

Sustainable Stabilization of Clayey Soil Using Palm Oil Fuel Ash: Influence on Plasticity, Compaction, and Strength Characteristics

G. Chamundeswara Rao¹, T. Subramanyam Sai¹, Y. Yamuna Sai¹, P. Nandu¹

1. Department of Civil Engineering, Sasi Institute of Technology & Engineering, Tadepalligudem, Andhra Pradesh, India.

Abstract

Clayey soils are widely recognized for their problematic behavior, including high plasticity, low strength, and poor load-bearing capacity, which limit their suitability for construction. This research investigates the stabilization of clayey soil using Palm Oil Fuel Ash (POFA), an industrial by-product with pozzolanic properties, to evaluate its effectiveness as a sustainable stabilizer. A systematic methodology was adopted, beginning with material collection and specimen preparation, followed by laboratory testing of untreated soil and soil treated with varying POFA contents (1–14%). The tests conducted included Atterberg's limits, Standard Proctor compaction, California Bearing Ratio (CBR), and Unconfined Compressive Strength (UCS), with additional curing studies to assess long-term performance. The Atterberg's limits results revealed that POFA modifies soil plasticity in a non-linear manner. At low dosages (1–2%), POFA reduced plasticity and improved workability, while higher levels (around 10%) increased liquid limit and plasticity index due to enhanced ash–clay binding. Curing further strengthened POFA's effect, reducing plasticity and improving soil consistency over time. Compaction results showed that POFA increased Optimum Moisture Content (OMC) steadily from 23% to over 31%, while Maximum Dry Density (MDD) improved up to 10% POFA (1.61 g/cc) before declining at higher percentages. Strength tests confirmed POFA's stabilizing potential. The soaked CBR value of virgin soil was only 0.86, but improved to 3.85 at 10% POFA, identifying this dosage as optimum for subgrade applications. Similarly, UCS values rose from 32.63 kg/cm² in virgin soil to 115.06 kg/cm² at 10% POFA, with curing further enhancing strength to 119.35 kg/cm². Beyond 10%, strength declined, emphasizing the importance of dosage control. Overall, the study demonstrates that POFA is an effective and sustainable stabilizer for clayey soils. It reduces plasticity, enhances compaction, and significantly improves strength, particularly at an optimum dosage of 10% POFA. These findings highlight POFA's potential to transform weak soils into durable, workable materials suitable for geotechnical and construction applications, while promoting environmental sustainability through waste utilization.

Keywords: *Palm Oil Fuel Ash (POFA), Clayey Soil Stabilization, Atterberg's Limits, Compaction Characteristics, Strength Improvement*

1. Introduction

The rapid pace of urbanization and industrial growth has intensified the demand for natural resources while simultaneously generating vast amounts of waste materials that often remain underutilized. Among these, Palm Oil Fuel Ash (POFA) has emerged as a particularly significant by-product of the palm oil industry. Produced from the combustion of oil-palm residues in mill boilers, POFA is typically discarded in open fields or landfills, leading to environmental concerns such as the occupation of fertile land, contamination of groundwater, and air pollution (Sumadi and Hussin, 1995; Tonnayopas et al., 2006). This indiscriminate disposal not only creates ecological hazards but also represents a missed opportunity to recycle a material that possesses considerable engineering potential. Rich in silica and alumina, POFA exhibits strong pozzolanic properties, meaning it can react with calcium hydroxide to form cementitious compounds that enhance the strength and durability of soils and construction materials. Its chemical composition and fine particle structure make it a promising candidate for sustainable soil stabilization, particularly in regions where expansive clayey soils pose challenges to infrastructure development.

Clayey soils, especially expansive types such as black cotton soil, are widely distributed in India and other tropical regions. These soils are characterized by high plasticity, significant swelling when wet, and shrinkage upon drying, which often leads to structural damage in buildings, pavements, and foundations. Conventional stabilizers like lime and cement have long been used to improve the engineering properties of such soils, but their production is energy-intensive and contributes substantially to carbon dioxide emissions. In this context, POFA offers a dual advantage: it not only improves soil performance but also supports sustainability by reducing reliance on cement and diverting agricultural

waste from landfills. The utilization of POFA in soil stabilization thus aligns with global efforts to promote eco-friendly construction practices and circular economy principles.

Several studies have confirmed the potential of POFA in soil stabilization. Abdullah et al. (2009) investigated the stabilization of silty soil using lime and POFA under different curing conditions, reporting that the inclusion of POFA enhanced strength due to pozzolanic reactions. Similarly, Andriani et al. (2023) demonstrated that combining POFA with lime improved the load-bearing capacity of clay subgrades and reduced swelling behavior, making it suitable for pavement applications. Awal and Shehu (2013) emphasized that finely processed POFA exhibits higher reactivity due to increased silica availability, which enhances pozzolanic activity, reduces plasticity, and improves compaction characteristics. Hossain et al. (2021) further observed that POFA blended with cement improved the formation of cementitious compounds responsible for strength development, contributing to better microstructural densification. These findings highlight the importance of particle size and treatment processes in optimizing POFA performance for soil stabilization.

The role of POFA in geopolymer applications has also been widely studied. Khasib and Nik Daud (2020) reported that soft soil treated with POFA-based geopolymer showed improvements in compaction characteristics and alkalinity, while Khasib et al. (2021) found significant enhancements in strength and density of clayey soil stabilized with POFA-based geopolymer using alkaline activators. Pourakbar et al. (2015) investigated alkali-activated POFA for stabilizing high plasticity clay, where the formation of geopolymer gels improved mechanical behavior and stiffness, confirming POFA as an efficient and eco-friendly binding material. Ranjbar et al. (2014) similarly noted that finer POFA particles improved bonding and compressive strength, contributing to enhanced durability. Sukmak et al. (2017) and Toyeb et al. (2023) also validated POFA's effectiveness in improving strength and reducing plasticity, while Safiuddin et al. (2018) highlighted its high silica content and pozzolanic properties as key factors in improving strength, reducing permeability, and enhancing durability in treated soils.

Other researchers have explored POFA in combination with different stabilizers. Zaini et al. (2015) investigated the combined use of POFA and gypsum in clay soils and found improved strength and reduced plasticity, while Zaini et al. (2024) confirmed similar improvements in strength, plasticity, and compaction behavior. Kumar et al. (2017) evaluated POFA for stabilizing clayey soil and observed reduced plasticity and improved strength characteristics, concluding that POFA is suitable for subgrade stabilization. Lim and Shakri (2019) studied POFA with natural fibers in soft soil stabilization, reporting improvements in compaction and shear strength due to pozzolanic reactions. Mahmood et al. (2019) focused on peat soil stabilization using POFA and found improvements in density and load-bearing capacity, while Nik Daud et al. (2018) examined agricultural waste ashes including POFA and observed improvements in consistency limits and compaction behavior. Collectively, these studies confirm POFA's versatility across different soil types and stabilization contexts.

In summary, the literature demonstrates that POFA, particularly in micronized or alkali-activated form, significantly improves the engineering properties of clayey soils by reducing plasticity, enhancing compaction, and increasing strength. Its sustainable origin as an agricultural by-product further strengthens its appeal as an eco-friendly stabilizer. The current investigation builds upon these findings by focusing specifically on the strength behavior of clayey soil treated with micronized POFA, aiming to establish its suitability for infrastructure applications such as pavement subgrades and foundations. By integrating laboratory tests including liquid limit, plastic limit, maximum dry density, UCS, CBR, and sieve analysis, this study seeks to provide comprehensive insights into the performance of POFA-treated clayey soil. The outcomes are expected to contribute to the growing body of knowledge on sustainable soil stabilization and support the adoption of POFA as a cost-effective and environmentally responsible alternative to conventional stabilizers.

2. Materials

2.1. Clayey Soil

The soil used in this study was locally collected clayey soil, representative of expansive soils commonly found in India. Clayey soils are characterized by high plasticity, swelling when wet, and shrinkage upon drying, which often leads to cracks and uneven settlement in structures. These problematic properties are largely due to the presence of montmorillonite minerals. To establish its baseline characteristics, the soil was subjected to classification tests including Atterberg limits, sieve analysis, and grain size distribution. The results confirmed its low bearing capacity and high

plasticity index, making stabilization essential to improve strength, compaction, and long-term durability for use in pavements and foundations.

2.2. Palm Oil Fuel Ash (POFA)

Palm Oil Fuel Ash (POFA) is an agricultural by-product obtained from burning palm oil residues in mill boilers. It is often dumped in open fields, causing land and groundwater pollution (Sumadi & Hussin, 1995; Tonnayopas et al., 2006). Chemically, POFA is rich in silica and alumina, giving it strong pozzolanic properties. When mixed with clayey soil, it reacts with calcium hydroxide to form cementitious compounds that bind particles, reduce plasticity, and improve strength. Micronized POFA, ground into fine particles, shows higher reactivity and faster pozzolanic action. Studies confirm that it enhances compaction density, lowers plasticity index, and significantly increases Unconfined Compressive Strength (UCS) and California Bearing Ratio (CBR) values (Awal & Shehu, 2013; Pourakbar et al., 2015; Safiuddin et al., 2018). Thus, POFA is both an effective stabilizer for problematic soils and a sustainable solution that recycles agricultural waste while reducing reliance on cement.

3. Preparation of Test Specimens

For specimen preparation, the clayey soil was first dried, pulverized, and sieved to remove oversized particles. POFA was then added in varying percentages (such as 5%, 10%, 15%, and 20%) to study its effect on soil properties. The soil and POFA were thoroughly mixed to ensure uniform distribution, and moisture was adjusted to the Optimum Moisture Content (OMC) determined from compaction tests. Test specimens were prepared for Unconfined Compressive Strength (UCS), California Bearing Ratio (CBR), and compaction studies. UCS samples were cured for different periods (0 and 28 days) to evaluate strength gain over time, while CBR specimens were soaked for four days before testing to simulate subgrade conditions.

4. Tests Used in This Study

To evaluate the effect of micronized Palm Oil Fuel Ash (POFA) on clayey soil, a series of laboratory tests were conducted. These included Liquid Limit, Plastic Limit, Standard Proctor Compaction, California Bearing Ratio (CBR), and Unconfined Compressive Strength (UCS) at different curing periods. Each test was performed on untreated soil and soil stabilized with varying percentages of POFA to compare improvements in engineering properties.

4.1. Liquid Limit

The liquid limit test was performed using the Casagrande apparatus as per IS: 2720 (Part 5) – 1985. Soil passing through a 425 µm sieve was mixed with water to form a uniform paste. For treated samples, POFA was blended before adding water. The groove closure at 25 blows was used to determine the liquid limit. A flow graph between log N (number of blows) and water content (w) was plotted, and the liquid limit was obtained at N = 25. This test demonstrated the reduction in plasticity due to POFA addition.

4.2. Plastic Limit

The plastic limit test was conducted on untreated and POFA-treated soil as per IS: 2720 (Part 5) – 1985. Soil threads were rolled on a glass plate until they crumbled at 3 mm diameter. The corresponding water content was recorded as the plastic limit. The values of liquid limit and plastic limit were used to calculate the plasticity index (PI), and the soil was classified using the IS plasticity chart. POFA treatment was observed to lower PI, indicating reduced swelling potential.

4.3. Standard Proctor Compaction Test

Compaction tests were performed as per IS: 2720 (Part 7) – 1980 to determine the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD). Soil samples were compacted in three layers with 25 blows each using a standard rammer. For treated samples, POFA was mixed before adding water. The results showed how POFA influences compaction characteristics, leading to improved density and reduced void ratio.

4.4. California Bearing Ratio (CBR) Test

The CBR test was conducted on soaked specimens to evaluate subgrade strength. Soil samples were compacted in CBR moulds, surcharge weights applied, and penetration loads recorded at a constant rate of 1.25 mm/min. The CBR value was calculated as:

$$\text{CBR} = \frac{\text{Penetration Load}}{\text{Standard Load}} \times 100$$

Comparisons between untreated and POFA-treated soils highlighted improvements in load-bearing capacity, making POFA suitable for pavement subgrades.

4.5. Unconfined Compressive Strength (UCS) Test

UCS tests were performed as per IS: 2720 (Part 10) – 1991 on specimens prepared at OMC and MDD. Cylindrical samples (38 mm diameter, 76 mm height) were compacted and tested under axial load at a strain rate of 0.60 mm/min until failure. The maximum load was recorded to calculate UCS.

4.6. Curing

Specimens were cured for 0 and 28 days to study strength development. They were wrapped in polythene covers to prevent moisture loss and stored under controlled conditions.

5. Methodology

The research methodology adopted in this study involved a systematic sequence of activities to evaluate the stabilization of clayey soil using Palm Oil Fuel Ash (POFA). The process began with a comprehensive literature survey to identify research gaps and establish the significance of POFA as a sustainable stabilizer. Following this, clayey soil and POFA were collected and prepared in the laboratory. Specimens were prepared by incorporating varying percentages of POFA (1%, 2%, 4%, 6%, 8%, 10%, 12%, and 14%) into the soil by dry weight. Untreated soil samples were also prepared to serve as control specimens. All prepared samples were subjected to standard laboratory tests, including Liquid Limit, Plastic Limit, Compaction Test, California Bearing Ratio (CBR) under soaked conditions, and Unconfined Compressive Strength (UCS) at different curing periods (0 and 28 days). The experimental results were systematically recorded and analyzed. Comparisons were made between untreated and POFA-treated soils to evaluate improvements in plasticity, compaction density, load-bearing capacity, and strength. The findings were presented using tables, graphs, and charts, and conclusions were drawn regarding the optimum percentage of POFA required for effective stabilization of clayey soil.

6. Results and Discussions

6.1. Analysis for results of Atterberg's limits

POFA significantly influenced the plasticity of clayey soil. At low dosages (1–2%) (Table. 1, Fig. 1), the liquid limit dropped, showing reduced water-holding capacity, while higher contents (around 10%) increased it again due to ash–clay binding. The plastic limit rose up to 6% POFA, then declined, indicating initial improvement in deformation resistance that weakened at higher levels. The plasticity index fluctuated, dropping at 2%, peaking at 10%, and then reducing, showing a non-linear effect. Curing enhanced POFA's role: after 28 days, the liquid limit rose steadily to 8–10%, the plastic limit peaked at 6%, and the plasticity index generally reduced compared to virgin soil. This confirms that pozzolanic reactions develop over time, improving soil behavior. In short, POFA makes soil more granular, reduces plasticity at low levels, increases it at higher levels, and shows stronger stabilization with curing. Optimum improvement was observed around 6–10% POFA.

Table 1. Results of 0th day & 28th day Atterberg's limits tests for soil treated with POFA

S.no	POFA content (%)	0 th day plasticity index	28 th day plasticity index
1	VERGIN SOIL	42.03	42.03
2	1%	14.84	49.44
3	2%	8.60	32.78
4	4%	32.65	28.87
5	6%	53.06	26.61
6	8%	34.63	34.53
7	10%	48.55	34.63
8	12%	32.44	33.43
9	14%	37.76	35.47

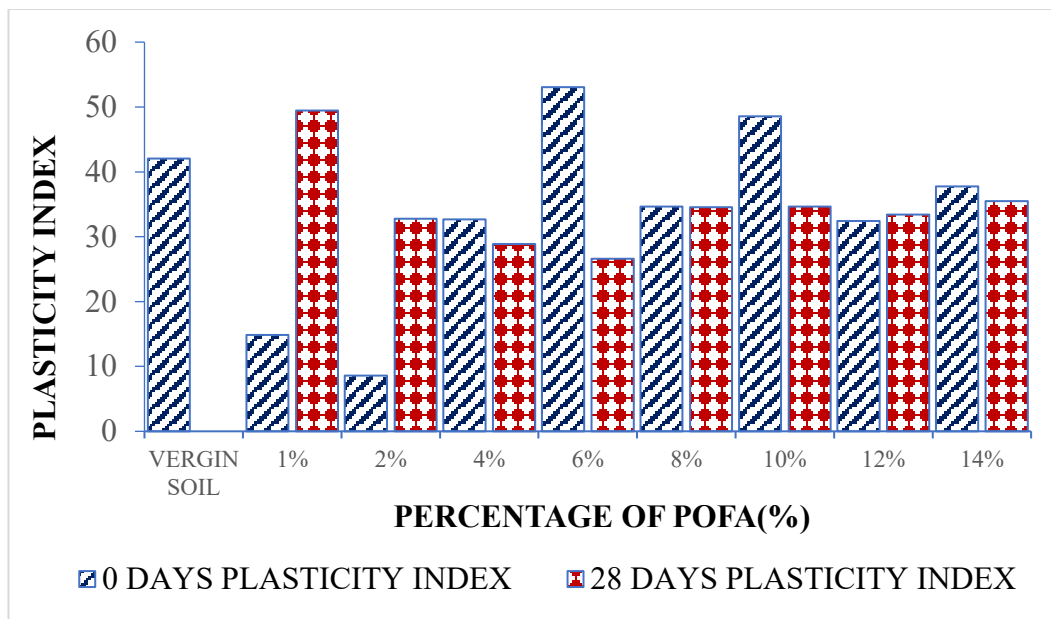


Fig. 1: Compare 0th day and 28th day plasticity index trend for soil treated with POFA

6.2. Analysis for results of proctor compaction test

For POFA-treated soil, the Optimum Moisture Content (OMC) increased steadily with higher POFA percentages, rising from about 23% in virgin soil to over 31% at 14% POFA (Table 2, Fig. 2). This indicates that the soil requires more water for compaction when POFA is added, likely due to the porous nature of ash particles. The Maximum Dry Density (MDD) showed improvement up to 10% POFA, reaching about 1.61 g/cc, but decreased at higher percentages. This trend suggests that moderate POFA content enhances soil compaction, while excessive amounts reduce density because surplus ash particles lower packing efficiency. Overall, the combined OMC–MDD behavior confirms that the best compaction occurs at mid-range POFA levels (around 6–10%), where moisture demand and density are balanced. Beyond this range, density decreases despite higher water content, highlighting the importance of dosage control.

Table 2. Results of proctor compaction tests for soil treated with POFA

S. No	POFA content (%)	OMC (%)	(MDD)	
			(g/cc)	KN/m ³
1	0	23.36	1.39	13.87
2	1	24.69	1.47	14.42
3	2	25.89	1.5	14.72
4	4	26.27	1.55	15.22
5	6	28.35	1.58	15.49
6	8	28.97	1.59	15.59
7	10	29.2	1.61	15.79
8	12	30.1	1.54	15.11
9	14	31.65	1.46	14.32

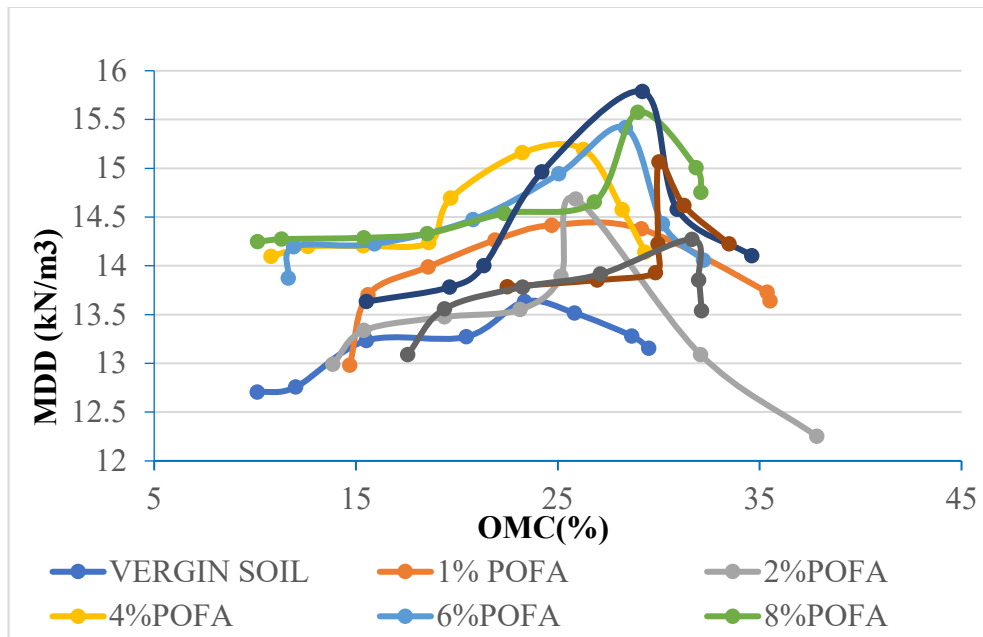


Fig. 2. OMC&MDD trend for soil treated with POFA

6.3. Analysis for results of California Bearing Ratio test

Virgin clayey soil showed a very low soaked CBR value of 0.86, confirming poor strength and unsuitability for construction. With the addition of POFA, strength improved steadily up to 10% POFA, where the CBR reached 3.85 (Table 3, Fig. 3). This demonstrates that POFA can significantly enhance soil performance, making it more resistant to penetration and load. However, beyond the optimum dosage, strength declined sharply. At 12% POFA, the CBR dropped to 1.71, and at 14% POFA it returned to the virgin soil value of 0.86. This indicates that excessive POFA content reduces soil strength due to poor particle packing and reduced bonding efficiency. In summary, POFA moderately improves the load-bearing capacity of clayey soil, with 10% POFA identified as the optimum level for stabilization. Beyond this, the benefits diminish, highlighting the importance of dosage control in achieving effective soil improvement.

Table 3. Results of California Bearing Ratio tests for soil treated with POFA

S.no.	POFA content (%)	Soaked CBR value
1	VERGIN SOIL	0.86
2	1%	2.14
3	2%	2.78
4	4%	2.99
5	6%	3.42
6	8%	3.64
7	10%	3.85
8	12%	1.71
9	14%	0.86

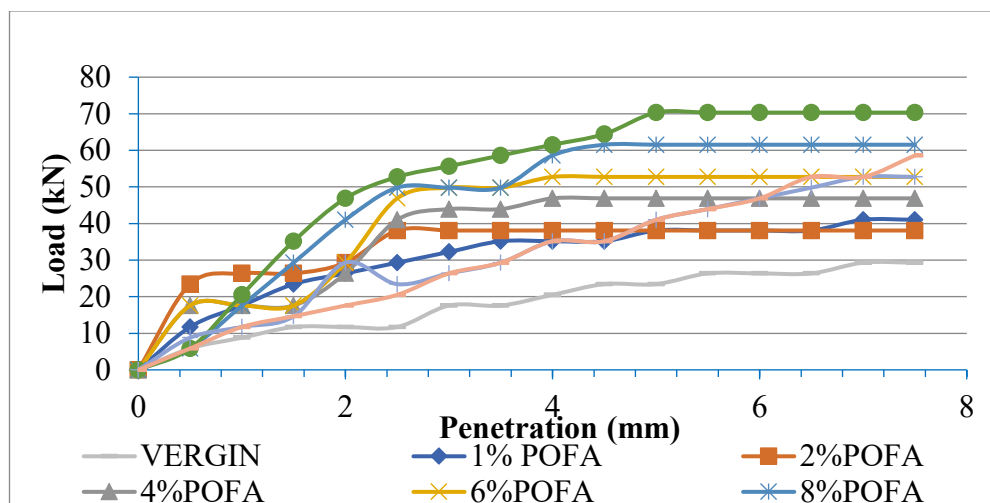


Fig 3. California bearing ratio tests trend for soil treated with POFA

6.4. ANALYSIS FOR RESULTS OF UNCONFINED COMPRESSIVE STRENGTH TEST

Virgin clayey soil had a UCS of 32.63 kg/cm², indicating weak strength. With POFA addition, strength increased gradually, reaching 45.88 kg/cm² at 8% POFA and peaking sharply at 115.06 kg/cm² at 10% POFA (Table 4, Fig. 4). Beyond this optimum dosage, strength declined, with 12% POFA at 109.74 kg/cm² and 14% POFA at 79.12 kg/cm², confirming that excessive POFA reduces effectiveness. Curing enhanced POFA's stabilizing role. After 28 days, UCS values rose further, peaking at 119.35 kg/cm² at 10% POFA, showing that pozzolanic reactions continue over time, making the soil stronger and more durable. In summary, POFA improves UCS significantly up to an optimum of 10%, while curing amplifies this effect. Excessive POFA content reduces strength, highlighting the importance of dosage control for effective stabilization.

Table 4. Results of compare unconfined compressive strength tests for untreated and cured soil treated with POFA

POFA content (%)	UCS of untreated soil	UCS of treated soil
1	30.58	50.32
2	33.12	50.78
4	36.14	53.43
6	39.58	60.10
8	45.88	107.81
10	115.06	119.35
12	109.74	114.18
14	79.12	103.47

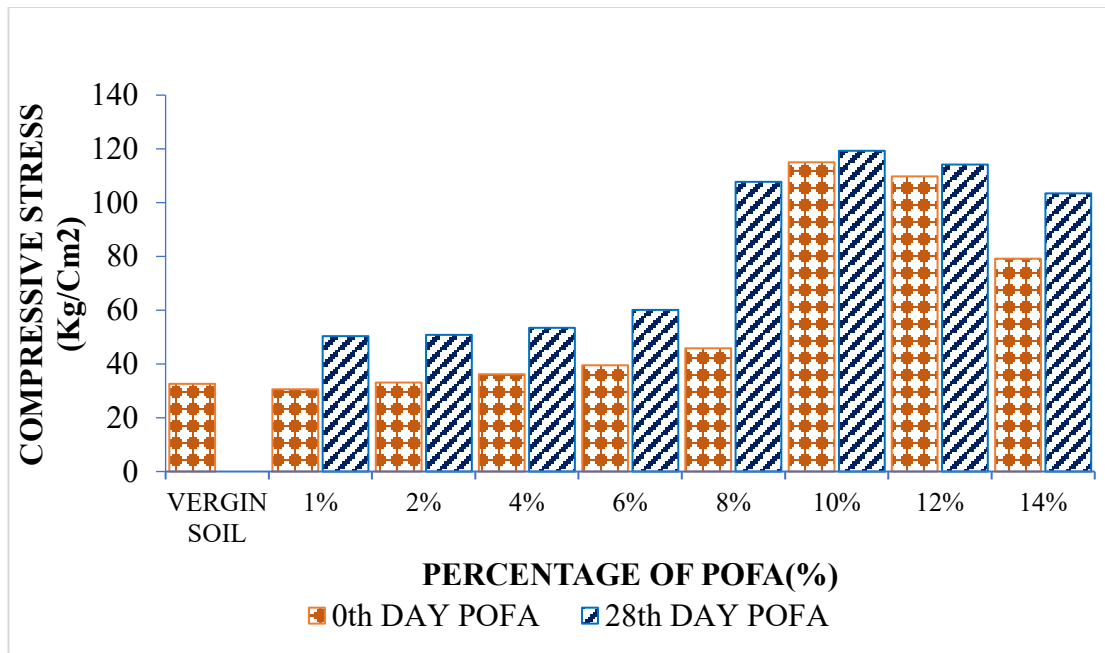


Fig 4. Compare unconfined compressive strength tests for untreated and cured treated with POFA

7. Conclusions

The study confirms that Palm Oil Fuel Ash (POFA) has a significant influence on the engineering properties of clayey soil. At low percentages, POFA reduces plasticity and improves workability, while at higher levels (around 10%) it enhances strength and compaction before declining with excessive addition. Compaction tests showed increased Optimum Moisture Content and improved Maximum Dry Density up to 10% POFA, while California Bearing Ratio values rose to 3.85 at the same dosage, marking the optimum level for load-bearing capacity. Unconfined Compressive Strength results further highlighted POFA's effectiveness, with strength peaking at about 115 kg/cm² initially and 119 kg/cm² after 28 days of curing, demonstrating the long-term benefits of pozzolanic reactions. Overall, POFA acts as a sustainable stabilizer that improves soil texture, density, and strength, provided its dosage is carefully controlled to avoid reductions in performance at higher contents.

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