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Strength Behavior of Cohesive Soil Reinforced with Portland Limestone Cement and Palm Oil Fuel Ash

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ABSTRACT
This research project aimed to investigate the strength behavior of cohesive soil when reinforced with a combination of palm oil fuel ash (POFA) and Portland limestone cement (PLC). The objective was to examine how POFA and PLC influence the engineering properties of cohesive soil by enhancing its compressive strength and bearing capacity. To achieve this, a series of laboratory tests were conducted, including unconfined compressive test (UCS), moisture content, specific gravity, Atterberg limit and particle size distribution tests for the cohesive soil only. Afterward, the modified soil sample was subjected to an unconfined compressive strength test using different mix ratios of POFA and PLC for 7, 14, 21, and 28 days to determine its compression strength and bearing capacity. The mix ratios used were 1% POFA 9% PLC, 2% POFA 8% PLC, 3% POFA 7% PLC, 4% POFA 6% PLC, 1% PLC 9% POFA, 2% PLC 8% POFA, 3% PLC 7% POFA, 4% PLC 6% POFA, and 5% PLC 5% POFA. The results of the study showed that the modified soil's strength and bearing capacity increased as the proportion of PLC and POFA increased over the curing period of 7, 14, 21, and 28 days. It was found that the mixture of 9% PLC and 1% POFA had the highest compressive strength and bearing capacity after 28 days of curing. However, even with a 3% PLC and 7% POFA mix, the soil had improved from soft clay to stiff clay. The use of POFA in geotechnical engineering has several benefits, such as addressing waste disposal issues associated with the palm oil industry, enhancing soil strength, and reducing construction costs.
Keywords: *Cohesive soil, Portland limestone cement, soil stabilization, Palm oil fuel ash, bearing capacity.*

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I. INTRODUCTION

Cohesive soils are affected by inherent cohesion, friction between particles, and normal stresses that act on them, all of which influence their shear strength. This type of soil has poor workability, weak bearing capacity, low undrained shear strength, and high compressibility, as reported by Dimgba et al. (2023). Clayey silt, silty clay, clay, organic clay and sandy clay are types of cohesive soils which are fine-grained, poorly structured, and easily deformable. Such soils have low bearing capacity, which can lead to issues for structures built upon them (Gautam, 2018). During the rainy season, clay soils retain moisture, making it challenging for water to pass through and causing significant volume expansion. A suitable soil must maintain stability throughout all seasons. The primary aim of strengthening a soil mass, according to Mali and Singh (2014) is to improve its bearing capacity, decrease lateral deformation, and enhance stability.

Soil stabilization is a process where soil properties are improved to meet engineering standards using chemical, physical, or mechanical methods (Koukouzas & Karkalis, 2022). Many cementitious materials, such as PLC and lime, have been studied for their potential to stabilize soil (Harichane et al., 2018). Traditional stabilizers usually rely on pozzolanic reaction and cation exchange to modify and stabilize soil (Humada et al, 2017). The primary objective of soil reinforcement is to increase strength and bearing capacity. Fly ash, PLC, lime, or palm oil fuel ash can be used as additives to modify or strengthen cohesive soil if it doesn't meet the minimum allowable bearing capacity and settlement.

PLC is a good material for stabilizing soil due to its excellent properties and wide availability. However, its high selling price makes it difficult for many people to use it for their sites. As a result, research efforts have focused on finding affordable, less-polluting materials that are more readily available to reduce the cost of soil stabilization and minimize negative environmental impacts (Awarri & Otto, 2022; Awarri et al., 2022).

Palm oil fuel ash (POFA) is an industrial by-product generated by burning palm oil waste to produce energy in power plants. POFA possesses excellent chemical, physical, and morphological properties that enable it to be reused in various civil engineering projects. It is also cost-effective and has the potential to stabilize soil, as supported by past research (Santhosh et al., 2022). Despite its benefits, POFA disposal can be problematic because it can contaminate groundwater, water, and land. Globally, 12 tons of POFA are disposed of every year.

This research aims to analyze the strength of POFA-PLC stabilized cohesive soil response to loading.

II. MATERIALS AND METHODS

2.1 Materials

The study involved obtaining clayey soil samples from Rivers State University in Port Harcourt, located in the Rivers State of Nigeria. The PLC was acquired from a cement merchant at Rumuokwuta, Port Harcourt, while the palm oil fuel ash was obtained from a palm kernel factory in Etche, Rivers State. Plate 1 displays the collection of soil samples.

2.2 Methods

A hand auger was used to collect soil samples from 1.0 to 2.0 meters below ground level. The samples were then transported to the Civil Engineering Laboratory at Rivers State University for laboratory testing. All laboratory procedures and data analysis followed the British Standard (BS 1377: 1975; 1990) for soil testing.

Initially, the cohesive soil was tested for its bulk density, Atterberg limit, specific gravity, moisture content, particle size distribution and UCS test. Additionally, the specific gravity of POFA and PLC was determined. For determining the optimal stability, PLC was combined in different mix ratios with the cohesive soil at 5%, 10%, 15%, and 20% by soil weight. Once the optimum content of PLC was determined for the modified cohesive soil, various combinations of POFA and PLC were tested, such as 1% POFA 9% PLC, 2% POFA 8% PLC, 3% POFA 7%PLC, 4%POFA 6%PLC, 1%PLC 9% POFA, 2%PLC 8% POFA, 3%PLC 7%POFA, 4%PLC 6% POFA and 5%PLC 5%POFA.

Plate 1: Collection of Soil Sample

2.2.1 UCS Test of PLC and POFA Modified Soil

The soil sample was mixed with different proportions of POFA and PLC, such as 1% POFA - 9% PLC, 2% POFA - 8% PLC, 3% POFA - 7% PLC, 4% POFA - 6% PLC, 1% PLC - 9% POFA, 2% PLC - 8% POFA, 3% PLC - 7% POFA, 4% PLC - 6% POFA and 5% PLC - 5% POFA. Then, the split mold was lubricated and samples measuring 76 mm in height and 38 mm in diameter were placed in the mold as per usual procedures. The loading device's bottom plate held the sample, and the upper plate contacted the specimen. Both the load and strain dial gauges were set to zero. The specimen was compressed until cracks appeared, and the load readings were taken around every 20 mm of specimen deformation. Afterward, the specimen was extracted and its failure height and weight were noted. A free-hand drawing of the specimen was made, and the moisture content was determined by placing the sample in a porcelain evaporating dish. The modified soil sample preparation for the UCS test is shown in Plate 2.

Plate 2: Modified Soil Samples Preparation for UCS Test

Stress and strain values were obtained following the UCS test, and stress-strain curves were drawn. This curve's maximum stress provided the unconfined compressive strength, q_u. Cohesion was obtained from equation (1).

Cohesion, $C_u = \frac{q_u}{2}$ (1)

Since it is a cohesive soil, angle of internal friction, $\boldsymbol{\Phi}= 0$.

To obtain the bearing capacity of the soil, the Terzaghi's ultimate bearing capacity method was employed as given in equation (2);

$Q_u = CN_c + qN_q + B\text{ɣ}N_\text{ɣ}$ (2)

As stated earlier, for cohesive soils: $\boldsymbol{\Phi}= 0$, $N_\text{ɣ} = 0$, $N_c = 5.7$ and $N_q=1$

Therefore, from equation (2) we have;

$Q_u = CN_c + q$ (3)

Where;

Surcharge

$q = \text{ɣ}D_f$ (4)

D_f = depth of foundation

N_C , N_q, $N_\text{ɣ}$ = dimensionless numbers called bearing capacity factors.

III. RESULTS AND DISCUSSION

3.1 Index Properties of the Soil

Table 1 provides a summary of the soil's index properties, while Table 2 lists the physical and chemical properties of POFA and PLC. The cohesive soil has a natural moisture content of 82.86%, indicating that it has a good water-holding capacity. The specific gravity of the cohesive soil is 2.61, while that of POFA and PLC are 1.71 and 3.38, respectively. The soil's coefficient of uniformity is 2.23, indicating that it is poorly graded based on the results of the sieve analysis test. The bulk density and unit weight of the soil are 1615 kg/m^3 and 15.84 kN/m^3 respectively. The Unified Soil Classification System categorizes the soil as low to medium plasticity clay (CL), with a liquid limit of 42% and a plasticity index of 14.75%.

Table 1: Index Properties of the Lateritic Soil

Parameters	Value
Moisture content (%)	88.86
Specific gravity	2.61
Liquid limit (%)	42
Plastic limit (%)	27.25
Plasticity index (%)	14.75
USCS	CL
Bulk Density (kg/m3)	1615

Unit weight (kN/m3)	15.84
UCS (kN/m^2)	35
Bearing capacity(kN/m^2)	40

Table 2: Physical and Chemical Properties of Fly Ash

Description	PLC	POFA
Specific Gravity	3.38	1.71
Silica (SiO_2)	19.35	61.26
Alumina (Al_2O_3)	4.57	4.98
Iron oxide (Fe_2O_3)	1.21	3.98
Magnesia (MgO)	1.39	3.93
Calcium oxide (CaO)	68.64	25.59
Potassium oxide (K_2O)	0.48	5.10
Carbon dioxide (CO_2)	0.22	0.28
Sulfur trioxide (SO_3)	5.10	1.52
Titanium dioxide (TiO_2)	4.36	0.33
Loss in Ignition	2.40	2.8

3.2 USC of Modified Cohesive Soil

The unstabilized soil had an unconfined compressive strength (UCS) of 35 kN/m^3, indicating that it consisted of soft clay. However, the UCS increased when different ratios of PLC and POFA were added, namely 1% POFA - 9% PLC, 2% POFA - 8% PLC, 3% POFA - 7% PLC, 4% POFA - 6% PLC, 1% PLC - 9% POFA, 2% PLC - 8% POFA, 3% PLC - 7% POFA, 4% PLC - 6% POFA, and 5% PLC - 5% POFA. This trend continued after 7, 14, 21, and 28 days of curing. In fact, after 28 days of curing, the soil improved from soft clay to stiff clay (35 kN/m^3 - 158 kN/m^3).

Before stabilization, the sticky texture of the cohesive soil made it easy to mold. However, after stabilization, it developed a stiff consistency. The increase in UCS with the addition of PLC and POFA indicates that both additives have good pozzolanic properties. Additionally, the pozzolanic reactions between silicon dioxide (SiO_2) in POFA and Calcium oxide (CaO) in PLC can be credited with improving the UCS. These reactions formed calcium silicate hydrate (CSH), which improved the binding of the clay soil. This is in line with Tonduba et al. (2019). You can see the UCS behavior of the unstabilized and stabilized soil after 7, 14, 21, and 28 days of curing in Figure 1.

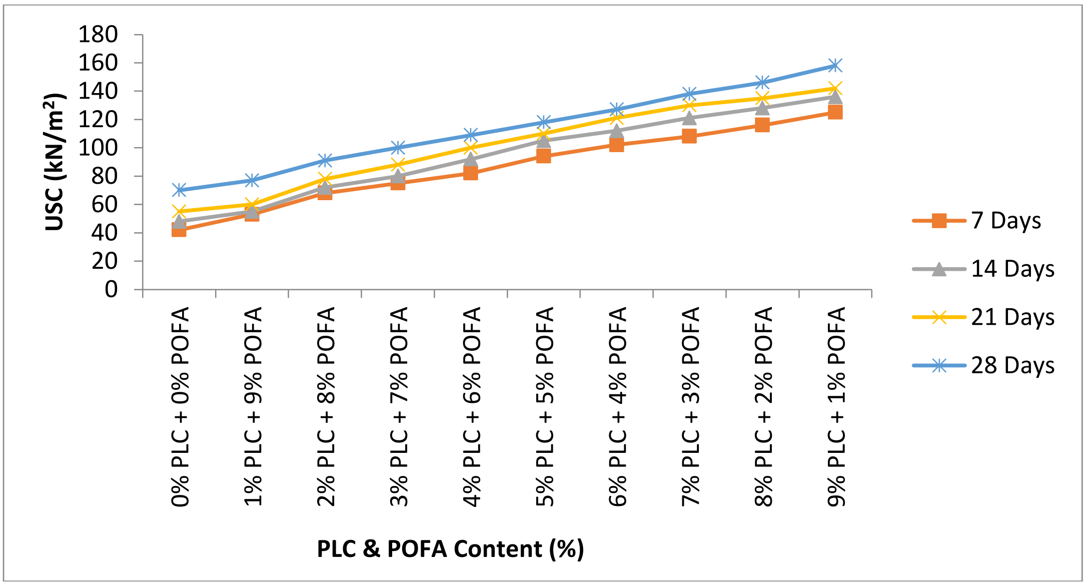

Figure 1: UCS of Unstabilized and Stabilized Soil with their Curing Days

3.3 Bearing Capacity of Modified Cohesive Soil

It has been determined that the soil in question is a soft clay, as its bearing capacity without stabilization measures was 40 kN/m^3. However, after adding different ratios of POFA and PLC (including 1% POFA - 9% PLC, 2% POFA - 8% PLC, 3% POFA - 7% PLC, 4% POFA - 6% PLC, 1% PLC - 9% POFA, 2% PLC - 8% POFA, 3% PLC - 7% POFA, 4% PLC - 6% POFA, and 5% PLC - 5% POFA), the bearing capacity increased. This trend was observed after 7, 14, 21, and 28 days of curing. After 28 days of curing, the soil improved from a soft clay (40 kN/m^3) to a stiff clay (154 kN/m^3). The same principle that explains the UCS illustration also accounts for variations in the soil's bearing capacity. Figure 3 shows the bearing capacity behavior of the unstabilized and stabilized soil after 7, 14, 21, and 28 days of curing.

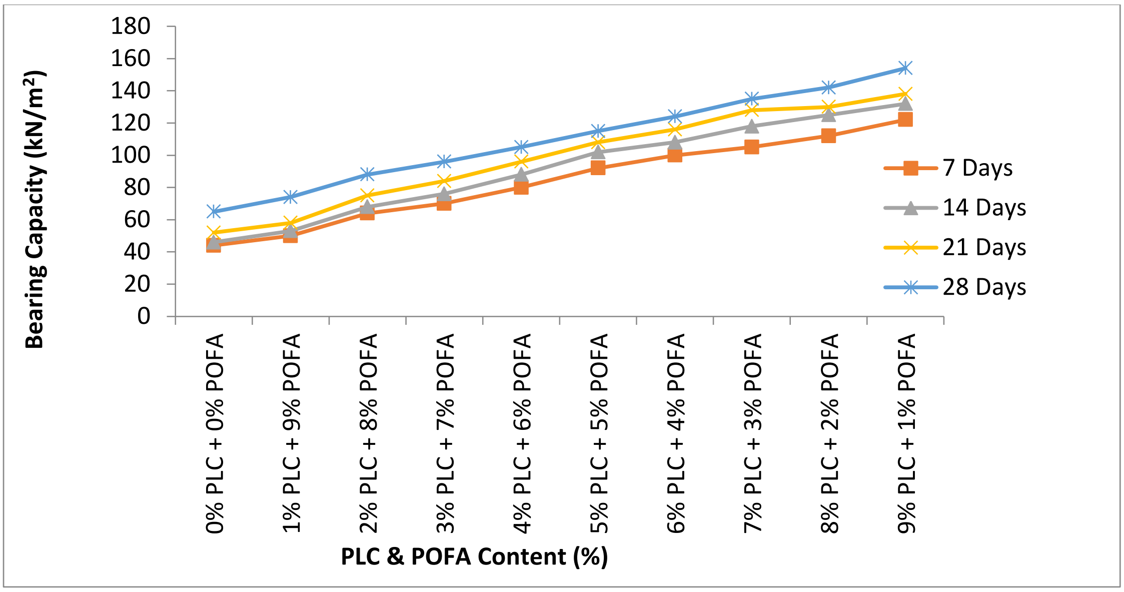

Figure 2: Bearing Capacity of Unstabilized and Stabilized Soil with their Curing Days

IV. CONCLUSIONS

The study's findings lead to the following conclusions:

1. Cohesive soils treated with both POFA and PLC show higher UCS values compared to untreated soils. The addition of POFA and PLC has a positive impact on UCS values.
2. Cohesive soils treated with both POFA and PLC have better bearing capacity values than untreated soils. The addition of POFA and PLC has a positive impact on bearing capacity values.
3. To improve the stability, cost-effectiveness, and environmental benefits of cohesive soil, it is recommended to use a mix ratio of 7% POFA and 3% PLC.

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