

# Enhancing the Mechanical Properties of Soil using Orange Peel Ash: Modeling and Experiments

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## Abstract

Using agricultural waste products as sustainable resources significantly contributes to the country's development. This research aims to assess the efficacy of mixing soil with orange peel ash by employing Atterberg limits, unconfined compressive strength, and collapse as evaluation parameters. Four models were developed to measure the cumulative failure loads both before and after soil treatment using a combination of 9% orange peel and 3% cement ash. The experimental tests will be undertaken at 7, 14, and 28 days. Moreover, two mathematical equations were derived to demonstrate the correlation between the liquidity index, soil-bearing capacity, and cohesion. The models revealed that the foundation's bearing capacity on saturated clay soil increased from 49 KPa without treatment to 115, 275, and 460 KPa at 7, 14, and 28 days of drying. Mixing 9% orange peel ash with 3% cement improves soil properties and reduces the percentage of cement. To evaluate the effectiveness of soil, it is necessary to apply orange peel ash to the area that lacks nutrients. Ash has properties that decrease soil reactivity, increase cohesiveness, and strengthen the soil's resistance to external stresses. Through the implementation of sustainable waste recycling, the productivity of low-quality clay soil can be improved.

**Keywords:** Agricultural waste, Cement, Collapse, Orange peel ash, Waste recycling

## 1. Introduction

The progress of a nation relies not only on its technological developments but also on its infrastructure [1]. Soil is essential for infrastructure because of its capacity to absorb and retain substances. Structural loads refer to the forces and pressures exerted on a structure, such as buildings or bridges, which may induce stress or deformation. These loads may encompass dead loads, representing the weight of the structure itself, and live loads [2]. The choice of stabilizing technology depends on factors including soil composition, project requirements, and environmental considerations [3]. However, not all soil types possess good quality. Attributes about the physical and mechanical properties. Mud soil is categorized as well-developed soil characterized by a large particle size and intense color intensity. It demonstrates an escalation in humid circumstances and a reduction in arid situations,

significantly affecting infrastructure. To assess or assess the value of.

The probability of experiencing such conditions and the status of stability. The soil is prepared to meet the technical criteria. Specifications. Soil remediation can be accomplished by several means, including the enhancement of the soil's mechanical and chemical qualities. I have performed a comprehensive study to improve soil compaction by integrating additives into the soil mixture. The use of fly ash and the reduction of ash content provide a specific advantage. Utilization of industrial waste [4]. Fly ashes have often been utilized as a substitute for cement in prior studies owing to their pozzolanic characteristics, which stem from their high CaO content [5]. For structures that come into contact with the ground, waterproofing is critical in harsh or corrosive conditions. Waterproofing the underlying materials helps protect underground structures from moisture and groundwater

contamination [6]. However, the effectiveness of waterproofing systems largely depends on proper installation and regular maintenance. Neglecting these aspects can lead to deterioration over time, ultimately compromising the integrity of the structure. This is expensive, so researchers are now looking to treat the soil before construction using inexpensive and environmentally friendly products because most of the materials used are expensive and harmful to the environment.

Several researchers [7]-[12] have conducted thorough investigations on the methods of enhancing the characteristics of expansive soil. These methods involve the utilization of coffee husk ash, rice husk ash, cornhusk fiber, coir fiber, wheat straw, and various other forms of agricultural waste or biomass. The findings demonstrated the enhancements in the California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS), and shrinkage, together with a decrease in the occurrence of cracks [10],[13]-[16]. Therefore, these materials can enhance the durability of the road base/subgrade for low-traffic gravel roads [17], [18].

The combustion of rice husks results in ashes that contain a significant proportion of biomass silica. The application of this biomass silica has enhanced the geotechnical characteristics of soil and reduced the reliance on natural resources, such as clayey soil. Rice husk ash (RHA) is a pozzolanic substance because of its significant amorphous silica content [19].

In previous research, it was discovered that the unconfined compressive stress of clay reinforced with rice husk ash increased by 340 kPa after 28 days of curing. Additionally, it has been asserted that the maximum dry density (MDD) of the reinforced soil was reduced to 13.2 when 30% rice husk ash was added. Furthermore, adding rice husk ash reduced the soil's swelling pressure to 75% [20].

One kilogram of palm oil produces four kilos of biomass ash. Malaysia is a leading producer of palm oil in Asia. After the oil extraction operation, we collected the residual palm oil and submitted it to pyrolysis at a suitable temperature [21]. Consequently, biomass silica was generated, comprising 63.7% silica and 7.16% calcium oxide. The citation originates from a study conducted [22].

It has been stated from the results of Barišić et al. [17] that barley, sunflower seed hulls, and wheat fly ash could serve as lime substitutes for soil stabilization for road works. The strength properties of stabilized soils containing biomass fly ash depend mainly on their chemical composition [23]. Researchers have discovered that orange and banana peels greatly enhance the structural properties of concrete. Therefore, researchers can utilize them as supplementary materials in concrete production for various applications in concrete reinforcement [24]. Adding orange peel fiber to composites or concrete improved the material's overall structural quality. Researchers [25] researched enhancing epoxy composites by incorporating fiber derived from orange peel. They found that the amount of orange peel powder (OPP) varied between 5% and 30%, with

increments of 5%. It was also observed that the strength of concrete mortar reinforced with orange peel ash was lower than that of concrete reinforced with ash [25]. It was clarified that the concentration of dried orange peel led to a decrease in the usage of building insulating material. The rate of reduction was from  $168.63 \pm 12 \text{ kg/m}^3$  (W75) to  $558.46 \pm 13 \text{ kg/m}^3$  (W100); around a 16% decrease. As a result, dried orange peel is beneficial for creating lightweight concrete [26].

This study aims to enhance the soil's mechanical characteristics and cohesiveness by investigating the conversion of orange peel into ash and utilizing its chemical qualities to improve compatibility and tolerance among soil particles.

### 1.1. Related Researches

Previous research has concentrated on exploiting agricultural and biological waste as sustainable additives to bolster the soil's geotechnical and mechanical characteristics. Materials like rice husk ash, and plant fibers such as coconut husks, corn husks, and straw have demonstrated promise in augmenting parameters like Unconfined Compressive Strength and also California Bearing Ratio [14], [10], [17], [27].

### 1.2. The Strong Points of Similarity Research

1. Using agricultural and biological waste as sustainable additives has been a notable strength [19].
2. Enhancement in geotechnical properties such as CBR and UCS, and reduction in soil cracking have been consistently observed [20].
3. Improvement of bearing capacity for road base and subgrade, especially for low-traffic gravel roads [21].

### 1.3. The Weak Points of Similarity Research

1. The results of previous research have fluctuated depending on the quality and consistency of the agricultural and biological waste used [17].
2. Some methods may require substantial quantities of waste, potentially leading to increased costs [23].

The present work examines the new application of orange peel ash as a novel supplementary material to improve soil qualities [23]. It presents a refined method that utilizes sustainable and renewable resources to enhance mechanical and geotechnical soil characteristics [24].

### 1.4. The Similar Studies

The study parallels the utilization of orange peel ash as a cement alternative [28]. The research investigated the impact of orange peel ash (OPA) as a partial cement replacement on consistency, setting durations, safety, compressive strength, and flexural strength in cement-OPA mixtures, with cement substitution levels ranging from 2.5% to 10% in 2.5% increments. Calcination at 600°C, 700°C, and 800°C for durations of 1 hour and 2 hours established the ideal calcination temperature and time for orange peel (OP).

The incorporation of orange peel ash enhances the characteristics of concrete. Katla et al [24] concentrated on the

mechanical examination of incorporating orange peel ash with banana peel ash in concrete.

This study contributes to the understanding of mechanical soil improvement through the use of orange peel ash, offering practical methods for promoting environmental sustainability and bolstering infrastructural resilience. Prior research has not thoroughly investigated the impact of orange peels on the mechanical characteristics of soil. The novelty of this study is the use of orange peel ash as a novel and efficient supplementary material for improving soil characteristics.

**2. Methodology**

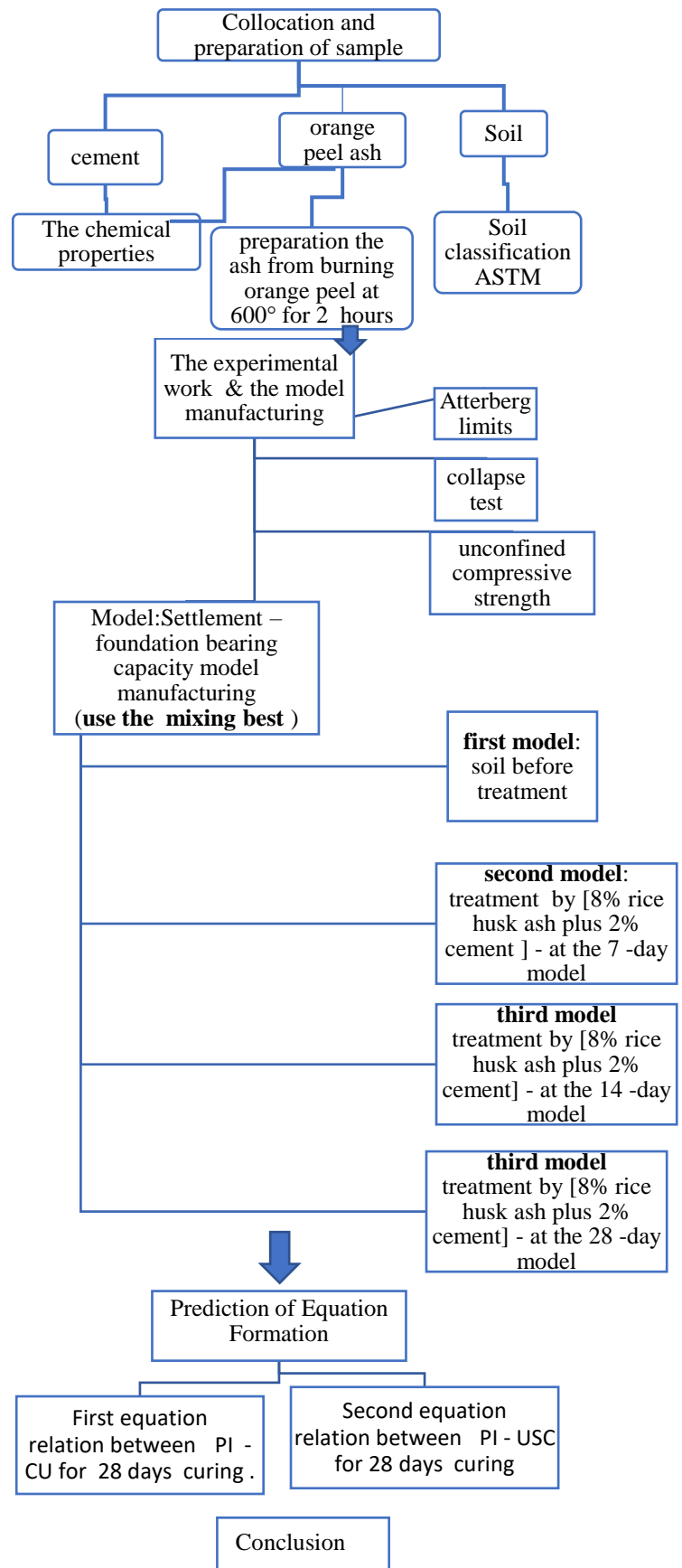
This research encompassed an investigation of the impact of cement orange peel ash on thermal and physical properties. A macemsoil on model will be formulated to investigate the foundation's ability to withstand cumulative loads before and after treatment. Fig. 1 comprises the subsequent steps.

**2.1. Soil**

Soil samples were taken from Baghdad and taken to the lab for examination. The engineering features of soil, such as natural water content, specific gravity, maximum dry density, ideal moisture content, unconfined strength at compression, collapse, and limit of (liquid, plasticity, shrinkage) particle size distribution, were examined. These properties affect soil behavior under various treatment settings. Table 1 explains the soil classification.

**Table 1.** The soil classification

<b>Gs</b>	<b>2.72</b>	[29] ASTM D 891 – 95
<b>% Gravel</b>	2.1	[30] ASTM: D 1140–2000
<b>% sand</b>	46.9	
<b>% Silt</b>	12	
<b>% Clay</b>	44	
<b>Soil type</b>	cl	
<b>L.L</b>	74 %	[31] ASTM D 4318 – 2000
<b>P.L</b>	35 %	
<b>P.I</b>	39 %	
<b>A</b>	0.98	
<b>W%</b>	15%	[32] ASTM, D698-12, 2012
<b>γ</b>	1.65	
<b>UCS</b>	60	[33] ASTM D2166-16,2016
<b>Cu</b>	21	
<b>Ie</b>	9.24	[34] ASTM D 5333 – 03



**Figure 1.** Methodology of the research

## 2.2. Preparing the Test Samples

The chemical characteristics of orange peel ash and cement are presented in Table 2.

Orange peel ash was collected and categorized following sun drying to diminish moisture content. The peels were incinerated at various temperatures and durations to ascertain the optimal temperature of 600°C for 2 hours to yield OPA. OPA was subjected to size reduction with a 75 µm sieve. The percentages utilized for mixing with Portland cement are 3%, 6%, 9%, and 12%.

Portland Cement used in this study includes ordinary Portland cement CEM I 42.5R obtained from the local market. The percentage used were 3%, 6%, 9%, and 12%

**Table 2.** Chemical properties of orange peel ash and cement

Chemical properties	C %	OPA %
SiO <sub>2</sub> + Al <sub>2</sub> O <sub>3</sub> + Fe <sub>2</sub> O <sub>3</sub>	29.3	27.83
CaO	65.01	31.02
MgO	0.97	3.83
SO <sub>3</sub>	1.63	0.81
K <sub>2</sub> O	0.95	26.28
Na <sub>2</sub> O	0.13	0.36

These are then weighed and mixed with water to form a paste. The mixing is done manually, and care is taken to ensure that the mixture is homogenous. Shows the chemical composition of ordinary Portland cement and orange peel ash via X-ray Fluorescence analysis. The user's text is empty. The chemical analysis displayed that orange peel, when heated to 600 °C for 2 hours, contained less than 70% of (SiO<sub>2</sub> + Al<sub>2</sub>O<sub>3</sub>+Fe<sub>2</sub>O<sub>3</sub>) to be (27.8%) [35]. However, the CaO content was 31.02%, which exceeds the minimum requirement of 10% for class C. Therefore, the ash derived from orange peel meets the necessary criteria for this class. This particular category of ash possesses both pozzolanic and cementitious characteristics. The OPA required a loss on ignition of 6.54 % which indicates a high degree of carbon ash, which is also accountable for the increase in the water requirement due to the OPA's high porosity particles, resulting in mixture segregation [36].

## 2.3. Model Producer

Soil replacement, pre-loading, and chemical stabilization. Since these procedures are harmful to the environment, the trend has become to use environmentally friendly resources [37]. Thus, four model tests are established.

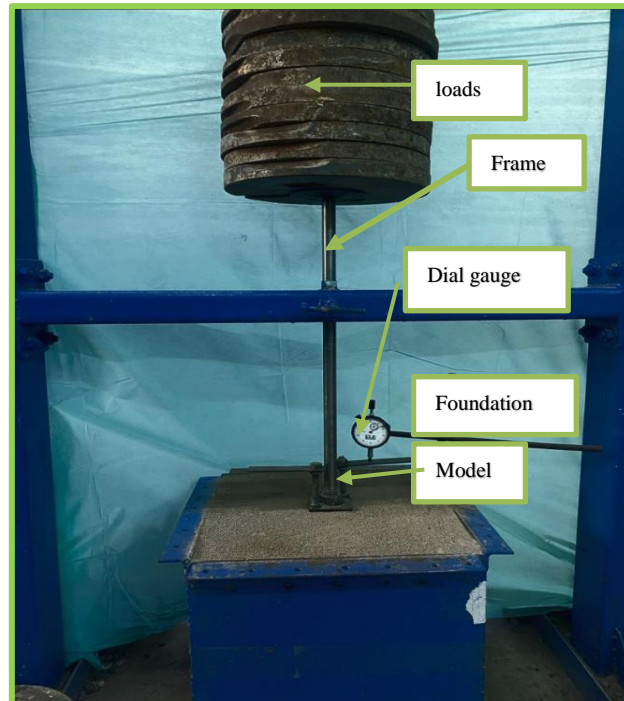
The tests were performed on a homogeneous clay layer with a depth of 250 mm. The clay layer was positioned inside a steel box with internal measurements of (600\*300\*300) mm. The construction of the container involved welding together six mm-thick steel plates to ensure sufficient

rigidity, thereby preventing any lateral deformation during the preparation of the clay soil or the testing process. To measure the settlement, standard weights were applied to the experimental setup until failure occurred. To measure settlement, two 0.01 mm dial gauges were placed on opposite corners of the footing. The clay was divided into five equal sections, each measuring 50 mm. Fig. 2 shows the parts of the model.

In the first model, a model foundation was tested on soil before treatment by the load as a cumulative measure of the depth of the downward movement of the soil when a load is applied to it.

The second model, after the 7-day model, was tested for the foundation on soil after treatment by mixing 9% OPA+3%C of soil weight, following the same work style as the first model. However, the mixed soil was extended to depths of 1B.

According to the third model, which has the same style as the first model but starts after curing period 14-days of mixing with 99% OPA+3%C of soil weight, the mixed soil was extended to depths of 1B. as well as the fourth mode which has the same style as the first model but starts after curing period 28 days of mixing with 9% OPA+3%C of soil weight, the mixed soil was extended to depths of 1B. To measure the settlement, standard weights were applied to the experimental setup until failure occurred. To measure settlement, two 0.01 mm dial gauges were put on opposite corners of the footing. The clay was divided into five equal sections, each measuring 50 mm, and the width of the foundation was labelled as B. Fig. 3 provides a schematic detail of the experimental setup.



**Figure 2.** Model Test

The model test utilized an optimal combination of additives, consisting of (9%OPA + 3% C). This combination was employed in the experiments conducted as part of the study. The experiments were carried out over three specific durations: the

first experiment took place on the seventh day, the second on the fourteenth day, and the third on the twenty-eighth day. For each experiment, a square foundation with a rigid steel plate measuring 50 mm was utilized for testing.

**3. Results and Discussion**

The choice of soil foundation material is crucial in achieving a stable and durable structure. Orange peel ash and cement have been identified as potential soil stabilizers due to their ability to enhance the engineering properties of the soil. In this study, the effect of cement and orange peel ash on soil stability was examined in different soil conditions.

**3.1. The Atterberg Limit**

Fig. 3 refers to the liquid limits of lower from 74 to 55, 56, and 59 at 9% OPA+3%C, 9% OPA, and C, respectively.

Fig. 4 shows an increase in its plastic limit before curing to be 35 while after mixing to be 50, 46, and 45 at (9%C, 9% OPA+3%C, and 9% OPA), respectively.

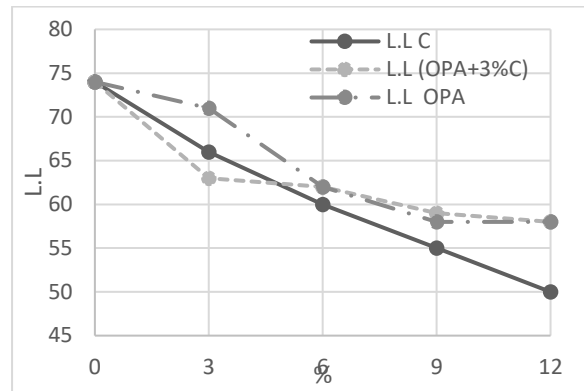
Also, from Fig. 5 it is noted that the soil plastic index (pI) percentage is 39% high plasticity and the change is made when the soil is treated to reduce be (9,10, and 11), which means the effect of the soil to be (low plastic, low plastic, and medium plastic) at (9% C,

9% OPA+3%C, and 9% OPA, respectively, according to the classification of plasticity for soil [31]. The plastic index reduces when mixing the soil with OPA. This is the raw moisture from the soil. As illustrated in the. Fig. 6 shows that the soil activity decreases from 0.98 to 0.31 when the carbon content is at 8%. Similarly, as the combination of 9% OPA +3%C, the soil activity decreases to 0.30, indicating an inactive state. Finally, as the OPA content alone is 9%, the soil activity is noted to be 0.42, which is classified as inactive according to the classification of activity for soil. The value of activity in the foundation soil is a critical factor that can have a significant impact on the stability and safety of a structure [38].

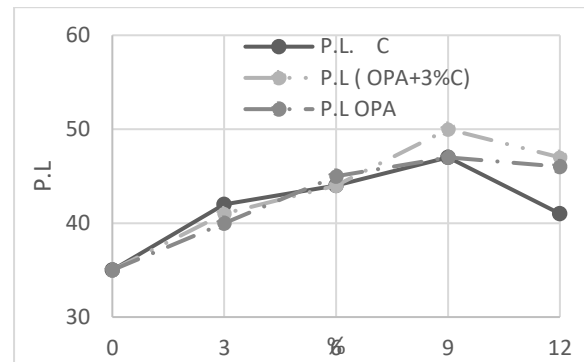
Noted that the maximum water concentration at which the interaction between clay particles is lost indicates that the liquid limit has been reached. Liquid Limit values were continuously decreasing, and plastic limit values were increasing with increasing OPA percentage, resulting in reduced PI. While there was an increase in both the liquidity limit and the plasticity limit, there was a reduction in the plastic index.

A decrease in the plasticity index of soil is an indicator of a rise in soil strength. Cement stabilizes soil by reducing plasticity index (PI) and boosting strength [39].

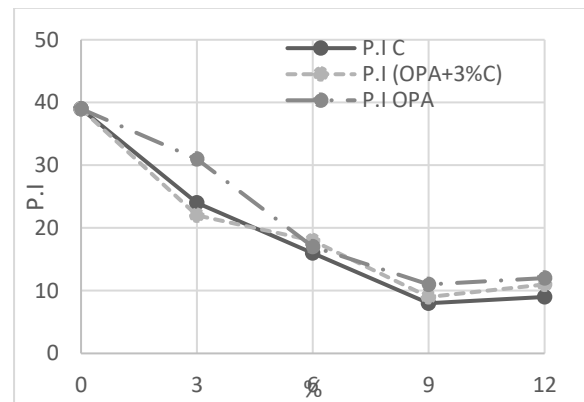
The results show that orange peel ash (OPA) and cement reduce the soil's liquid limitations, moisture susceptibility, and volume change. OPA's absorbency reduces PI, and soil weakens and contracts. Reduced soil activity increases stability, reducing moisture-induced volume changes and structural safety. Our results show that OPA and cement additives stabilize soil, reduce flexibility, and improve load-bearing for long-lasting buildings.



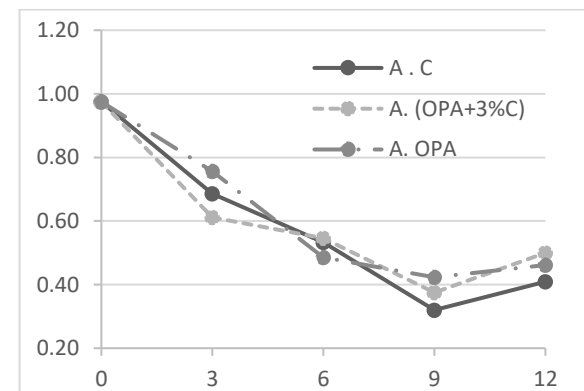
**Figure 3.** Liquid limit - soil mixture



**Figure 4.** Plastic limit - soil mixture



**Figure 5.** Plastic index - soil mixture



**Figure 6.** Activity - soil mixture

### 3.2. Unconfined Compressive Strength

Tables 3, 4, and 5 explain the results of the unconfined compressive strength test according to the strength value UCS. And cohesion CU before and after mixing the soil with three types of mixing. The first mixing cement and Portland, the second mixing orange-peel ash with a constant percentage of cement (3%), and the third mixing only orange-peel ash.

Fig. 7 The experimental results indicate that before and after a curing period of 28 days, the addition of 9% cement to the soil results in a soil strength of 135KN/m<sup>2</sup>. Similarly, when the soil is mixed with 9% orange peel ash, the soil strength is measured to be 94 KN/m<sup>2</sup>. Also, the soil strength is found to be 129.5 KN/m<sup>2</sup> at a mix with (9% OPA+3%C).

In Fig. 8, the experimental results determined that the soil cohesiveness before the curative procedure was measured to be 21 KN/m<sup>2</sup>. Next, a curative time of 28 days, the addition of 10% cement to the soil caused a notable increase in cohesion, specifically by 57.5 KN/m<sup>2</sup> units. In a comparable, the soil cohesiveness is 42 KN/m<sup>2</sup> after the soil is mixed with a 12% OPA.

Furthermore, the incorporation of 9% OPA+3%C into the soil results in a significant enhancement of soil cohesiveness to 51 KN/m<sup>2</sup>. From these deductions, it can be inferred that the orange peel ash incorporation into clay soil causes an increase in soil cohesion, strength, and enhancement in soil properties. Additionally, when a constant percentage of 9% C is mixed with OPA, a further enhancement in soil performance is observed, which closely resembles the behaviour exhibited by clay soil cured with a higher percentage of cement (9%). From all note the best percentage is 9%OPA+3%C During 28 day curing that to be replaced to cement or reduced cement using at the unconfined compressive strength test in this study that the unconfined compressive strength increased value to be (105 KN / m<sup>2</sup>) During a 7-day at the percentages OPA of 9%, remarked the unconfined compressive strength increased value to be 121.7 while it used mixed proportions of 12% RHA and 3% C at 28 day curing period.

Utilizing orange peel ash in cement improves its strength [24]. The amount of water content absorbed by cement decreases with increasing cement content [40],[41]. Cementitious soil undergoes pozzolanic reactions, resulting in a progressive increase in its strength [42], especially if orange peel ash is added. Moreover, the use of OPA as a soil stabilizer would reduce the CO<sub>2</sub> emissions from other soil stabilizers, similar to cement, because of the CO<sub>2</sub> emissions associated with cement use. Also, to reduce the cost of cement. Therefore, the OPA can be successfully recycled as a soil stabilizer, thereby reducing the environmental pollution produced by the open dumping of OPA.

**Table 3. UCS - Cu TEST - OPA**

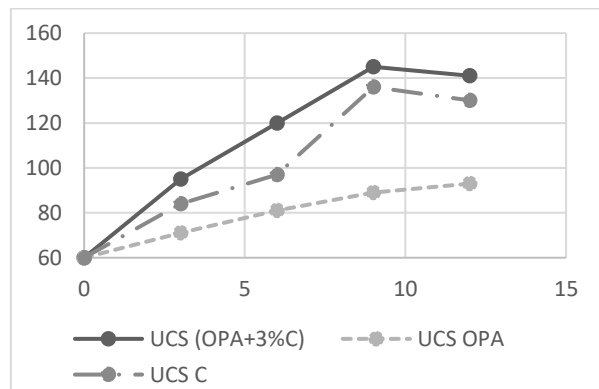
%	UCS	Cu
<b>Natural soil</b>	60	21
<b>3%OPA</b>	71	26
<b>6%OPA</b>	81	33
<b>9% OPA</b>	89	42
<b>12% OPA</b>	93	48

**Table 4. UCS-Cu TEST - C**

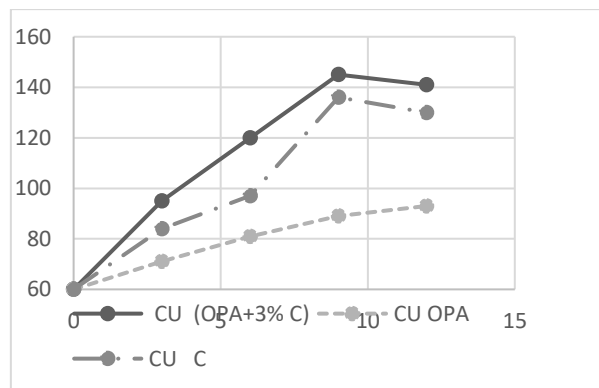
%	UCS	Cu
<b>Natural soil</b>	60	21
<b>3%C</b>	84	34
<b>6%C</b>	97	48
<b>9%C</b>	136	56
<b>12%C</b>	130	55

**Table 5. UCS - Cu TEST – OPA MIX C**

%	UCS	Cu
<b>Natural soil</b>	60	21
<b>3%OPA+C</b>	95	39
<b>6%OPA+3%C</b>	120	52
<b>9% OPA +3%C</b>	145	59
<b>12% OPA +3%C</b>	141	58



**Figure 7. UCS – soil mixture**



**Figure 8. CU - soil- mixture**

### 3.4. The Model Test

Fig. 9 illustrates the first model for the first day without addition, representing the relationship between bearing capacity, measured in kilopascals (kPa), and settlement per foundation width, denoted as S/B. The ultimate bearing capacity (q) of the soil in its completely saturated condition, without any additional substances, was measured to be 49 kPa.

The link between settlement per foundation width (S/B) and bearing capacity (q Kpa) is depicted in Fig. 10 for the second model. The soil's ultimate bearing capacity (q) is determined to be 115 kPa when using a mixture consisting of (9% OPA and 3% C), with a base width. Subsequently, the model is subjected to a period of complete water saturation lasting for seven days, upon the incorporation of OPA plus a 3% cement content.

In Fig. 11, a comparison is made between settlement per foundation width (S/B) and bearing capacity (q Kpa) for a given scenario. After 14 days from the initial foundation width, the third model incorporates an additional 8(9% OPA and 3% C). The soil's bearing capacity at failure (q) was determined to be 275 kPa after the incorporation of OPA and 3% C.

Fig. 12 presents a comparison between settlement per foundation width (S/B) and bearing capacity (q kPa) for the Fourth model. The soil's ultimate bearing capacity (q) is measured to be 460 kPa after the incorporation of (9% OPA and 3% C). The duration of this procedure spans 28 days, measured at a distance corresponding to the breadth of the saturated base.

The criterion for failure utilized in all model experiments is the one proposed by [39], which defines the load required to produce a settlement per width of foundation (S/B) equal to 10% of the footing's width to find the bearing capacity at failure. In general, three types of shallow foundation failure exist: punching failure, general shear failure, and local failure. The failure type is determined by comparing the ratio of the clay to the foundation's depth and width, as previously noted [41]. Fig.13 presents the relation between strength and load for the fourth model. In the fourth series of model loading tests, the load-bearing capacity of a model footing placed on submerged clay soil exhibited an increase from 49 KPa for untreated soil to 115, 275, and 460 KPa, respectively, during the curing period of 7, 14, and 28 days. This increase was observed when the soil was mixed with a combination of (9% OPA and 3% C), and extended to a depth corresponding to the first. The behavior of rice husk ash in enhancing the characteristics of clay soil closely resembles the effects observed in soil treatment with cement. This similarity arises from the pozzolanic capabilities exhibited by rice husk ash, which closely resemble the chemical properties of cement.

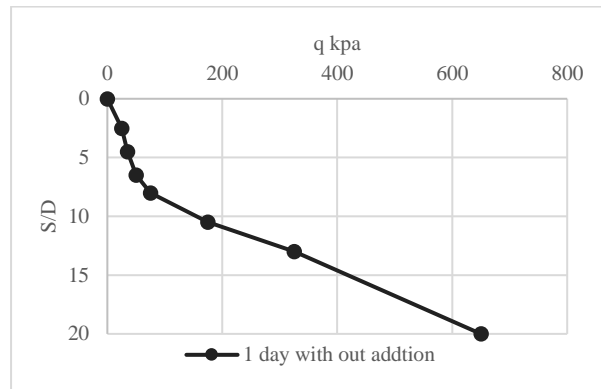


Figure 9. First model -1 day without addition

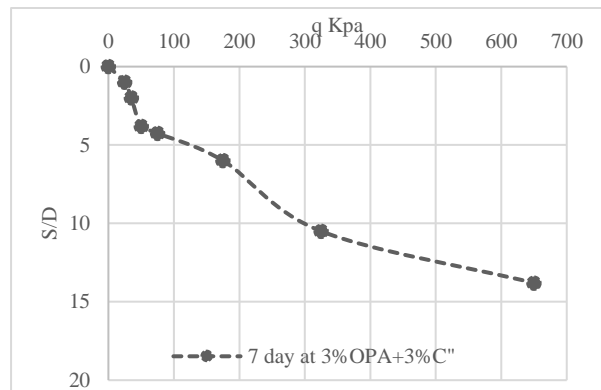


Figure 10. Second model -7 day at 9% OPA+3% C

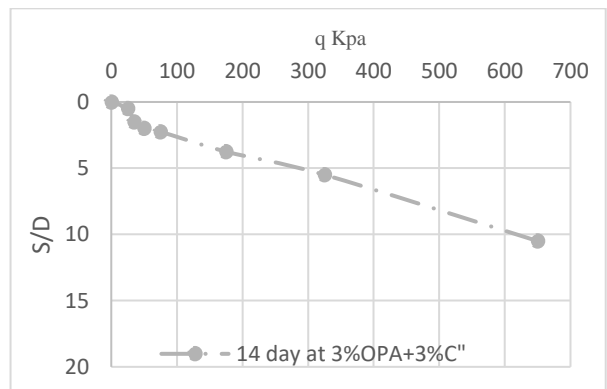


Figure 11. Third model -14 day at 9% OPA+3% C

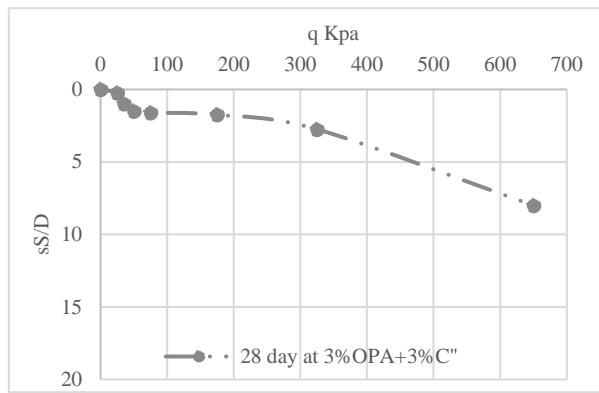


Figure 12. Fourth model -28 day at 9%OPA+3%C

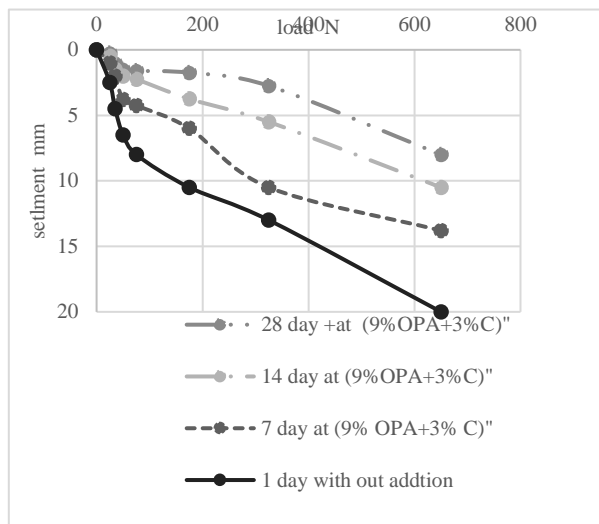


Figure 13. Strength –load for the model

The criterion for failure utilized in all model experiments is the one proposed by [43], which defines the load required to produce a settlement equal to 10% of the footing's diameter as the failure load. In general, three types of shallow foundation failure exist: punching failure, general shear failure, and local failure. The failure type is determined by comparing the ratio of the depth of the foundations to the width, as previously noted [44]. However, this failure mechanism does not apply to walled foundations because the wall connects to the circumference of the foundation and extends to a depth (d) that encloses the clay within a skirt cell beneath the foundation. This must be done. Therefore, the skirt cell and foundation together make up a single system that constitutes a deeper system as the wall's height increases, causing the shallow foundations also to become deeper. This occurs because the skirt cell and foundation are connected.

**4. Prediction of Equation Formation**

The foremost purpose of this study is to improve cost competence and minimize labor requirements in model creation by contributing a comprehensive soil depiction

behavior over the entire treatment process. Also, the aim is to create a comprehensive correlation between the dynamic behavior of soil parameters and the underlying bearing capacity in situations involving cumulative loading. The equations presented above have been derived from graphical representations.

Table 6 outlines the first equation related to the relative plasticity index of soil cohesion after 28 days of treatment, as illustrated in Fig. 14. This information is further supported by Fig. 5 and Fig.8, which demonstrate a systematic approach to enhancing the mechanical properties of the soil. To achieve this objective, a mathematical equation was developed to define the precise relationship between the plasticity index (PI) and the soil cohesion properties throughout the 28-day treatment period. Also, Table 5 noted that the second equation illuminates the relative plastic index-unconfined compressive strength test of soil for treatment after 28 days, as seen in Fig.15, and based on Figs. 5 and 7, represents a scholarly pursuit aimed at maximizing efficiency while effectively controlling costs and time limitations. To achieve this objective, a mathematical equation was formulated to create a direct relationship between the coefficient of plasticity (PI) and soil strength, specifically regarding the unconfined compressive strength, within the framework of a 28-day treatment regimen.

The experiment showed that cement plus orange peel ash increased soil strength, cohesiveness, and plasticity. The use of orange peel ash improves soil properties. This results in lower CO2 emissions and better performance than cement stabilizers. Stability depends on soil activity, as lower activity values reduce settlement and structural damage. Overall, this study shows that rice husk ash can replace cement in soil augmentation. This switch may improve foundation performance, save money, and reduce environmental impact.

In conclusion, the objective of this work is to optimize cost and labor efficiency in model construction by providing a thorough depiction of soil behavior during the treatment process. The main aim of this study is to prove expressive correlations between soil property behaviors and its ability to resist load, specifically in the location of cumulative loading. The expansion of relevant equations, founded on graphical analyses, plays a crucial role in attaining these goals.

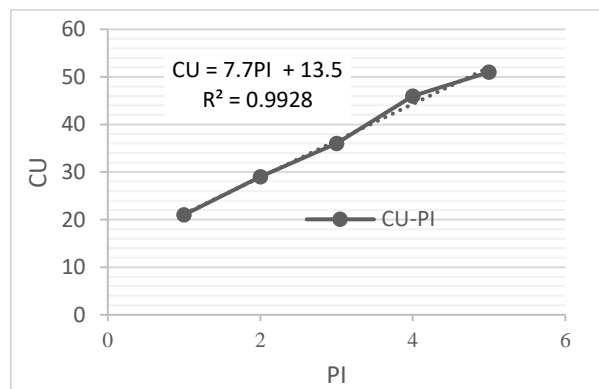
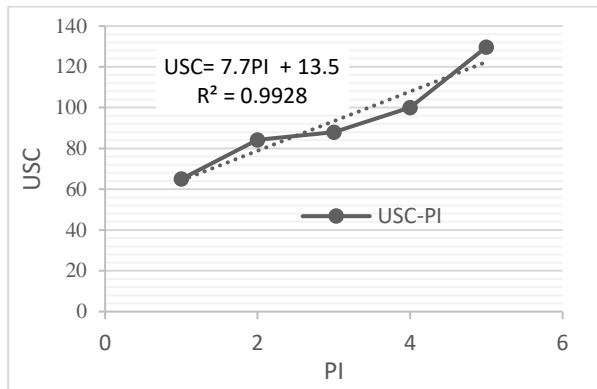


Figure 14. Relation CU test – PI of soil - for 28 days curing



**Figure 15.** Relation PI of soil - USC test of soil - for 28 days curing

**Table 6:** Prediction of the equation formula

Information	Formula
<b>The first equation is the relation between</b> PI -CU for 28 days curing <b>True factor</b> $R^2 = 0.99$	$CU = 7.7 PI + 13.5$
<b>The second equation is the relation between</b> PI - USC for 28 days curing <b>True factor</b> $R^2 = 0.99$	$USC = 7.7 PI + 13.5$

**5. Conclusion**

The study demonstrates that orange peel ash improves soil and foundations when integrated with cement. The significant observations can be succinctly expressed as follows: The use of orange peel ash (OPA) in cement significantly affects the unconfined compressive strength and splitting strength of clayey soil. The most pronounced impact is observed in the splitting power. OPA may fill minute spaces between moisture molecules, leading to uniform pressure distribution both within cells and externally. OPA augments strength by expediting the chemical reaction and enhancing durability

and cohesiveness, particularly when combined with increased amounts of CaO. OPA-stabilized soil exhibits a stronger bond than unstable clayey soil as soil cohesion increases. The ideal percentage of OPA has been established at 9% using diverse cement ratios. The distinctive curve of the soil-liquid index for stabilized soil is markedly affected by OPA. The incorporation of OPA significantly elevates the air entry value of the curve, signifying a more homogeneous distribution of pore sizes and a more compact soil structure. The capacity of OPA to interact with cement and establish robust connections within the soil may result in soil compaction. Soil compaction diminishes larger voids. Silicon dioxide (SiO<sub>2</sub>) enhances soil compaction by filling voids and decreasing porosity. This procedure enhances the

air entry value in the liquid index curve, resulting in a more uniform pore size distribution and a more consistent soil structure. We utilized four mathematical models to assess the influence of soil elasticity and strength on the bearing capacity of foundations subjected to cumulative stress, concluding that the optimal ratio for soil stabilization is 9% OPA combined with 3% cement for addressing depressions. Superior clay soil. Furthermore, examining soil remediation techniques, performing tests in a regulated environment, formulating mathematical equations to replicate soil characteristics, and creating models to evaluate the effects of additives preserve resources while minimizing time and labor requirements.

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**Abbreviations**

C	Cement
UCS:	The unconfined compressive strength (kN/m <sup>2</sup> )
OPA+3%C	Orange Peel Ash + 3% cement
OPA	Orange Peel Ash
L.L.	Liquid limit
P.L.	Plastic limit
P. I	Plastic index
A	Activity
Cu	Cohesion ( kN/m <sup>2</sup> )
Gs	Specific Gravity
W%	Optimum Moisture Content
D	Diameter mm
q	Bearing capacity at failure
CP	Collapse
Ie	Collapse index
e	Void ratio
γ	Density (kg/m <sup>3</sup> )
w%	Natural Moisture Content

**Conflict of Interest**

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

**Author Contribution Statement**

Shaimaa M. Abdulrahman identified the research problem, developed the theory, and conducted the practical work, computations, and data analysis.

Maha Al-Soudani and Salman Dawood Salman AL-Dulaimi carried out the language editing, verified the analytical methods, and studied the theoretical aspects.

Svetlov Dmitry Anatolyevich supervised the findings of this work and performed the language editing. All authors discussed the results and contributed to the final version of the manuscript.

## References

- [1] M. A. M, Dinesh Kumar M, M. C. J, and Vani G, "Replacement of Cement Using Eggshell Powder," *International Journal of Civil Engineering*, vol. 3, no. 3, pp. 1–2, Mar. 2016, doi: <https://doi.org/10.14445/23488352/ijce-v3i3p101>
- [2] K. Bezih, A. Chateaufneuf, M. Kalla, and C. Bacconnet, "Effect of Soil–structure Interaction on the Reliability of Reinforced Concrete Bridges," *Ain Shams Engineering Journal*, vol. 6, no. 3, pp. 755–766, Sep. 2015, doi: <https://doi.org/10.1016/j.asej.2015.01.007>
- [3] S. A. Nugroho, A. Zulnasari, F. Fatnanta, and A. D. Putra, "Mechanical Behavior of Clay Soil Stabilized with Fly Ash and Bottom Ash," *Makara Journal of Technology*, vol. 26, no. 1, pp. 1–7, Apr. 2022, doi: <https://doi.org/10.7454/mst.v26i1.1444>
- [4] M. Çınar, M. Karpuzcu, and H. Çanakçı, "The Measurement of Fresh Properties of cement-based Grout Containing Waste Marble Powder," *Measurement*, vol. 150, p. 106833, Jan. 2020, doi: <https://doi.org/10.1016/j.measurement.2019.07.061>
- [5] S. A. Nugroho, G. Wibisono, A. Ongko, and A. Z. Mauliza, "Effects of High Plasticity and Expansive Clay Stabilization with Lime on UCS Testing in Several Conditions," *Journal of the Civil Engineering Forum*, vol. 1000, no. 1000, Jan. 2021, doi: <https://doi.org/10.22146/jcef.59438>
- [6] B. Sari Ahmed, H. Gadouri, M. Ghrici, and K. Harichane, "Best-fit Models for Predicting the Geotechnical Properties of FA-stabilised Problematic Soils Used as Materials for Earth Structures," *International Journal of Pavement Engineering*, vol. 21, no. 7, pp. 939–953, Sep. 2018, doi: <https://doi.org/10.1080/10298436.2018.1517874>
- [7] S. D. S. Al-Dulaimi, S. I. Bazhenova, I. V. Stepina, I. V. Erofeeva, and V. Afonin, "Development of Efficient Compositions of Hydrophobic Materials Resistant to Chemical and Biological Environments," *Journal of Infrastructure Preservation and Resilience*, vol. 5, no. 1, Dec. 2024, doi: <https://doi.org/10.1186/s43065-024-00113-z>
- [8] S. M. Abdulrahman, A. Kindi, and Elaf Abd Al-Azai Ihsan, "Sustainable Stabilization of Clay Soil with Rice Husk Ash," *Journal of Engineering and Technological Sciences*, vol. 56, no. 04, pp. 450–462, Aug. 2024, doi: <https://doi.org/10.5614/j.eng.technol.sci.2024.56.4.2>
- [9] R. Munirwan, A. Taib, M. Taha, N. Rahman, and M. Munirwansyah, "A Sustainable Solution of Coffee Husk Waste Disposal for Soil Stabilization," *Proceedings of the 9ICEG 9th International Congress on Environmental Geotechnics 25-28 June, 2023* / Chania, Greece, 2023, doi: <https://doi.org/10.53243/ICEG2023-318>
- [10] S. Pandey and N. Kumari, "Utilisation of Agricultural Waste Biopolymer for Soil Erosion Management," *Elsevier eBooks*, pp. 249–260, Jan. 2024, doi: <https://doi.org/10.1016/b978-0-443-15291-7.00019-5>
- [11] C. B. Ammar *et al.*, "Properties of High-Entropy Fe<sub>30</sub>Co<sub>20</sub>Ni<sub>20</sub>Mn<sub>20</sub>Al<sub>10</sub> Alloy Produced by High-Energy Ball Milling," *Materials*, vol. 17, no. 1, p. 234, Dec. 2023, doi: <https://doi.org/10.3390/ma17010234>
- [12] S. Wang, W. Dai, and G. Y. Li, "Distributionally Robust Receive Beamforming," *arXiv.org*, 2024. <https://arxiv.org/abs/2401.12345>
- [13] Shagun K., P. Sharma, and O. P. Pandey, "Green Sorbents from Agricultural Wastes: a Review of Sustainable Adsorption Materials," *Applied Surface Science Advances*, vol. 19, pp. 100562–100562, Feb. 2024, doi: <https://doi.org/10.1016/j.apsadv.2023.100562>
- [14] F. A. Gidebo, H. Yasuhara, and N. Kinoshita, "Stabilization of Expansive Soil with Agricultural Waste additives: a Review," *International Journal of Geo-Engineering*, vol. 14, no. 1, Sep. 2023, doi: <https://doi.org/10.1186/s40703-023-00194-x>
- [15] H. M. Jafer, Z. H. Majeed, and A. Dulaimi, "Incorporating of Two Waste Materials for the Use in Fine-Grained Soil Stabilization," *Civil Engineering Journal*, vol. 6, no. 6, pp. 1114–1123, Jun. 2020, doi: <https://doi.org/10.28991/cej-2020-03091533>
- [16] Z. M. Dawood and Z. H. Alqaissi, "Impact of Date-Palm Fibers on Fine Soil's Compaction and Strength Properties," *Journal of Engineering*, vol. 30, no. 06, pp. 67–82, Jun. 2024, doi: <https://doi.org/10.31026/j.eng.2024.06.05>
- [17] S. O. Malongweni *et al.*, "Impact of Agricultural Waste on the Shrink–swell Behavior and Cracking Dynamics of Expansive Soils," *International Journal of Recycling of Organic Waste in Agriculture*, vol. 8, no. 4, pp. 339–349, Apr. 2019, doi: <https://doi.org/10.1007/s40093-019-0265-7>
- [18] I. Barišić, I. Neteringer Grubeša, T. Dokšanović, and B. Marković, "Feasibility of Agricultural Biomass Fly Ash Usage for Soil Stabilisation of Road Works," *Materials*, vol. 12, no. 9, p. 1375, Apr. 2019, doi: <https://doi.org/10.3390/ma12091375>
- [19] D. Basu, A. Misra, and A. J. Puppala, "Sustainability and Geotechnical Engineering: Perspectives and Review," *Canadian Geotechnical Journal*, vol. 52, no. 1, pp. 96–113, Jan. 2015, doi: <https://doi.org/10.1139/cgj-2013-0120>
- [20] I. J. Fernandes *et al.*, "Characterization of Rice Husk Ash Produced Using Different Biomass Combustion Techniques for Energy," *Fuel*, vol. 165, pp. 351–359, Feb. 2016, doi: <https://doi.org/10.1016/j.fuel.2015.10.086>
- [21] B. R. Phanikumar and T. V. Nagaraju, "Effect of Fly Ash and Rice Husk Ash on Index and Engineering Properties of Expansive Clays," *Geotechnical and Geological Engineering*, vol. 36, no. 6, pp. 3425–3436, Apr. 2018, doi: <https://doi.org/10.1007/s10706-018-0544-5>
- [22] B. S. Thomas, S. Kumar, and H. S. Arel, "Sustainable Concrete Containing Palm Oil Fuel Ash as a Supplementary Cementitious Material – a Review," *Renewable and Sustainable Energy Reviews*, vol. 80, pp. 550–561, Dec. 2017, doi: <https://doi.org/10.1016/j.rser.2017.05.128>
- [23] M. N. Borhan, A. Ismail, and Riza, "Evaluation of Palm Oil Fuel Ash (POFA) on Asphalt mixtures," *Australian Journal of Basic and Applied Sciences*, vol. 4, no. 10, pp. 5456–5463, Oct. 2010.
- [24] A. Kilani, A. Olubambi, B. Ikotun, O. Adeleke, and O. Adetayo, "Structural Performance of Concrete Reinforced with Banana and Orange Peel Fibers -A Review," *Journal of Sustainable Construction Materials and Technologies*, vol. 7, no. 4, Dec. 2022, doi: <https://doi.org/10.47481/jscmt.1144427>
- [25] Katla. Praveen. Kumar and C. Nagaraj, "An Investigation of Mechanical Characterization of Orange Peel Reinforced Epoxy Composite," *IOSR Journal of Mechanical and Civil Engineering*, vol. 16, no. 053, pp. 33–41, Dec. 2016, doi: <https://doi.org/10.9790/1684-16053023341>
- [26] O. O. Olubajo, O. A. Odey, and B. Abdullahi, "Potential of Orange Peel Ash as a Cement Replacement Material," *Path of Science*, vol. 5, no. 7, pp. 2009–2019, Jul. 2019, doi: <https://doi.org/10.22178/pos.48-3>
- [27] N. Mahato, K. Sharma, M. Sinha, and M. H. Cho, "Citrus Waste Derived nutra-/pharmaceuticals for Health benefits: Current Trends and Future Perspectives," *Journal of Functional Foods*, vol. 40, pp. 307–316, Jan. 2018, doi: <https://doi.org/10.1016/j.jff.2017.11.015>
- [28] N. Mahato, K. Sharma, M. Sinha, and M. H. Cho, "Citrus Waste Derived nutra-/pharmaceuticals for Health benefits: Current Trends and Future Perspectives," *Journal of Functional Foods*, vol. 40, pp. 307–316, Jan. 2018, doi: <https://doi.org/10.1016/j.jff.2017.11.015>

- [29] ASTM, D 891 – 95, Specific Gravity, "Standard Test Methods for Specific Gravity, Apparent, of Liquid Industrial Chemicals," ASTM D 891 – 95 (Reapproved 2000), June 1995. [Online]. Available: <https://www.astm.org/Standards/D891.htm>. [Accessed: 03-Oct-2024]
- [30] ASTM D1140-2000, 'Sieve Analysis of Fine and Coarse Aggregates', ASTM International, 2000. <https://cdn.standards.iteh.ai/samples/3142/b6d745036a6243698ceb54329ac53430/ASTM-D1140-00.pdf>. [Accessed: 03-Oct-2024].
- [31] ASTM, "D4318 - 00: Standards for Liquid Limit, Plastic Limit, and Plasticity Index of Soils," ASTM D 4318-2000, vol. 04, pp. 1–14, 2000, <https://www.astm.org/d4318-17e01.html>
- [32] ASTM "D698-12, 2012. Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort," American Society for Testing and Materials, West Conshohocken, PA, 2012, <https://cdn.standards.iteh.ai/samples/80785/1f09081d070c47e3a953b587da221c23/ASTM-D698-12.pdf>.
- [33] ASTM, "D2166–16, Standard Test Method for Unconfined Compressive Strength of Cohesive Soil," ASTM International, West Conshohocken, PA, vol. D2166-16, pp. 1–6, 2016, <https://cdn.standards.iteh.ai/samples/94791/55c0a7ad962440cdb164b6ebac3f0033/ASTM-D2166-D2166M-16.pdf>
- [34] ASTM, "D 5333 – 03, Standard Test Method for Measurement of Collapse Potential of Soils," West Conshohocken, PA 19428-2959, United States, 1996, [https://www.academia.edu/8713281/D\\_5333\\_03\\_Standard\\_Test\\_Method\\_for\\_Measurement\\_of\\_Collapse\\_Potential\\_of\\_Soils](https://www.academia.edu/8713281/D_5333_03_Standard_Test_Method_for_Measurement_of_Collapse_Potential_of_Soils)
- [35] ASTM International, "Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete (ASTM C618-19)," 2019. DOI: [https://10.1520/c0595\\_c0595m-19](https://10.1520/c0595_c0595m-19)
- [36] S. M. Abdulrahman, K. W. A. Al-Kaream, and E. A. Ihsan, "Enhancing Soil with Low-Cost Pozzolanic Materials: Rice Husk Ash and Groundnut Shell Ash Compared to Cement," *Mathematical Modelling of Engineering Problems*, vol. 11, no. 4, Apr. 2024, doi: <https://doi.org/10.18280/mmep.110430>
- [37] R. M. Tremiño, T. Real-Herraiz, V. Letelier, and J. M. Ortega, "Microstructure and Mechanical Properties of Ternary Mortars with Brick powder, Glass powder, slag, Fly ash, and Limestone," *International Journal of Applied Ceramic Technology*, vol. 19, no. 4, pp. 2135–2147, Feb. 2022, doi: <https://doi.org/10.1111/ijac.14012>
- [38] H. Gadouri, "Behavior of Natural Pozzolana-Lime-stabilized Clayey Soils Artificially Contaminated by Sulfates," *Jordan Journal of Civil Engineering*, vol. 17, no. 4, Oct. 2023, doi: <https://doi.org/10.14525/jjce.v17i4.07>
- [39] P. Samui, S. Kumari, V. Makarov, and P. Kurup, *Modeling in Geotechnical Engineering*. Academic Press, 2020.
- [40] M. Basu, P. B. S. Bhadoria, and S. C. Mahapatra, "Comparative Effectiveness of Different Organic and Industrial Wastes on peanut: Plant growth, yield, Oil content, Protein content, Mineral Composition and Hydration Coefficient of Kernels," *Archives of Agronomy and Soil Science*, vol. 53, no. 6, pp. 645–658, Nov. 2007, doi: <https://doi.org/10.1080/03650340701591569>.
- [41] S. Manikantha, A. S. P.V.V, V. Nagaraju.T, and A. Moin, "Geotechnical Application of Rice Husk Ash and Lime Admixtures of Black Cotton Soil Having High Expansive Nature," *International Journal of Civil Engineering*, vol. 3, no. 5, pp. 158–163, May 2016, doi: <https://doi.org/10.14445/23488352/ijce-v3i5p134>
- [42] T. I. Sani, K. Jantsho, M. A. Khan, R. A. Bapon, and V. G. Gopalakrishna, "Experimental Investigation for Stabilizing Soil Using Rice Husk Ash," *International Journal of Engineering Research & Technology*, vol. 12, no. 5, May 2023, doi: <https://doi.org/10.17577/IJERTV12IS050336>
- [43] D. E. Wibowo, D. A. Ramadhan, Endaryanta, and H. Prayuda, "Soil Stabilization Using Rice Husk Ash and Cement for Pavement Subgrade Materials," *Scientific Electronic Library Online (Scientific Electronic Library Online)*, vol. 22, no. 1, pp. 192–202, Jan. 2023, doi: <https://doi.org/10.7764/rdlc.22.1.192>
- [44] A. S. A. Al-Gharbawi, A. M. Najemalden, and M. Y. Fattah, "Expansive Soil Stabilization with Lime, Cement, and Silica Fume," *Applied Sciences*, vol. 13, no. 1, p. 436, Dec. 2022, doi: <https://doi.org/10.3390/app13010436>