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Sustainable Reuse of Waste Palm Oil Fuel Ash in Geopolymer Stabilization of Silty Soil: A Comprehensive Assessment of Mechanical Strength and Leaching Toxicity for Environmentally Conscious Infrastructure Development

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Abstract
Soil plays a vital role in infrastructure development, but certain types, such as silty soil, require stabilization due to their poor load-bearing capacity. With a growing emphasis on sustainable construction highlights palm oil fuel ash (POFA), a byproduct of biomass combustion in palm oil mills, as a viable alternative for soil stabilization, particularly in regions such as Sultan Kudarat, Philippines, where it is readily accessible. This study addresses the limited research on using POFA-based geopolymer for stabilizing silty soils, particularly in evaluating its environmental impact, and applicability in infrastructure development. It aims to assess the effectiveness of POFA-based geopolymer in enhancing the strength, stability, and load-bearing capacity of silty soil in Sultan Kudarat. A post-test-only controlled group experimental design was used to evaluate the effectiveness of POFA-based geopolymer in stabilizing silty soil, and mechanical strength tests were conducted on both the natural soil and treated samples. The study assessed shear strength, compressive strength, and California bearing ratio (CBR) using ASTM-standard methods alongside a Toxicity Characteristic and Leaching Procedure (TCLP) to evaluate environmental safety. Results showed that POFA-based geopolymer significantly improved shear strength, with optimum performance at 27.5% and 30% of POFA after 28 days of curing. Whereas compressive strength and CBR values were lower than in natural soil, treated samples showed enhanced ductility, reduced swell potential, and stable failure modes. TCLP confirmed that all heavy metals tested were below regulatory limits, with a non-corrosive pH of 10.95 and no hazardous reactivity or flammability observed. These results highlight POFA-based geopolymer as a safe, environmentally friendly option for stabilizing silty soils and offer potential for sustainable infrastructure development.

Keywords: Soil Stabilization, Silty Soil, Palm Oil Fuel Ash, Geopolymer

1. INTRODUCTION

Soil is a critical factor in constructing significant infrastructures, as not all soils can sustain the loads imposed. According to Ural et al. (2018) [1], from a geotechnical perspective, problematic soils were prone to expansion, collapse, dispersion, excessive settlement, or failure under relatively low-stress conditions. Examples included soft soils such as silty, clayey, peat, and organic soils, where stabilization is necessary to achieve desirable engineering properties.

Soil stabilization techniques enhance geotechnical properties through the integration of diverse additives. Geopolymers have attracted significant attention from researchers in recent years because of their varied chemistries and extensive applications. Geopolymers, recognized as high-performance inorganic materials, have experienced considerable advancement worldwide.

The increasing number of biomass boiler plants led to the rapid accumulation of biomass combustion byproducts. One such alumino-silicate source material, as identified by Abdeljouad et al. (2019) [2], was palm oil fuel ash (POFA); It is an industrial waste product that is made when palm oil waste is burned to generate electricity. In the Philippines, oil palm production is considered a developing industry relative to its neighboring countries, in which the top oil palm producers in the world market of 76.26 million MT as of 2023-2024 are Indonesia (56%) and Malaysia (26%), according to USDA Foreign Agricultural Service (2025). Oil palm cultivation began in the Philippines in Basilan in 1966, and in 1970, Kenram Industry, Inc. in Sultan Kudarat transformed their ramie plantation into oil palm production [3]. Two oil palm mills were operating in Sultan Kudarat as of 2025: Kenram Palm Oil Industry, Inc. in Isulan and A.C. Garcia Palm Oil Mill Corporation in Tacurong City, both in Sultan Kudarat. Since oil palm mill uses steam boilers for the production of palm oil, an abundance of boiler ash was produced, which is the palm oil fuel ash. Thus, this agricultural waste must be utilized and innovated as a construction material.

Studies by different researchers have shown that palm oil fuel ash (POFA) is effective for soil stabilization for soft soils whether it used alone or together with other mixtures such as cement, fly ash, and others [4–9]. The literature review reveals that using POFA-based geopolymer in soil stabilization is still a developing study compared to the well-developed stabilization of soils using Ordinary Portland Cement (OPC). Most studies focused on physical and mechanical improvements. However, there was a limited investigation into other critical parameters, including long-term sustainability and performance in the subgrade, subbase, and base course applications. A significant research gap identified was the lack of environmental impact assessment of POFA-based geopolymer as a soil stabilizer.

Thus, this study addressed these gaps by evaluating the mechanical strength of soil stabilized with POFA-based geopolymer. Laboratory tests were conducted, including direct shear tests for shear strength, unconfined compression tests for compressive strength, and California Bearing Ratio (CBR) tests to assess its suitability for subgrade applications. Furthermore, the study examined the environmental impact of POFA-based geopolymer, including toxicity characteristics and reactivity. Findings show that this study contributed a more comprehensive knowledge of POFA-based geopolymer as a sustainable option for stabilizing silty soil.

2. Methodology

2.1 Research Design

This study employed a true experimental design, specifically the post-test-only controlled group. The subjects were assigned to two groups: the natural soil and the stabilized soil. The natural soil was the control group, while the stabilized soil was the experimental group that received the treatment. Post-tests were conducted to both groups to determine if the stabilized silty soil showed a significant increase in its shear strength, compressive strength, and California Bearing Ratio (CBR) values compared to the natural soil sample.

2.2 Research Locale

The researcher collected the POFA at Kenram Industry, Inc. in Isulan, Province of Sultan Kudarat. Samples of the natural soil were obtained from Sultan Kudarat State University – ACCESS Campus, Tacurong City, Sultan Kudarat, and were classified as silty soil.

The testing was conducted in collaboration with the following accredited laboratory testing centers: Megatesting Center Inc., General Santos City – performed sieve analysis and Atterberg limits tests on the natural soil. Qualitest Solutions & Technologies, Inc., Davao City – determined the specific gravity, compaction characteristics, unconfined compressive strength, and California Bearing Ratio (CBR) for both the natural soil and treated samples. Notre Dame of Marbel University, Koronadal City, South Cotabato – carried out the direct shear tests to evaluate shear strength parameters. FAST Laboratories, Cagayan de Oro City (DENR-accredited) – conducted the Toxicity Characteristic Leaching Procedure (TCLP).

2.3 Research Materials

The following were the materials used to synthesize the geopolymer material through a standard geopolymerization process. A brief description of each material is provided below.

Silty Soil. It is composed of an accumulation of mostly silt-sized particles (< 0.075 mm), often with a small percentage of clay.

Palm Oil Fuel Ash (POFA). It is a solid waste palm oil plants byproduct, derived from the ash produced by the combustion of palm kernel shells, husks, and palm fronds utilized as fuel in palm oil mills' steam generator [10].

Sodium Hydroxide (NaOH). It is a white solid in pellets, flakes, granules, and various concentrations of prepared solutions. A 12 Molarity of NaOH solution was prepared.

Sodium Silicate (Na_2SiO_3). It is a silicon-oxygen polymer with ionic sodium (Na^+) components that form an oxygen-silicon polymer backbone that houses water in molecular matrix pores.

Geopolymer. It is an inorganic polymer that can be synthesized by combining Na_2SiO_3 and NaOH as the alkali activator in the geopolymerization process. In this study, the alkali activator will be mixed with POFA, an aluminosilicate source material, then geopolymerization reaction occurs, resulting in the formation of the geopolymer material.

2.4 Research Instrument

The tests were used to measure shear strength, compressive strength, bearing capacity, and potential environmental impact of POFA-based geopolymer in silty soil stabilization were the following with an overview of the instruments and methods used, along with their roles in the study.

Direct Shear Test Apparatus. It is a device that applied a shear force to a specimen with enough capacity and control to deform it at the required displacement rate. (ASTM D3080/D3080M-23, 2023).

Unconfined Compression Test Apparatus. It is an instrument used to precisely assess the unconfined compressive strength of soil samples. The motorized mechanism enabled accurate and regulated application of axial load to a soil specimen, free of the confining pressure commonly utilized in other compression tests (ASTM D2166-00, 2017).California Bearing Ratio Test Apparatus. It is a loading machine with a minimum capacity of 5000 kg, having a movable head that allowed a plunger with a diameter of 50 mm to penetrate the specimen at a rate of 1.25 mm per minute (ASTM D1883-21, 2021).

Toxicity Characteristic and Leaching Procedure (TCLP). It is a standardized chemical analysis method used to determine if a waste is hazardous due to toxicity. It simulates the leaching of contaminants from waste in a landfill under acidic conditions, and the resulting leachate is then analyzed to determine the presence and concentration of hazardous substances (USEPA Method 1311, 1992).

2.5 Data Gathering Procedure

This research method was similar to the study conducted by Khasib et al. (2021) [11]. The data gathering began with the collection of experimental samples: the natural soil and palm oil fuel ash (POFA). The process of determining the strength properties and environment assessment of POFA-based geopolymer stabilized silty soil involves the following:

Physical Properties of Natural Soil

First was to determine the properties of the natural soil sample based on moisture content, soil gradation, specific gravity, soil indices, and soil classification. The properties of soil have distinct characters and have varying influences on various types of civil engineering structures. These properties have significance in achieving favorable outcomes and optimizing the utilization of all materials involved.

Samples Preparation

Six mixtures were studied with POFA-based geopolymer percentages, as shown in Table 1. The soil was first mixed with POFA-based geopolymer with 0% (control), 25%, 27.5%, 30%, 32.5%, and 35% proportions (by mass of soil solids) until a homogeneous mixture was obtained. NaOH pellets (99% pure) were dissolved in distilled water to create a 12M solution, which was left to cool for 24 hours before being mixed with liquid Na_2SiO_3. The activator ratio (Na_2SiO_3/NaOH) was fixed at 2.5, and the solid-to-liquid (S/L) ratio was maintained at 1.5, following recommendations from previous studies.

Table 1: Geopolymer ingredients for each 1 kg of soil specimen

Mixture	Soil (g)	POFA (%) with Soil Mass	POFA (g)	Liquid Acti-vator with S/L = 1.5 (g)	Na_2SiO_3/NaOH = 2.5 (2.5:1)	
					Na_2SiO_3 (g)	NaOH(g)
Natural Soil	1000	0	0	0	0	0
T1	1000	25.0%	250	167	119.28	47.72
T2	1000	27.5%	275	184	131.43	52.57
T3	1000	30.0%	300	200	142.85	57.15
T4	1000	32.5%	325	217	155.00	62.00
T5	1000	35.0%	320	234	167.15	68.85

The palm oil fuel ash (POFA) was air-dried and sieved through a 200 µm mesh to eliminate coarse or unburnt particles. Finer particles were used, as they helped improve the geopolymer's strength. The sieved POFA was then blended with the alkaline solution and manually stirred for 10 minutes to ensure a consistent mix.

This geopolymer blend was then mixed with soil and a controlled amount of water for another 10 minutes to achieve a uniform mixture. The amount of water was adjusted to meet optimum compaction conditions. Samples were prepared at moisture levels corresponding to the soil's maximum dry density. To ensure reliable results, each test was performed in triplicate, and results were accepted if they differed by no more than 5%.

Soil Compaction

Optimum moisture content (OMC) and maximum dry density (MDD) were determined using the compaction test following ASTM D1557/AASHTO T-180. Using a 4-inch mold and 10-pound hammer, five specimens per group were compacted at varying moisture contents to generate a compaction curve. Approximately 2 kg of soil passing sieve No. 4 was mixed with water using the volcano method, then compacted in three layers with 25 blows per layer. The mold's mass and volume were recorded, and the compacted sample was weighed, extruded, and samples were taken for moisture content determination, specifically from top and bottom. The moist unit weight was calculated, and dry unit weights were plotted against moisture contents to generate the compaction curve, from which MDD and OMC were obtained.

Curing Time

The development of strength over time was dependent on the quality of the materials and curing techniques used. Here, specimens were cured for 7 and 28 days. During the curing period, the specimens were stored in a plastic sheet to prevent moisture loss. All specimens were secured at the previously specified laboratories prior to testing. The samples cured were for direct shear test and unconfined compression test.

Direct Shear Tes

Shear strength parameters (cohesion and angle of internal friction) of the soil were determined using a direct shear testing (DST). A shear box apparatus equipped with porous stones, gripper plates, loading devices, and dial gauges. Cured and compacted soil samples were placed and trimmed in the shear box, ensuring correct alignment of components. An initial normal load of 0.5 kg/cm² was applied during consolidation, with vertical and horizontal displacements recorded over time. After consolidation, a 0.64 mm gap was created between the shear box halves, and shear stress was applied until failure. Shear load, displacement, and vertical movement were monitored at regular intervals. The test was repeated with increasing normal loads (50 kPa, 100 kPa, and 200 kPa), and shear strength values were plotted against normal stress to derive cohesion (c) and the angle of internal friction (ϕ) using the Mohr-Coulomb equation:

$$\tau_f = c + \sigma \tan \phi \qquad (1)$$

Unconfined Compression Test

The unconfined compression test, following ASTM D2166, was performed to determine the compressive strength of both the natural soil and POFA-based geopolymer stabilized soil. Cylindrical specimens with a 2:1 height-to-diameter ratio were tested using a vertical load applied at a constant rate of 1.22 mm/min until failure. Axial stress and strain were recorded throughout the test to plot stress-strain curves. The peak compressive strength was calculated and results were used to compare the strength and deformation behavior of the stabilized soil at different POFA proportions.

California Bearing Ratio Test

The California Bearing Ratio (CBR) test (ASTM D1883) was conducted to evaluate the strength and load-bearing capacity of both the natural soil and POFA-based geopolymer stabilized soil. Samples were compacted in a CBR mold to their OMC and MDD, then soaked for 4 days. The saturated specimens were tested using a 50 mm diameter piston to apply vertical loads, with penetration resistance measured at specific depths (e.g., 0.25 to 7.5 mm). The CBR value was calculated as the ratio of the sample's penetration resistance to that of a standard crushed stone, expressed as a percentage.

Toxicity Characteristic Leaching Procedure

The Toxicity Characteristic Leaching Procedure (TCLP) was conducted to assess the leaching potential and reactivity of POFA-based geopolymer-stabilized soil. Following mechanical strength tests, a sample was subjected to TCLP, wherein a buffered extraction fluid was prepared per standard guidelines and added to the sample at a 20:1 liquid-to-solid ratio. The mixture was agitated to ensure thorough contact, then filtered to separate the leachate from solid residues. The leachate was analyzed for contaminants such as heavy metals and organic compounds using standard methods. Results were compared with regulatory limits to evaluate environmental compliance.

3. Results and Discussion

3.1 Physical Properties of the Natural Soil

The physical characterization of the natural soil sample was conducted through laboratory tests, including initial moisture content, gradation, specific gravity, soil indices, and soil classification. The initial moisture content was 5.39% (ASTM D2216), which helps determine the required water addition for optimal compaction. Figure 1 shows the gradation curve of the natural soil, sieve analysis revealed that 58.9% of the soil passed the No. 200 sieve (0.075 mm), classifying it as fine-grained, predominantly silty material. Specific gravity was 2.57 (ASTM C128), and soil indices showed a liquid limit of 26%, plastic limit of 22.5%, and a plasticity index of 3.5%, indicating low plasticity and limited cohesion. According to AASHTO, the soil falls into group A-4, suitable for subgrade use but with fair to poor performance, while the USCS classifies it as ML (low plasticity silt).

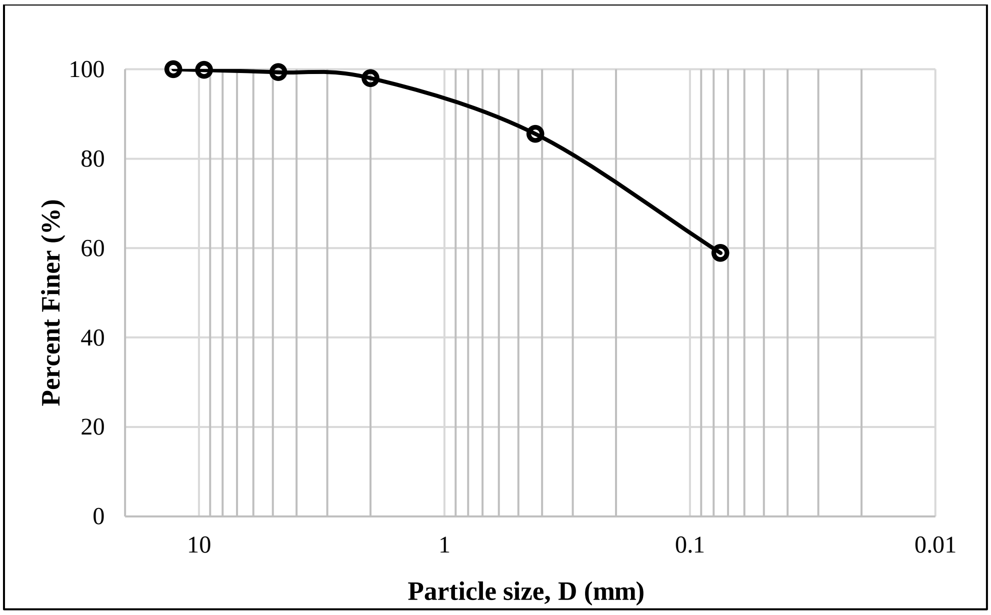


Figure 1: Gradation Curve of the Natural Soil

In summary, the AASHTO and USCS yielded similar results, confirming that the natural soil sample was silty soil with low plasticity. Silty soil is generally considered a suitable subgrade material; however, it is often categorized as soft soil due to its sensitivity to moisture content, compaction, and loading conditions. One concern with silty soils is their susceptibility to liquefaction, especially under dynamic or seismic loading, as their fine-grained structure and low plasticity can lead to a loss of strength when saturated [12]. Because of these limitations, additional measures such as chemical or mechanical stabilization are often necessary to enhance the soil's performance and reliability for engineering applications. Summary of the Physical Properties of the Natural Soil was shown in Table 2.

Table 2: Summary of the Physical Properties of the Natural Soil

Soil Properties	Unit	Standards	Natural Soil
Initial Moisture Content	%	ASTM D2216	5.39
Specific Gravity	-	ASTM C128	2.57
Plastic limit	%	ASTM D4318	22.5
Liquid Limit	%	ASTM D4318	26
Plasticity Index	%	ASTM D4318	3.5
Soil Classification	-	AASHTO / USCS	A - 4(0) Mostly silty soils / ML - Silt

3.2 Compaction Properties (OMC and MDD)

The Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) of the natural soil and treated soil samples mixed with 25%, 27.5%, 30%, 32.5%, and 35% proportions of POFA-based geopolymer were determined using the ASTM D1557/AASHTO T-180 (Modified Proctor Test), that provides a higher compaction effort than the Standard Proctor Test.

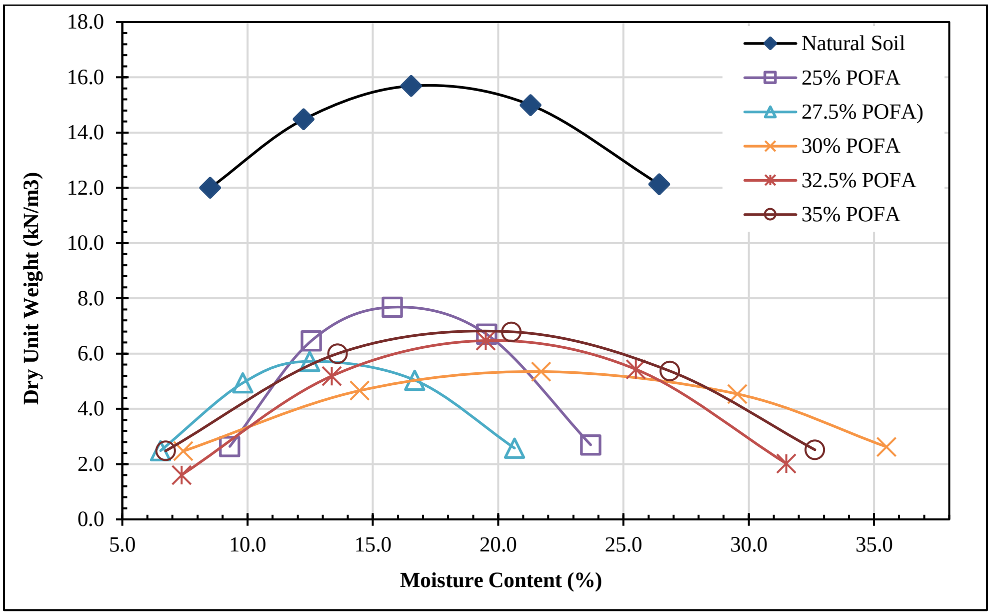


Figure 2. Moisture-Density Curve of the Natural Soil and Treated Samples

As observed in the moisture-density curves in Figure 2, increasing moisture content initially improves soil compaction by lubricating the particles, allowing them to pack more closely and increasing dry density. However, excess moisture fills the voids beyond a certain point, leading to a drop in dry density. That peak of the curve indicates the MDD and the corresponding OMC.

The peak was determined through the following steps:

- The equations in Table 3 representing the treatment's curve were obtained from the trendline function of MS Excel and observed to be a second-order polynomial (parabolic curve).
- The compaction properties were calculated by analyzing this equation.
- The equation was derived to find the slope (f'(x)) of the curve.
- The peak of the curve occurs where the slope is zero, so f'(x) = 0 was solved to find the OMC (x-value at the peak).
- MDD was then determined by substituting the OMC into the original equation f(x).

The results of the Compaction Properties (OMC and MDD) shown in Table 3 with the corresponding Moisture-Density Curve illustrated in Figure 2.

Table 3: Results of the Compaction Properties (OMC and MDD)

Treatment	**Equation**	**OMC (%)**	**MDD (kN/m³)**
Natural Soil	$f(x) = -0.0454x^2 + 1.589x + 1.7689$	17.51	15.71
25% POFA	$f(x) = -0.0973x^2 + 3.200x - 18.55$	16.44	7.75
27.5% POFA	$f(x) = -0.0649x^2 + 1.763x - 6.207$	13.58	5.74
30% POFA	$f(x) = -0.0144x^2 + 0.6227x - 1.3610$	22.24	5.56
32.5% POFA	$f(x) = -0.03204x^2 + 1.263x - 5.956$	19.71	6.48
35% POFA	$f(x) = -0.0258x^2 + 1.013x - 3.115$	20.26	7.14

3.3 Shear Strength Parameters under Direct Shear Test

Shear strength is a key factor in geotechnical engineering, influencing slope stability, foundations, and soil-structure interaction [13]. POFA-based geopolymer were evaluated using direct shear test. The test measures maximum shear stress under horizontal force until failure.

After 7 and 28 days of curing, the natural soil and treated samples were subjected to direct shear testing. Three replicate samples from each group were tested under normal stresses of 50 kPa, 100 kPa, and 200 kPa. The peak shear strength results were presented in Tables 4 and 5.

Table 4: The peak shear strength results for the Natural Soil and Treated Samples after 7 days of curing

Mixture	**Samples**		
	50 kPa	**100 kPa**	**200 kPa**
Natural Soil	30.44	69.92	116.43
25% POFA	37.24	84.49	138.47
27.5% POFA	49.03	91.19	159.84
30% POFA	49.35	86.72	149.97
32.5% POFA	45.19	82.57	140.39
35% POFA	31.59	31.59	109.72

Table 5: The peak shear strength results for the Natural Soil and Treated Samples after 28 days of curing

Mixture	**Samples**

	50 kPa	100 kPa	200 kPa
Natural Soil	32.61	86.47	133.68
25% POFA	42.45	100.14	153.55
27.5% POFA	50.69	105.28	169.59
30% POFA	50.08	114.83	177.99
32.5% POFA	47.46	100.65	163.07
35% **POFA**	42.10	87.36	141.32

The peak shear strength data were consolidated and plotted in Figures 3 and 4 to demonstrate the relationship between normal stress and peak shear stress. Mohr-Coulomb failure envelopes were generated by plotting best-fit lines through the three data points for each sample group. Regression equations and corresponding R^2 values, produced using MS Excel, were used to evaluate the linearity of these relationships.

Figure 3: Mhor-Coulomb Failure Envelope for Shear Strength of both the Natural Soil and Treated Samples after 7 Days of Curing

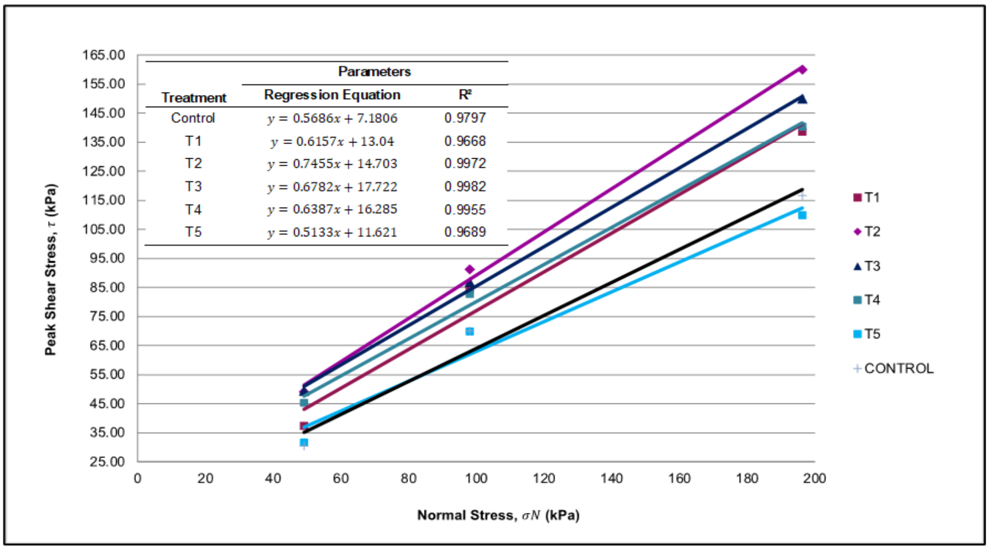
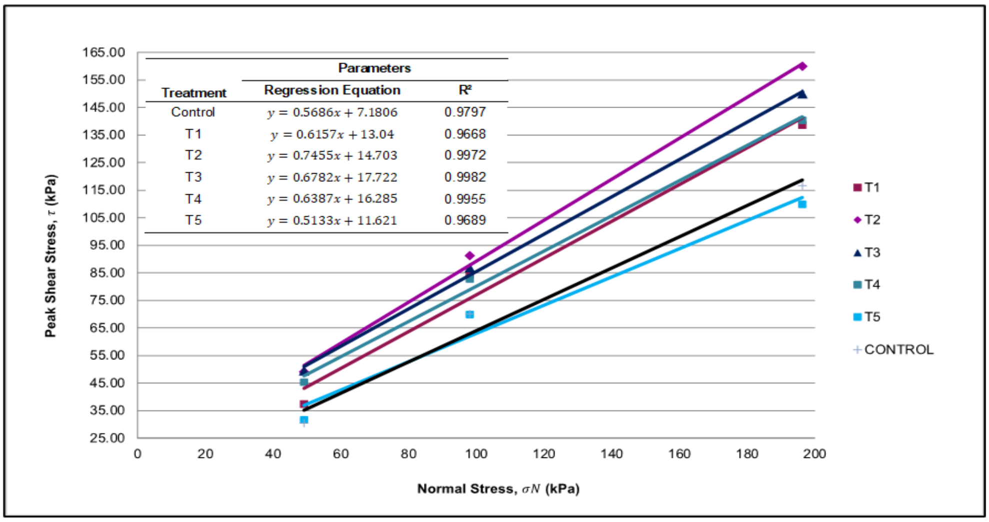


Figure 4: Mhor-Coulomb Failure Envelope for Shear Strength of both the Natural Soil and Treated Samples after 28 Days of Curing



Results after 7 and 28 days of curing, including cohesion, friction angle, and shear strength at 1 kPa normal stress, are discussed below.

Figure 5 compares cohesion values for the natural soil and treated samples after 7 and 28 days of curing. The key observations were the following:

- Treatment 3 (30% POFA) achieved peak cohesion values at both curing periods (17.72 kPa at 7 days and 18.51 kPa at 28 days), demonstrating optimal geopolymer effectiveness;
- Cohesion showed significant improvement, increasing from 7.18 kPa (natural soil at 7 days) to 9.00 kPa (natural soil at 28 days) through natural consolidation, with treated samples exhibiting more significant enhancements;
- Cohesion enhancement peaked at 30% POFA, with higher doses (>30%) reducing effectiveness (11.62 kPa at 35% POFA for 7-day curing and 15.21 kPa for 28-day curing);
- Treatment 1 (25% POFA) showed the highest percentage gain (53.56%) among treated samples after 28 days of curing; and
- A critical threshold was identified at 30% POFA, beyond which cohesion performance declined at both curing periods.

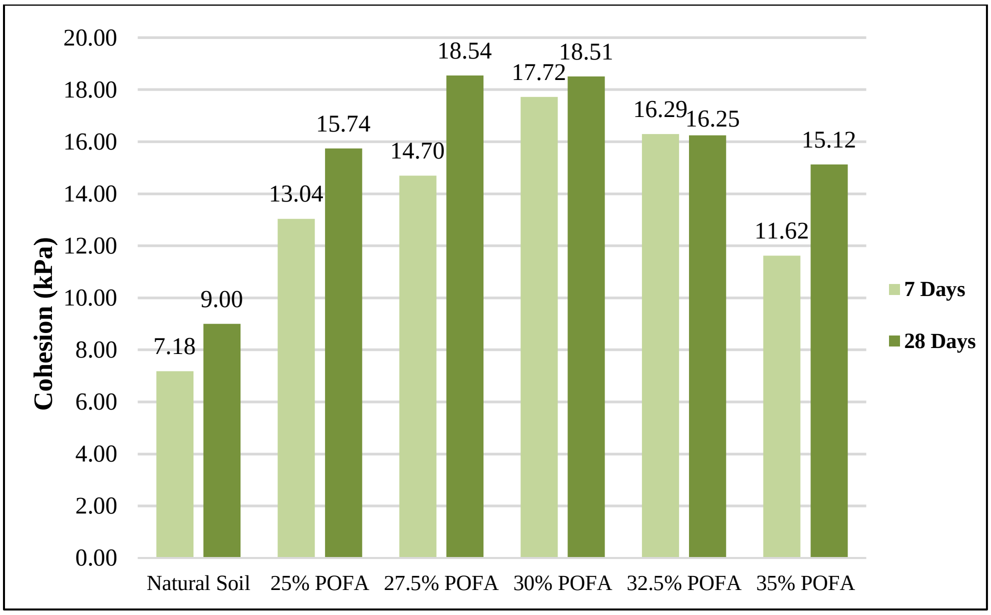


Figure 5: Cohesion of the Natural Soil and the Treated Samples after 7 and 28 Days of Curing

Figure 6: Angle of Internal Friction of the Natural Soil and the Treated Samples after 7 and 28 Days of Curing

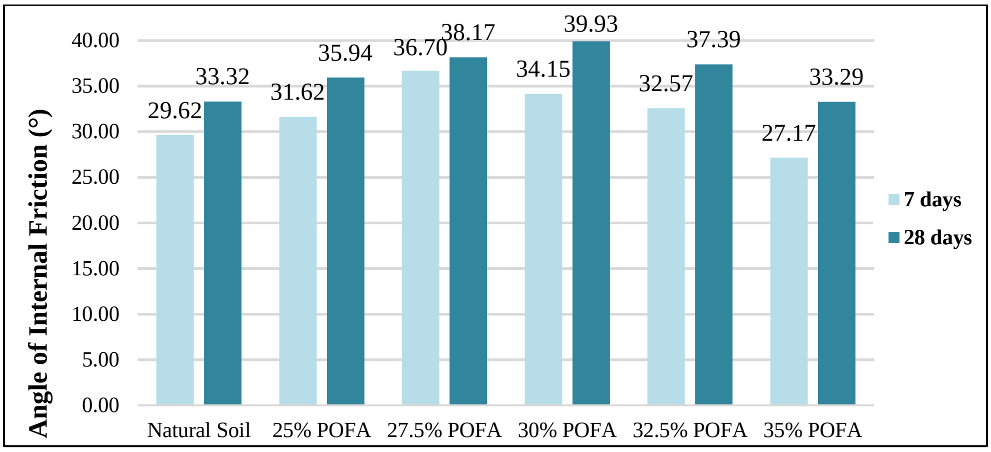


Figure 6 compares the angle of internal friction for the natural soil and treated samples after 7 and 28 of curing. The key observations were the following:

- Treatment 2 (27.5% POFA) achieved the highest initial friction angle (36.70°) at 7 days, demonstrating early geopolymer effectiveness;
- Friction angles showed progressive improvement, increasing from 29.62° (natural soil at 7 days) to 33.32° (natural soil at 28 days) through natural consolidation, with treated samples exhibiting greater enhancements;
- Treatment 3 (30% POFA) reached peak performance (39.93°) after 28 days of curing, followed by Treatment 2 (27.5% POFA) at 38.17°;
- All POFA treatments maintained higher friction angles than natural soil at both curing periods; and
- The results confirm that friction angles, like cohesion, continue to improve with extended curing time.

Figure 7: Shear Strength (at 1kPa Normal Stress) of the Natural Soil and the Treated Samples after 7 and 28 Days of Curing

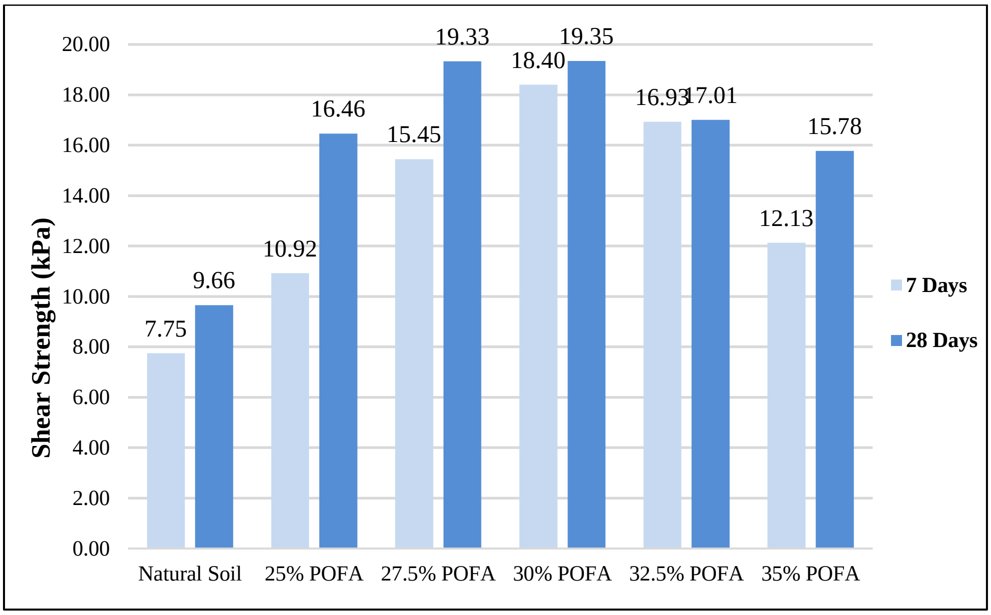


Figure 7 compares the shear strength of stabilized silty soil at 1 kPa normal stress for 7-day and 28-day curing periods. The key observations were the following:

- Treatment 3 (30% POFA) achieved the highest shear strength (19.35 kPa) after 28 days, demonstrating optimal geopolymer effectiveness;
- Shear strength showed progressive improvement with curing time, with Treatment 1 (25% POFA) exhibiting the highest percentage gain (50.73%) between 7 and 28 days;
- All treated samples showed increased shear strength after 28 days, confirming ongoing pozzolanic reactions [11,14];
- Treatment 5 (35% POFA) showed consistently lower performance than Treatment 3, indicating diminishing returns at higher POFA content; and
- The results confirm that 30% POFA delivers peak shear strength while extended curing further enhances performance.

POFA-based geopolymer significantly enhances soil cohesion, friction angle, and shear strength, with optimal results observed at 30% POFA for cohesion and shear strength and 27.5% to 30% POFA for friction angle. Longer curing times, particularly 28 days, further enhance the performance of the treated soils.

Comparing the shear strength parameters in Figures 3 and 4 reveals that cohesion contributes most of the increase in shear strength across all samples to curing time. The analysis of stabilized soils incorporating POFA-based geopolymer reveals a notable enhancement in cohesion, alongside a slight increase in the angle of internal friction, as influenced by the duration of curing. These results highlight the importance of curing time and the appropriate POFA content to ensure optimal performance and strength gains in soil stabilization using POFA-based geopolymer.

3.4 Unconfined Compressive Strength

The unconfined compression test (UCT) provides valuable insights into how the addition of Palm Oil Fuel Ash (POFA)-based geopolymer affects compressive strength of soil. The unconfined compressive strength (UCS) was a measurement of the soil's ability to withstand axial stress without lateral support. ASTM D2116 was used to determine the values of UCS on the natural soil and treated samples with three (3) replications.

After 7 and 28 days of curing, the natural soil and treated samples underwent unconfined compression tests (UCT). The peak strength values (UCS) for each sample are summarized in Tables 6 and 7 and illustrated in Figure 8.

Table 6: UCS Test Results after 7 Days of Curing

Mixture	Samples			Average UCS (kPa)
	50 kPa	100 kPa	200 kPa	
Natural Soil	160.90	158.62	154.18	157.90
25% POFA	86.47	87.47	88.28	87.39
27.5% POFA	68.88	69.78	70.72	69.98
30% POFA	68.62	69.19	70.61	69.48
32.5% POFA	68.26	68.46	68.07	68.26
35% POFA	52.30	51.60	52.30	52.06

Table 7: UCS Test Results after 28 Days of Curing

Mixture	Samples			Average UCS (kPa)
	50 kPa	100 kPa	200 kPa	
Natural Soil	230.01	264.54	235.67	243.42
25% POFA	104.50	104.89	104.72	104.70
27.5% POFA	105.16	117.50	120.49	114.49
30% POFA	87.96	86.61	87.91	87.50
32.5% POFA	67.91	67.93	69.59	68.47
35% POFA	86.65	88.19	88.25	87.70

Figure 8: UCS of Natural Soil and Treated Samples after 7 and 28 Days of Curing

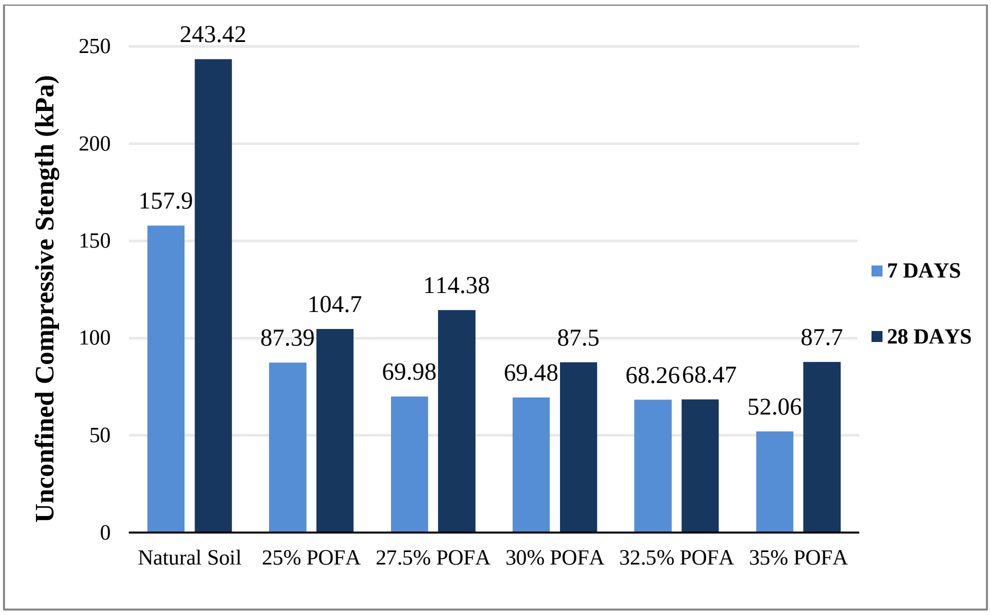


Figure 8 compares the unconfined compressive strength of natural soil and treated sample to the 7 days and 28 days of curing time. The key observations were the following:

- At 7 days of curing, the natural soil had a UCS of 157.9 kPa, while all POFA-treated samples showed lower values, with Treatment 5 (35% POFA) the lowest at 52.06 kPa;
- After 28 days, the UCS of natural soil increased to 243.2 kPa, marking a 54.02% strength gain, likely due to thixotropy, a reversible property common in clayey and silty soils [13];
- All treated samples also gained strength over time. Treatment 2 exhibited the highest UCS among them at 114.48 kPa, showing a 63.45% increase from its 7-day value; and
- Treatment 4 showed the lowest UCS gain, increasing to only 68.47 kPa at 28 days, with a minimal 0.31% improvement.

Whereas the natural soil has the highest UCS among all treatments, the fluctuation in UCS values at 28 days of curing illustrates the complex interplay between POFA-based geopolymer content and soil properties. This implies that at different percentages of POFA, different strength developments occurred over time.

3.5 California Bearing Ratio

California Bearing Ratio (CBR) provide an assessment of the strength of soil's load bearing capacity. To replicate the most critical situation of flooding or intense rainfall affecting the subgrade material post-pavement construction, soaking CBR tests were conducted on all soil samples in accordance with ASTM D1883. All CBR specimens were submerged for 4 days and then drained before to testing. The CBR values of the samples were determined by representing 0.1 in. and 0.2 in. penetrations as a ratio of the standardized force from a reference material (well-graded crushed stones).

With the corresponding penetration, a dial reading was observed to calculate the value of loads. Pressure load was then calculated based on the corresponding axial load divided by the area of the CBR plunger with a diameter of 50 mm; it was then converted into psi (pound per square inch). After which, the pressure load corresponding to 2.54 mm (0.1 inches) and 5.08 mm (0.2 inches) penetrations was then used to calculate the CBR values by dividing it with the standard pressure load of 1000 psi (0.1 inches) and 1500 psi (0.2 inches) expressed in percentage. The CBR value was taken as the higher of the two penetrations.

Figure 9: Summary of CBR values for Natural Soil and Treated Samples

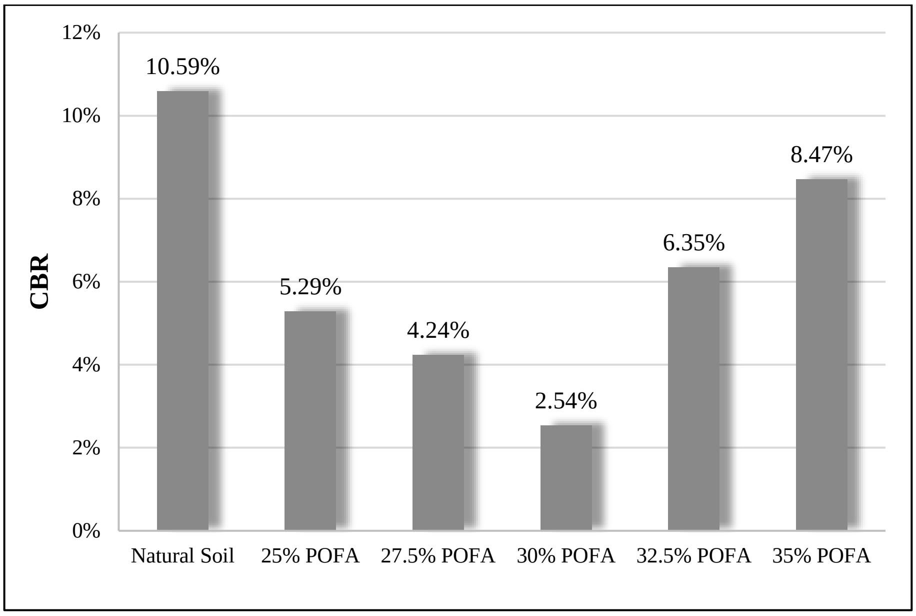


Figure 9 shows the summary of CBR values for both the natural soil and treated samples. The key observations were the following:

- The natural soil exhibited the highest CBR value at 10.59%;
- The addition of POFA-based geopolymer reduced CBR; at 25%, CBR drops significantly at 5.29%;
- CBR Value continues to decrease to 4.24% (27.5% POFA) and reaches the lowest at 2.54% (30% POFA); and
- An increased CBR beyond 30% POFA was observed, specifically at 32.5% POFA with 6.35% and 35% POFA with 8.47%, suggesting improved strength at higher POFA content.

The result shows a non-linear trend, with an initial decline followed by a recovery and improvement in CBR at higher POFA percentages. Although still lower than the natural soil, the 35% POFA mixture shows the highest improvement in CBR among all POFA-treated samples.

The reduced CBR values observed at lower POFA contents can be attributed to the soaking of samples during testing, which likely diluted the alkaline activator and contributed to the lower strength values, as supported by the findings of Khasib et al. (2023) [15], that geopolymerization tends to achieve more favorable strength under dry curing conditions. Higher temperatures during dry curing enhance water evaporation, facilitating better interaction between silicon and aluminum ions and increasing the mixture's pH. In contrast, wet or soaked conditions introduce excess water, which hinders effective contact between the dissolved ions and slows down, or even inhibits, the polycondensation process necessary for developing the geopolymer matrix.

3.6 TCLP (Toxicity Characteristic Leaching Procedure)

The toxicity and reactivity characteristics of the material were evaluated following the U.S. Environmental Protection Agency (USEPA) methodologies. The Toxicity Characteristic Leaching Procedure (TCLP) was performed to assess the potential leaching of hazardous metals and other substances. This test was specifically conducted on the sample from Treatment 5, which contained 35% POFA-based geopolymer, the highest percentage among all the treatments.

The results shown in Table 8 indicated that arsenic, chromium, silver, selenium, and cyanide were present in amounts below detection limits, specifically arsenic (< 0.01 mg/L), chromium (< 0.02 mg/L), silver (< 0.02 mg/L), and cyanide (< 0.025 mg/L), confirming their negligible concentrations (USEPA Method 6010B, 3113B; SMEWW 3120B; Ion Selective Electrode, SM 4500 CN-F). The detected concentrations of other heavy metals, including barium (0.03 mg/L), cadmium (0.0008 mg/L), lead (0.006 mg/L), and mercury (0.0013 mg/L), were all significantly below USEPA's regulatory limits under the TCLP, indicating the material's non-hazardous classification (USEPA, 1994). These findings suggest that when used for soil stabilization, the material presents a minimal risk of heavy metal leaching into groundwater, reinforcing its environmental safety.

In addition to toxicity testing, the material's reactivity was assessed using USEPA Method 3045C to determine its potential to generate toxic gases, such as hydrogen sulfide, or undergo explosive reactions when exposed to water or heat. As shown in Table 9, the results were all negative, indicating that the material does not react with water, does not liberate toxic gases, and does not produce an explosive reaction under high temperatures. This confirms that the material is non-reactive and safe for handling, storage, and disposal.

Table 8: Results on TCLP Test

Parameters	unit	Results as (TCLP)	Regulatory Level	Test Method
Arsenic	mg/L	Less than 0.01	5.0	Colorimetric Method (Modified)
Barium	mg/L	0.03	100.0	ICP-OES (SMEWW3120B/USEPA 6010B)
Selenium	mg/L	Less than 0.008	1.0	
Chromium	mg/L	Less than 0.02	5.0	Flame ASS
Silver	mg/L	Less than 0.02	5.0	
Cadmium	mg/L	0.0008	1.0	3113 B. Electrothermal Atomic Absorption Spectrometry Method
Lead	mg/L	0.006	5.0	
Mercury	mg/L	0.0013	0.2	Cold Vapor AAS
Cyanide	mg/L	Less than 0.025	0.2	Ion Selective Electrode (SM 4500 CN-F)

Flammability / Ignitability	mm/sec	Negative	-	USEPA 1030
Corrosivity (100% Solution w/v)	-	10.95@21.7°C	-	USEPA 9045C

Table 9: Results on Reactivity Test

Reaction with Water	**Generates toxic gases, vapors when mixed with Water**	**Hydrogen Sulfide (Liberation)**	**Explosive Reaction with Strong Heat**
Negative	Negative	Negative	Negative
Test Method	**USEPA Method 3045 C**		

These findings show that the substance is safe for use in soil stabilization and other applications due to its low toxicity and reactivity. The absence of harmful leaching and reactivity underlines its potential for environmentally safe engineering uses, aligning with the goals of sustainable waste utilization in construction materials.

4. Conclusion

Palm Oil Fuel Ash (POFA)-based geopolymer was evaluated as a feasible soil stabilizer in improving geotechnical properties of silty soil. Key parameters assessed included compaction properties (OMC and MDD), shear strength parameters (cohesion and angle of internal friction), unconfined compressive strength (UCS), California Bearing Ratio (CBR), and environmental safety through the Toxicity Characteristic Leaching Procedure (TCLP).

The natural soil exhibited moderate compaction properties (MDD: 15.71 kN/m^3, OMC: 17.51%) and relatively high UCS (243.42 kPa) but was brittle with low shear resistance (cohesion: 9.00 kPa; shear strength at 1 kPa normal stress: 9.66 kPa). Stabilization with POFA-based geopolymer altered the compaction behavior, with MDD generally decreasing and OMC fluctuating due to increased porosity and water retention.

Shear strength parameters significantly improved with POFA-based geopolymer additions, particularly between 25% and 30%. The 27.5% POFA-treated sample exhibited the highest cohesion (18.54 kPa) and improved internal friction angle (38.17°) after 28 days of curing. However, excessive POFA content (>30%) led to declines in strength, due to the dominance of POFA fine particles.

UCS results showed that although the natural soil had the highest strength, optimal POFA treatments (25%–27.5%) improved strength over time, particularly after 28 days of curing, highlighting the importance of pozzolanic reactions in strength development. Higher POFA content reduced UCS, indicating diminished bonding and increased structural imbalance.

CBR values decreased with increasing POFA, but moderate treatments (25%–27.5%) balanced bearing capacity and swelling behavior. Treatment 5 (35%) exhibited a recovery in CBR (8.47%) but showed that excessive POFA may only marginally restore strength while controlling swelling.

Failure modes shifted from brittle (natural soil) to more ductile (treated samples) with optimal POFA content and curing, enhancing mechanical resilience. However, overly high POFA content weakened soil structure, underscoring the need for content optimization.

Environmental assessment through TCLP confirmed that the POFA-based geopolymer is safe for soil stabilization application. All heavy metal concentrations were far below regulatory thresholds, and assessments for reactivity, flammability, and corrosivity indicated no adverse environmental impacts.

In conclusion, POFA-based geopolymer confirms its potential as a sustainable soil stabilizer. The optimal content of 27.5%–30% significantly improves mechanical properties and ductility while also ensuring environmental safety.

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