compaction and mini-compaction [14] procedures are also conducted to identify any variation in results due to varying compaction efforts and procedure. The paper therefore presents an elaborate discussion of the results in comparison to relevant literature.
2. Material and Methodology

The kaolin sample used in this study was procured commercially. The kaolin sample was tested in the laboratory to evaluate its basic geotechnical properties. Table 1 tabulates the laboratory procedures used and the geotechnical properties of the kaolin sample. OPS samples used this study were procured from an oil palm mill/plantation located in Klang region of the Selangor state in Peninsular Malaysia. The OPS samples thus transported to the Soil Research Laboratory located at Monash University Malaysia were initially washed with clean water to remove any oil residues. The samples were then dried to remove moisture using oven-drying method in the laboratory—Under a constant temperature of 105 °C for 24 h. Table 2 tabulates the key physical properties of the OPS samples used in this study. Please note that the variations in the properties are expressed as a range denoting the top and bottom limits of the measured properties.

Table 1. Geotechnical properties of the kaolin used in this study.

| Soil Type | Kaolin | Procedure |
|-----------|--------|-----------|
| Specific Gravity, $G_s$ | 2.65 | ASTM D854-14 [16] |
| **Particle Size Distribution** | | |
| Clay (%) | 22 | ASTM D422-07 [17] |
| Silt (%) | 78 | |
| Sand (%) | 0 | |
| Gravel (%) | 0 | |
| $D_{90}$ (mm) | 0.013 | |
| $D_{60}$ (mm) | 0.008 | |
| $D_{50}$ (mm) | 0.004 | |
| $D_{30}$ (mm) | 0.003 | |
| $D_{10}$ (mm) | 0.001 | |
| Coefficient of uniformity, $C_u$ | 8.0 | |
| Coefficient of curvature, $C_c$ | 1.1 | |
| **Consistency Limits and Soil Classification** | | |
| Liquid Limit ($w_L$) | 64 | ASTM D4318-17 [18] |
| Plastic Limit ($w_P$) | 38 | |
| Plasticity Index ($I_p$) | 26 | |
| USCS soil classification | MH $^a$ | ASTM D2487-17 [19] |

Compaction Characteristics—Standard Proctor Test

| Optimum moisture content, $w_{opt}$ (%) | 14.8 | ASTM D698-12 [20] |
| Maximum dry unit weight, $\gamma_{dmax}$ (kN/m$^3$) | 13.0 | |

Compaction Characteristics—Mini-compaction Test

| Optimum moisture content, $w_{opt}$ (%) | 12.7 | Sridharan and Sivapullaiah [14] |
| Maximum dry unit weight, $\gamma_{dmax}$ (kN/m$^3$) | 13.1 | |

$^a$ Elastic silt.

Table 2. Properties of the OPS (oil palm shell) samples used in this study.

| Soil Types | OPS |
|------------|-----|
| Specific gravity, $G_s$ | 1.23 |
| Shell thickness (mm) | 0.3–3.0 |
| Field moisture content (%) | 13.7–24.5 |
| Organic content (%) | 72.5–87.8 |
| 24-h water absorption (%) | 20.9–37.1 |

Commercially available liquid rubber (Flex seal, www.flexsealproducts.com) was used in this study for the surface coating of the OPS samples. The steps/procedure included dipping individual
was set (curing for a period of around 24–30 h). In this study, single layer rubber-coated OPS and double layer rubber-coated OPS are identified as ROPS<sub>SL</sub> and ROPS<sub>DL</sub>, respectively. Figure 1 shows the images of the OPS and ROPS samples. The ROPS samples were then preserved in air-tight containers before using them in the laboratory experiments as detailed further in this section. The dimensions of the OPS used in this study typically ranged between 4.75 mm and 15 mm. The thickness of the rubber layer for single-layer and double-layer coating was observed to vary between 0.04–0.8 mm and 0.15–2 mm respectively. Thickness values were basically influenced by the surface irregularity of OPS.

![Image of the samples used in this study: (a) oil palm shell (OPS); (b) rubberized oil palm shell (ROPS<sub>DL</sub>).](image)

**Figure 1.** Image of the samples used in this study: (a) oil palm shell (OPS); (b) rubberized oil palm shell (ROPS<sub>DL</sub>).

### 2.1. Water Absorption Test

Water absorption tests were conducted as per the recommendations detailed in ASTM D570 [21]. Other than water, the water absorption performance of OPS, ROPS<sub>SL</sub>, and ROPS<sub>DL</sub> were conducted in the kaolin with 32%, 48%, 64%, and 128% moisture content, corresponding to 0.5<sub>W</sub>L, 0.75<sub>W</sub>L, 1<sub>W</sub>L, and 2<sub>W</sub>L of kaolin. A total of 15 scenarios with an average of 8 samples each were prepared for each scenario. Table 3 details the schedule used for the water absorption tests in this study.

| Scenarios | Descriptions (Sample + Medium) |
|-----------|--------------------------------|
| 1         | OPS + water                    |
| 2         | OPS + Kaolin (0.5<sub>W</sub>L) |
| 3         | OPS + Kaolin (0.75<sub>W</sub>L)|
| 4         | OPS + Kaolin (1<sub>W</sub>L)  |
| 5         | OPS + Kaolin (2<sub>W</sub>L)  |
| 6         | ROPS<sub>SL</sub> + water      |
| 7         | ROPS<sub>SL</sub> + Kaolin (0.5<sub>W</sub>L)|
| 8         | ROPS<sub>SL</sub> + Kaolin (0.75<sub>W</sub>L)|
| 9         | ROPS<sub>SL</sub> + Kaolin (1<sub>W</sub>L)|
| 10        | ROPS<sub>SL</sub> + Kaolin (2<sub>W</sub>L)|
| 11        | ROPS<sub>DL</sub> + water      |
| 12        | ROPS<sub>DL</sub> + Kaolin (0.5<sub>W</sub>L)|
| 13        | ROPS<sub>DL</sub> + Kaolin (0.75<sub>W</sub>L)|
| 14        | ROPS<sub>DL</sub> + Kaolin (1<sub>W</sub>L)|
| 15        | ROPS<sub>DL</sub> + Kaolin (2<sub>W</sub>L)|

The test procedure starts with recording the dry mass of OPS, ROPS<sub>SL</sub>, and ROPS<sub>DL</sub> samples using a standard weighing balance with accuracy of 0.001 g. The specimens were then immersed...
in preselected medium and moisture conditions as per the scenarios. The test was conducted at controlled laboratory temperatures of 25 ± 3 °C for up to 20 days (480 h). During the testing period, water absorption of the specimens was continuously monitored at fixed intervals of six minutes. For this purpose, a few OPS/ROPSS/ROPSDL samples were extracted out from the medium at every interval and wiped with clean cloth to remove excess surface moisture, and mass of the sample was then measured immediately to avoid unnecessary moisture loss from the samples. Each reading was taken thrice and their mean value was recorded to ensure representative measurement. This process was repeated until the saturation was achieved—that is, the consecutive measurements showed no additional water absorption. The percentage water absorption, $M_t$, was then determined using the following Equation:

$$M_t = \left( \frac{w_n - w_d}{w_d} \right) \times 100$$ (1)

where $w_n$ refers to the mass of sample after immersion, and $w_d$ refers to the dry mass of samples before immersion.

2.2. Compaction Tests

Compaction behavior of kaolin supplemented with different OPS or ROPSDL compositions, ranging from 0–30%, were analyzed using both the standard proctor compaction [20] and mini-compaction [14] test procedures. In both compaction test procedures, kaolin mixtures (kaolin + OPS or ROPSDL) were mixed thoroughly with a pre-determined amount of water. The mixture was then cured in plastic seal bags for 24 h prior to the compaction tests to ensure consistent distribution of water within the mixtures. For standard proctor compaction, the mixtures were compacted in three layers with 25 blows/layer using the conventional 2 kg rammer as stated in ASTM D698-12 [20]; whereas in mini-compaction, the mixtures were compacted in three layers with 36 blows/layer using 1 kg mini-compaction rammer. Since the specimens were prepared as a mixture of kaolin and OPS or ROPSDL, the specific gravity of these soil samples, $G_s$, was estimated theoretically using the below relationship [22].

$$G_{so} = \frac{M_{d1}}{G_{s1}} + \frac{M_{d2}}{G_{s2}}$$ (2)

where $M_{d1}$ is the mass of dry soil (kaolin in this study); $M_{d2}$ is the mass of OPS or ROPSDL; $G_{s1}$ is the specific gravity of the soil; and $G_{s2}$ is the specific gravity of OPS or ROPSDL. For both the compaction test procedures, a total of 8 samples across the dry and wet side of the optimum were measured to calculate the dry unit weight-water content relationships. These compaction curves were then used to estimate the optimum moisture content ($w_{opt}$) and maximum dry unit weights ($\gamma_{dmax}$).

3. Results and Discussion

Figure 2 shows the variation of water absorption over a duration of 500 h. In general, the linear trend of water absorption observed in the OPS soaked in water with time can be explained in accordance with Fickian diffusion theory, which is defined as the diffusion of water from an area of higher concentration to one of lower concentration [23,24]. Discussions in this theory also indicate the possibility of an initial linear relationship between the water content (water absorption of material) and time, but the linearity may fade away, with the relationship tending to flatten as the saturation point is approached.

3.1. Water Absorption of OPS and ROPS Samples

As is evident from Figure 2a, the water absorption rate for OPS is higher in the first 24 h of immersion in water. After the first 24 h, the rate of water absorption starts to flatten and remain constant over a prolonged time. Higher water absorption rates can be explained by capillary action due to water diffusion and swelling of OPS surface/fibers. The capillarity action is hypothesized as the flow of water
molecules along fiber–matrix interfaces and water diffusion through the OPS’s bulk matrix (surface fiber). Immersion of OPS in water understandably creates a concentration gradient between the dry OPS and water medium. Thus, diffusion owing to concentration gradient is the most likely reason for the increasing rates of water absorption in OPS samples. Literature presents a similar explanation, relating the increasing water absorption to water uptake by capillary action in micro-pores and surface fibers [25,26]. Thus, a potentially swollen OPS surface is prone to micro-cracks, which can further escalate the capillarity and transport of water; as also explained by Dhakalet [27]. The trends and observations from this experimental study agree with trends presented by Sreekala et al. [26]—A study on the water absorption behavior of oil palm fibers. With very limited data and research discussions in this specific field of study, comparison with the behavior of oil palm fibers was considered as the most appropriate option. Figure 2a also reveals that the maximum values of water absorption for OPS range from 17.4% to 31.2% (with soaking medium of 0.5wL kaolin to water-soaked sample respectively), as compared to values of water absorption (up to 39%) recorded during the initial stages of this research, presented in Loi et al. [28].

![Figure 2](image_url)

**Figure 2.** Water absorption of samples: (a) OPS; (b) ROPS_{SL}; (c) ROPS_{DL}; and (d) effect of rubber coating measured at 0.75wL.

Observations from Figure 2a also highlight the fact that that the OPS immersed in kaolin slurry prepared at 0.5wL showed lowest water absorption values as compared to other mediums, with OPS immersed in water recording the highest water intake values. The average water absorption values observed are 14.3%, 24%, 25.5%, and 26.1% for kaolin prepared at liquid limits of 0.75wL, 1wL, 2wL,
respectively. This shows that increasing the water content of kaolin will result in increased water intake of OPS. This behavior clearly relates to water content in the kaolin samples. Water within the soil voids accelerates and catalyzes the diffusion of water between the soil medium and dry OPS. Similar observations are presented by Eskander and Saleh [29]. The lower water absorption of OPS in 0.5w_L kaolin samples is partly attributed to low permeability of the compacted kaolin samples, because permeability of clays typically is inversely proportional to the degree of saturation. Thus, low permeability potentially retards the diffusion or movement of water between soil and OPS samples, which in higher w_L (≥1) would be the other way.

The results of the water absorption test for OPS also clearly suggest the possibility of higher biodegradation, due to the presence of water. This potentially is unavoidable without surface treatment, due to the higher water absorption nature of OPS. Hence, further studies were conducted using rubber coating of OPS. Figure 2b,c shows the water absorption behavior of ROPS_SL and ROPS_DL samples. Observation from ROPS_SL samples shows that the water absorption rate reduced drastically in comparison to OPS-kaolin samples, showing a decrease of up to five times using kaolin prepared at 0.5w_L as a soaking medium. Moreover, providing a second layer of rubber coating reduced the water intake rate by at least 5% in all mediums. Overall, both ROPS_SL and ROPS_DL have lower water absorption as compared to OPS. For instance, Figure 2d gives a clear insight into the effect of coating, by comparing the OPS with ROPS_SL and ROPS_DL immersed in kaolin prepared at 0.75w_L. The water absorption of ROPS_DL reduced to as low as 2.6% when compared to water absorption of 22.5% observed in OPS. This is nearly an eight-fold decrease. Thus, the rubber sealant selected to coat the OPS aided in reducing water movement or diffusion, which theoretically signifies the capability of ROPS to perform as a relatively long term reinforcement for kaolin samples.

3.2. Compaction Tests on OPS and ROPS Modified Kaolin

3.2.1. Specific Gravity of Kaolin Mixed with OPS and ROPS Sample

The variation in γ_d values is predominantly related to the changing specific gravity (G_s). Thus, additional studies were conducted to determine the reduction in G_s values of the kaolin-OPS and kaolin-ROPS_DL samples. Table 4 therefore tabulates the G_s values of every variation of the test samples used in this study. The values, as anticipated, follow a monotonic decrease depending on the composition of OPS or ROPS_DL in the kaolin mixtures. The higher the OPS or ROPS_DL, the lower the G_s. Further, as evident from the table, there is a nearly 20% decrease in the G_s values at higher OPS/ROPS_DL contents. This clearly relates to the lower G_s values of the OPS and ROPS_DL samples. Nonetheless, lower G_s values of kaolin-OPS and kaolin-ROPS_DL encourage utilization of OPS and ROPS_DL as lightweight construction material to substitute for conventional soil particles in geotechnical engineering works.

Table 4. Variation of specific gravity for kaolin-OPS and kaolin-ROPS samples.

| Test Sample       | Specific Gravity (G_s) |
|-------------------|------------------------|
| Kaolin            | 2.65                   |
| OPS               | 1.23                   |
| ROPS_DL           | 1.24                   |
| Kaolin + 5% OPS   | 2.51                   |
| Kaolin + 10% OPS  | 2.40                   |
| Kaolin + 20% OPS  | 2.22                   |
| Kaolin + 30% OPS  | 2.09                   |
| Kaolin + 5% ROPS_DL| 2.51                   |
| Kaolin + 10% ROPS_DL| 2.40                  |
| Kaolin + 20% ROPS_DL| 2.23                |
| Kaolin + 30% ROPS_DL| 2.10                   |
3.2.2. Compaction Characteristics of OPS-Reinforced Kaolin

Figure 3 shows the compaction curves for the OPS-kaolin samples, where the OPS content varied from 0–30% by weight using both standard proctor compaction and mini-compaction test procedures. General observations show typical compaction curves, with dry unit weight ($\gamma_d$) values increasing with increasing water contents ($w$) till the optimum, followed by decreasing $\gamma_d$ with further increase in $w$. Observations show that the inclusion of OPS in kaolin decreases the maximum dry unit weight ($\gamma_{d,max}$) of the soil-OPS mix. For comparison, the $\gamma_{d,max}$ values for kaolin and kaolin reinforced with 30% OPS were 13.95 kN/m$^3$ and 12.65 kN/m$^3$, corresponding to $w_{opt}$ values of 24.8% and 24.9% respectively. The trend of unit weight values is inversely proportional to the increasing OPS contents observed in this study for both standard proctor compaction and mini-compaction tests; which compare well with the literature [2,28,30,31]. The moderate reduction in the $\gamma_{d,max}$ values can be related to the substitution of soil mass with OPS, which has a lower specific gravity (see Section 3.2.1) in comparison to kaolin. Though $\gamma_d$ values show a clear decreasing trend with increasing OPS contents, the variation pattern of $w_{opt}$ is insignificant through different combinations of kaolin-OPS samples, especially for the standard proctor compaction test results. The $w_{opt}$ of kaolin-OPS for all the chosen percentage of OPS nonetheless ranges between 23.9% and 26.8% for standard proctor compaction tests and 24.4% to 25.5% for mini-compaction tests.

![Figure 3. Compaction curves for OPS-reinforced kaolin using (a) mini-compaction test; (b) standard proctor compaction test.](image)

3.2.3. Compaction Characteristics of ROPS$_{DL}$-Reinforced Kaolin

Similar to OPS, both standard proctor compaction and mini-compaction tests were conducted on five different compositions of ROPS$_{DL}$ in the kaolin-ROPS$_{DL}$ samples. Figure 4 shows the compaction curves of ROPS$_{DL}$-reinforced kaolin. In general, the experimental trends are comparable to that of kaolin-OPS mixes. The $\gamma_{d,max}$ of the kaolin-ROPS$_{DL}$ samples for the compaction curves obtained from both standard proctor compaction and mini-compaction tests show a decreasing trend with increasing ROPS$_{DL}$ content. For compaction curves obtained from standard proctor compaction tests, the $\gamma_{d,max}$ decreases from 13.95 kN/m$^3$ to 12.97 kN/m$^3$ and 12.54 kN/m$^3$ at 20% and 30% ROPS$_{DL}$ contents, respectively, while $w_{opt}$ shows a decreasing trend from 24.8% to 23.9% and 22.9%, respectively. More importantly, the compaction curve at optimum exhibits a downward-leftward shift over the $\gamma_d$-w dimension, indicating a significant reduction in both $\gamma_{d,max}$ and $w_{opt}$, as highlighted in Figure 4a,b. Decrease in $w_{opt}$ values with increasing ROPS$_{DL}$ content is mainly attributed to the hydrophobic nature and low water absorption capabilities of the ROPS$_{DL}$ particularly because, for ROPS$_{DL}$, the surface fibers have been covered by the rubber coating, thus resulting in lesser water intake. The increasing proportion of ROPS$_{DL}$ therefore replaces the kaolin (which would have absorbed and
held water in pores) with an equivalent volume, which leads to an additional decrease in values of $\gamma_{\text{dmax}}$. The reduction in $\gamma_{\text{dmax}}$ values can be attributed to the lower specific gravity of kaolin-ROPS$_{DL}$ samples (see Section 3.2.1). Hence, the replacement of kaolin with increasing ROPS$_{DL}$ proportion is expected to reduce the specific gravity, which further leads to the reduction in $\gamma_{\text{dmax}}$ values. It should be noted that there are studies which also relate the decrease in $\gamma_{\text{dmax}}$ values to the loss of compaction efficiency caused by the elastic response of rubber during compaction [32]. But in this study, the inclusion of ROPS$_{DL}$ caused only a 0.8% decrease in $\gamma_{\text{dmax}}$ values as compared to the $\gamma_{\text{dmax}}$ values of OPS, which is negligible. Overall, the obtained compaction studies prove reliable, since the observed compaction characteristics from this study are consistent and in good comparison with similar literature [32–36].

![Figure 4](image.png)

**Figure 4.** Compaction characteristics for ROPS$_{DL}$-reinforced kaolin using (a) mini-compaction test; (b) standard proctor compaction test.

### 3.2.4. Comparison of Results Obtained from Standard Proctor Compaction and Mini-Compaction Tests

There are frequent debates about the varying compaction behaviors/characteristics evaluated using standard proctor compaction and mini-compaction test procedures. The variations are typically related to the way soil particles rearrange themselves owing to varying rammer size and compaction efforts [15]. This study also presents a detailed insight and compares the results obtained from both standard proctor compaction and mini-compaction tests. Figure 5 shows the compaction curves of kaolin and OPS/ROPS$_{DL}$-reinforced kaolin samples obtained using both compaction procedures. As can be clearly observed in Figure 5a, there is no significant variation between the compaction curves from standard proctor compaction and mini-compaction test procedures. Similarly, even in the case of ROPS$_{DL}$-reinforced kaolin as shown in Figure 5b, the mini-compaction results observed in this study are comparable and consistent with the one obtained from standard proctor compaction test procedure. Hence, based on the results obtained in this study, it can be concluded that the mini-compaction procedure using 1 kg rammer involving 36 blows/layer of compaction frequency, proposed by Sridharan and Sivapullaiah [14], can be considered suitable for both kaolin and kaolin reinforced with OPS and ROPS$_{DL}$. This can be used as an alternative testing method to estimate the compaction characteristics over a shorter time duration compared to the standard proctor compaction test. However, due consideration is crucial owing to the smaller diameter mold used in the mini-compaction procedure with OPS and ROPS samples (maximum dimension extending up to 15 mm). For this reason, the mini-compaction procedure is advisable as a quick test to estimate the compaction behavior of kaolin-OPS and kaolin-ROPS samples.
As evident from the figure, kaolin-OPS samples show a contradicting trend compared to kaolin-ROPS samples. The surface treatment of OPS with rubber significantly reduces its water absorption potential, which is basically related to lower $\gamma_{\text{dmax}}$ values. This is clearly evident from Figure 6a further shows that the $\gamma_{\text{dmax}}$ values follow a gradually decreasing trend for both cases, with kaolin-ROPSDL samples having a higher tendency to decrease, as signified by the relatively higher value of $\Delta\gamma_{\text{dmax}}/\Delta\text{OPSDL}$ equal to $-0.045$, as against $\Delta\gamma_{\text{dmax}}/\Delta\text{OPSF}$ of $-0.029$. Rubber coating likely cause a mild decrease in the values of $\Delta\gamma_{\text{dmax}}$ compared to that of OPS, which is still within an acceptable limit of less than $1\%$. Overall, reduction in the $\gamma_{\text{dmax}}$ values basically relate to lower $G_S$ values of the OPS and ROPS, with loss of compaction efficiency due to rubber coating playing only a minor role, to our understanding. Nonetheless, further studies are suggested in this research focus.

3.2.5. Effect of Rubber Coating on Compaction Characteristics of Kaolin-OPS Samples

Figure 6 shows the variations of compaction characteristics evaluated with the OPS content in kaolin before and after double layer rubber coating. In general, the higher the OPS or ROPS DL content in the kaolin mixtures, the lower the $\gamma_{\text{dmax}}$ values. Figure 6a further shows that the $\gamma_{\text{dmax}}$ values follow a gradually decreasing trend for both cases, with kaolin-ROPSDL samples having a higher tendency to decrease, as signified by the relatively higher value of $\Delta\gamma_{\text{dmax}}/\Delta\text{OPSDL}$ equal to $-0.045$, as against $\Delta\gamma_{\text{dmax}}/\Delta\text{OPSF}$ of $-0.029$. Rubber coating likely cause a mild decrease in the values of $\Delta\gamma_{\text{dmax}}$ compared to that of OPS, which is still within an acceptable limit of less than $1\%$. Overall, reduction in the $\gamma_{\text{dmax}}$ values basically relate to lower $G_S$ values of the OPS and ROPS, with loss of compaction efficiency due to rubber coating playing only a minor role, to our understanding. Nonetheless, further studies are suggested in this research focus.

Figure 6 shows the variation of compaction characteristics with OPS/ROPS contents in kaolin: (a) maximum dry unit weight; (b) optimum moisture content.

Figure 6b shows the variation of $w_{\text{opt}}$ for kaolin samples reinforced with OPS and ROPS DL samples. As evident from the figure, kaolin-OPS samples show a contradicting trend compared to kaolin-ROPS samples. This is clearly evident from $\Delta w_{\text{opt}}/\Delta\text{OPSF}$ value of $0.035$, signifying a positive trend, whereas $\Delta w_{\text{opt}}/\Delta\text{OPSDL}$ results for kaolin-ROPS samples show a decreasing trend with a gradient of $-0.12$. The surface treatment of OPS with rubber significantly reduces its water absorption potential, which is
reflected well with $\omega_{\text{opt}}$ values showing a decreasing trend with increasing ROPS$_{DL}$ content in the kaolin, whereas the OPS-kaolin shows higher water absorption with increasing OPS content, which is related to the hydrophilic nature of exposed surface fibers on OPS [24]. To this end, the proposed rubber coating of OPS shows considerable improvement in terms of $\omega_{\text{opt}}$, and a moderate yet acceptable trend in the case of $\gamma_{\text{dmax}}$ with increasing ROPS$_{DL}$ content in kaolin.

4. Conclusions

Oil palm shell (OPS) is one of the biomasses produced in palm plantations whose improper disposal can cause a nuisance to the surrounding environment. And whose incineration may contribute to greenhouse gases. Thus, this experimental study presents a novel attempt to evaluate the suitability of OPS and rubberized OPS samples for soil stabilization in the construction industry. For this purpose, a series of laboratory experiments were conducted on OPS and rubber-coated OPS samples to assess their water absorption and compaction characteristics when mixed with kaolin. Following are the key conclusions derived based on the detailed observations and discussions presented in this paper:

1. High water absorption of OPS is generally detrimental to the OPS, leading to material degradation. Thus, the less the water’s interaction with the OPS biomass, the less the degradation. To this end, surface coating using rubber sealant is deemed to be a favorable and eco-friendly alternative. The water absorption of the ROPS in water reduced to as low as 1.5% of the OPS, which recorded the water absorption of 31.2%. The water movement or diffusion was observed to be less when OPS was coated with rubber sealant, thereby signifying the capability of ROPS$_{DL}$ to perform as a relatively long term soil reinforcement for kaolin samples. However, more research evaluating the performance ROPS$_{DL}$ and exploring other options for surface treatment is strongly advised.

2. For kaolin-ROPS samples, the compaction curves obtained using both standard proctor compaction and mini-compaction tests show $\gamma_{\text{dmax}}$ to decrease with increasing OPS contents. This is related to the substitution of kaolin particles with the equivalent volume of OPS. The lower specific gravity of OPS leads to decrease in $\gamma_{\text{dmax}}$. However, variation of $\omega_{\text{opt}}$ is insignificant in this case.

3. For kaolin-ROPS$_{DL}$ samples, the compaction curve at optimum exhibits a downward-leftward shift over the $\gamma_{d-w}$ dimension, indicating a significant reduction in both $\gamma_{\text{dmax}}$ and $\omega_{\text{opt}}$. The lower specific gravity along with minor loss of compaction efficiency due to the elastic response of rubber on OPS during compaction could have led to this reduction in $\gamma_{\text{dmax}}$, while the lower $\omega_{\text{opt}}$ clearly relates to reduced water absorption capability of ROPS$_{DL}$ samples.

4. This study also evaluated the possibility of using the mini-compaction test (a relatively quick test) to estimate the compaction characteristics of shell-like material in soil. The mini-compaction test results were compared with the standard proctor compaction test. The compaction curves for OPS and ROPS$_{DL}$-reinforced kaolin samples obtained using mini-compaction apparatus showed a comparable and consistent results with the results abstained using standard proctor compaction tests. Results from this study therefore suggests that the mini-compaction test procedure proposed by Sridharan and Sivapullaiah [14] can be considered to estimate the compaction behavior of kaolin-OPS and kaolin-ROPS samples.

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