

Experimental investigation on the stabilization of clayey soil using waste palm fiber and tire ash for geotechnical applications

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Abstract

Soil qualities need to be improved to address numerous geotechnical engineering issues. Improvements are needed in areas where soil cannot support loads. Soil improvement is essential in areas where the existing ground cannot support structural loads, particularly in problematic soils characterized by high water content, high compressibility, and low shear strength. This study evaluates the geotechnical performance of clayey soil stabilized with waste palm fiber (PF) and tire ash (TA). Soil samples made from clayey soil were used for these studies; four percentages (0.2, 0.4, 0.6, and 0.8%) of palm fiber and three percentages (1, 3, and 5%) of tire ash were employed. The test findings show that increasing the content of palm fiber in clayey soil increases the plastic limit value while decreasing the liquid limit and plasticity index values. Additionally, the liquid limit and clay plasticity index decrease when tire ash is added to mixed soil with the optimum percentage of palm fiber (0.8%). As the amount of palm fiber increases, the optimum moisture content increased while the maximum dry density decreased. By adding more tire ash, the maximum dry density rises. The optimum moisture content of clayey soil continues to decline as the amount of tire ash increases. The treated clay's unconfined compression strength gradually improved as the amount of palm fiber increased, the UCS increased from 60 kPa for untreated clay to 83 kPa representing an increase of 38.33%. Additionally, compared to untreated specimens, the addition of tire ash and the optimum dosage of palm fiber resulted in an extra improvement strength; with 0.8% palm fiber and 5% tire ash, the UCS reached 170 kPa, corresponding to a 183.33% increase relative to untreated soil.

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1. Introduction

Besides the foundation materials for projects, the soil properties are also significant in terms of construction material for many other projects. In order to solve many technical problems, soil improvement is necessary in areas where the existing soil cannot support imposed loads. For example, airfield runways and subgrade soil in highways need such improvements [1]. As the fine clay particles retain water and settle down more tightly than sand or loam. Clayey soils tend to retain water for extended periods due to their fine particle size. Incorporating granular materials, such as sand, can help achieve a balanced gradation and overcome these limitations.

Previous studies have investigated the variations in the hydrological properties of clayey soil with different proportions of sand particles. This process involving mixing of certain material with soil or blending of certain soils to enhance certain properties is referred to as stabilization [3]. According to [4], one of the most common techniques of fine soil improvement is stabilization through the addition of certain additives which modify the soil properties both physically and chemically. However, it is important to mention that the behavior of fine soils needs to be well understood prior

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to determining the soil improvement technique. The primary objectives of soil stabilization are to increase mechanical strength and bearing capacity, prevent structural subsidence, and reduce the plasticity index and adhesion of highly plastic soils.

Several studies have investigated the use of industrial and agricultural waste materials to improve the engineering properties of clayey soils. Singh and K.S.Gill found that the application of geogrid led to an enhancement in properties of the clayey foundation soil, where CBR increased from 2.9% to 9.4% at grid at 0.2 H depth [5]. Fattah et al. found that enhancement of three Iraqi clayey soils with the help of rice husk ash (RHA) caused a decrease in the liquid limit (11-18%) and plasticity modulus (32-80%) at 9% RHA, along with a reduction in the maximum dry weight and increase in the optimum moisture content. An increase in the unconfined compressive strength was also observed with 6-8% RHA contents [6]. Similarly, Kadhim et al. have proved that the addition of sludge ash (SSA) in percentages 10%, 15% and 20% to weak clayey soil leads to increase in unconfined compressive strength with curing times (3, 14, and 28 days). However, there was decrease in initial bearing capacity due to time curing; the best CBR ratio was 10% SSA. Other waste-based stabilizers have also demonstrated potential for improving clayey soils [7].

Cement was more effective in comparison with lime; stress-strain curves increased with fiber content increase. Strength enhancement of Kaolinite clayey soil through the addition of different percentages and mixes of Silica Fume and Cockle Shell Ash was studied by [8]. While Zaini et al. conducted a study on strengthening problematic soils by using Palm Oil Fuel Ash (POFA) combined with lime as a catalyst. They carried out various tests, including Atterberg limits, particle size distribution, compaction, and unconfined compression tests. The study involved adding 4%, 8%, and 12% POFA along with 6% hydrated lime to stabilize kaolinitic clayey soil over different curing periods (1, 7, 14, and 30 days). Compared to untreated kaolin, the mixture of POFA and lime resulted in an increase in undrained shear strength. The highest undrained shear strength value recorded was 32.68 kN/m² on the 30th day of curing, achieved when the kaolin was optimally stabilized with 6% lime and 12% POFA. The obtained UCS of 65.36 kN/m² was 185.04% higher than that of the untreated kaolinitic clayey soil [9].

Hasan and Shafiqu proved that the application of high-density polyethylene (HDPE) (6%, 9%, 12%) as non-traditional stabilizers leads to enhancement of physical characteristics of expansive clayey soils and decrease their swelling capacity [10]. In addition to particulate waste materials, fiber reinforcement has been investigated as a means of improving the mechanical behavior of soils. Shen et al. performed experimental investigations on clayey soil with reinforcement using polyester fibers and adding 5% of lime or cement. The findings indicated substantial improvements in soil strength in accordance with fiber content increase [11]. Sarkar et al. used waste plastic to support the clayey soil. Waste plastic and bottle strips are used as soil reinforcement to improve the engineering properties of subgrade soil. Waste plastic strips were manufactured for incorporation in two different proportions (1% and 2%) after being chopped in two distinct aspect ratios (5 mm x 5 mm and 5 mm x 10 mm). Unconfined Compressive Strength test was performed. The results show that the soil's shear strength increased when small bottle strips were combined in the bottle strip case [12]. Snodi et al. investigated the use of palm fibers to improve the collapsibility and shear strength of gypseous soil. Palm fibers were added at contents of 0.1%, 0.3%, and 0.5% by dry soil weight. The results showed that increasing the palm fiber content reduced the collapse potential and improved the shear strength parameters of the soil. At 0.5% palm fiber, the collapse potential decreased by about 40%, while cohesion and the internal friction angle increased by 52.78% and 18.57%, respectively. The study demonstrated that small amounts of natural palm fibers can effectively improve the engineering behavior of gypseous soil [13]. Qu and Zhu investigated the use of palm fibers as a sustainable material for improving clayey soil. The results showed that palm fiber reinforcement increased the soil's unconfined compressive strength, ductility, and energy absorption capacity, with the best performance obtained at 0.4% fiber content and 15 mm fiber length. However, the secant modulus decreased as the fiber content and length increased. The addition of palm fibers also changed the failure behavior from brittle to more ductile. Overall, palm fiber was found to be an environmentally friendly, economical, and effective material for soil stabilization in geotechnical applications [14].

While various additives have been explored, the synergistic effect of combining palm fibre (PF) and tyre ash (TA) remains under-researched. Therefore, this study aims to evaluate the mixing impact of these waste materials on the geotechnical performance of clayey soils.

2. Materials

2.1. Soil Properties

The clayey soil used in this study was collected from the Al-Taji site (East of Baghdad). The soil was first stored outdoors until it dried out, then stored inside an oven for 24 h to ensure complete drying at a temperature of 100–110 °C. The laboratory tests were performed on the soil to measure the physical and chemical characteristics of the soil. The main characteristics and classification of the soil are listed in Table 1. The grain size distribution of the soil was 2.8% sand, 40% silt and 57.2% clay. Based on USCS, the soil is classified as CL. ASTM D422-63 [15] was used for determination of the grain size distribution of the clayey soil.

Table 1. Characteristics of the soil used

Properties of soil	Values	Units
Specific gravity, G _s	2.68	-
Gravel	0	%
Sand	2.8	%
Silt	40	%
Clay	57.2	%
Classification by USCS		CL
Liquid Limit, LL	39	%
Plastic Limit, PL	20.5	%
Plasticity Index, PI	18.5	%
Maximum dry density, MDD	16.4	(kN/m ³)
Optimum moisture content, OMC	19.5	%
SO ₃ content	0.015	%
Total soluble salts (TSS)	1.012	%
pH value	7.91	-

2.2. Palm Fiber

There are more than 140 million palm trees in the Middle East and North Africa. Some of the countries which lead in the production include Egypt, Iran, Saudi Arabia, United Arab Emirates, Pakistan, and Sudan.



Fig. 1. Palm Fiber used in this study

The production of this palm fiber used in agriculture leads to generation of over 48.8 million tons of waste every year. As such, the production of this palm fiber has become an achievement to note. Such countries utilize sustainable textile fibers derived from different palm fiber wastes like fruit twigs, branches, leaves, and flyers. In this case study, the palm fiber (PF) had a diameter 0.2 cm and a length of 2cm, corresponding to an aspect ratio (L/d) of 10 obtained from the palm trees around Tikrit City, Fig. 1. The physical parameters of the fibers are high strength and have a high natural capacity for water absorption, often holding up to several times their dry weight due to their porous structure and hydrophilic nature.

2.3. Tire Ash

Waste tire materials can be made from waste tires that are generated on a daily basis. Tire ash was produced through the process of incineration of those tires that were discarded or used before. Incineration of such waste tires was carried out under normal atmospheric pressure and temperature conditions (burning air) at a combustion temperature of 600 °C for 2–3 hours to obtain the ash. After combustion, the resulting tire ash was allowed to cool and sieved through sieve No.200. The rubber ash was kept in sealed containers right after sieving in order to prevent pre-hydrating.

3. Experimental Program

3.1. Sample Preparation

Sample preparation is one of the most significant processes in every experimental research work. After oven drying, the clay was reduced to a powdered form and then sieved using a sieve having pore size of 4.75 mm. In addition, clay and PF were mixed and homogenized for five minutes. In order to obtain an optimal percentage of PF to be used in the stabilization process, the percentage of Palm fibers used in the mixing process included (0.2%, 0.4%, 0.6%, and 0.8 %) with respect to the dry weight of the clay. The soil samples were separated into four equal portions whereby each part of the soil samples was mixed thoroughly with different percentage of PF. After identifying 0.8% PF as the optimum content, tire ash (1%, 3%, and 5% by dry weight) was blended into the optimum PF-clay mixture. Finally, they were compacted based on "standard proctor test " at optimum moisture content and maximum dry density.

3.2. Testing Procedures

A series of laboratory tests was conducted to evaluate the effects of palm fiber (PF) and tire ash (TA) on the geotechnical properties of the clayey soil. The testing program included the determination of the Atterberg limits, standard Proctor compaction characteristics, and unconfined compressive strength (UCS). The liquid limit and plastic limit were determined in accordance with ASTM D4318 [16], while the standard Proctor compaction test was performed according to ASTM D698 [17]. The unconfined compressive strength (UCS) test was conducted in accordance with ASTM D2166/D2166M [18]. Cylindrical soil specimens were prepared with a diameter of 38 mm and a height of 76 mm, giving a height-to-diameter ratio of 2:1. The specimens were compacted at the corresponding maximum dry density (MDD) and optimum moisture content (OMC). During the UCS test, an axial strain rate of 1% per minute was applied continuously until the specimen reached its peak stress. The maximum axial stress recorded during the test was taken as the unconfined compressive strength (UCS) of the specimen. The experiment flowchart for the study shown in Fig. 2.

4. Results and Discussion

Based on the experimental work done with PF, 0.8% was the optimum value of PF percentage. After that, experimentations were carried out with the optimum percentage of PF and different percentages of TA as follows.

4.1. Atterberg Limit Test

The effect of PF on the Atterberg limits of the soil was evaluated using the measurement of the Atterberg limits for PF-clayey soil. The Atterberg limits provide an indication of the presence of clay particles within the soil. The higher values of P.I and L.L indicate that the soil is more likely to expand

and contract due to changes in the moisture content of the soil. The Atterberg limits are shown in Table 2 and Fig. 3.

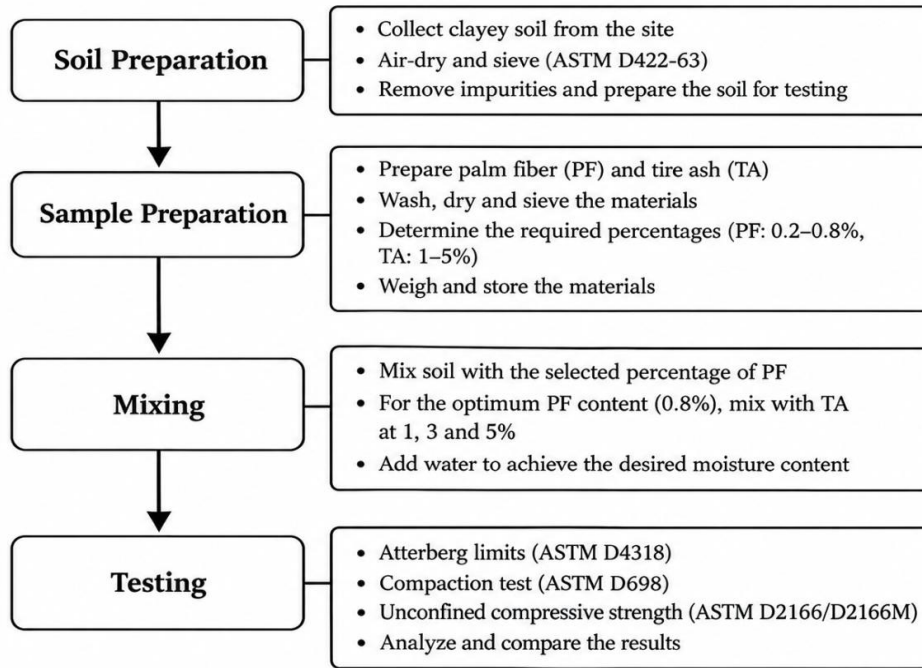


Fig. 2. Flowchart for the study

Table 2. Influence of PF on Atterberg limit

PF (%)	L.L (%)	P.L (%)	P.I (%)
0	39.0	20.5	18.5
0.2	37.9	24.4	13.5
0.4	36.3	25.1	11.2
0.6	33.8	25.2	8.6
0.8	32.4	26.0	6.4

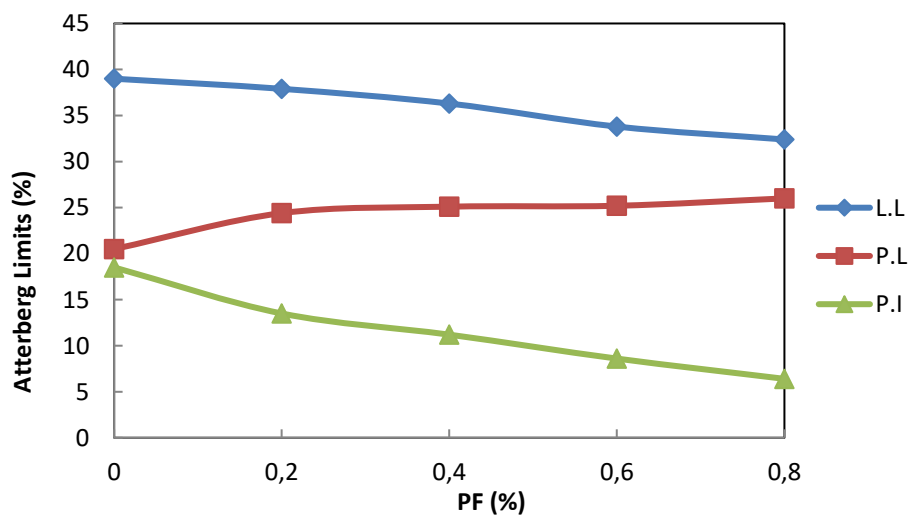


Fig. 3. Variation of atterberg limits with different percentage of PF

Based on the significant decrease in PI, 0.8% was the optimum value of PF percentage used. The above behaviors have also been noted in Ref. [19]. Results of Liquid Limit and Plastic Index test for clay with addition of PF and TA are listed in Table 3, where with increase in percentage of additive

used, there is decrease in liquid limit and plastic index of clay. From the above results, it can be inferred that the plasticity of the soil sample is decreasing with increase in the percentage of PF and TA.

Table 3. Influence of TA on Atterberg Limits of Clayey Soil Treated with Optimum of PF

% TA with optimum Palm Fiber	L.L. (%)	P.L. (%)	P.I.(%)
0.8 % PF+ 1% TA	32.1	25.8	6.3
0.8 % PF+ 3% TA	30.7	24.7	6.0
0.8 % PF+ 5% TA	29.8	24.3	5.5

4.2. Standard Proctor Test

Effect of PF on MDD and OMC is calculated from the compaction test of PF-clayey soil. Results for MDD and OMC of soil samples mixed with PF are given in Table 4 below and presented in Fig. 4.

Table 4. Influence of PF on (MDD) and (OMC)

PF (%)	MDD (kN/m ³)	OMC (%)
0	16.4	19.5
0.2	16.0	22.7
0.4	15.6	23.9
0.6	15.3	25.7
0.8	15.2	27.6

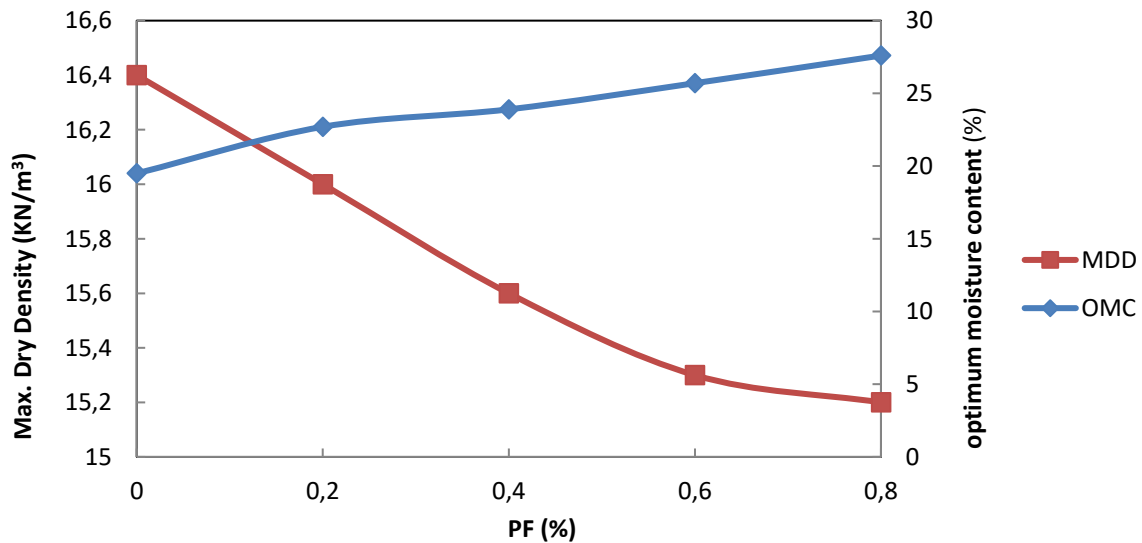


Fig. 4. Variation of MDD and OMC with different percentage of PF

From the result, the increment in OMC and decrement in the amount of MDD with an increasing proportion of PF addition can be seen. Similar trend has been observed in another study [20] in various materials mixture and stabilized soils. The increase in OMC with increasing palm fiber (PF) content can be attributed primarily to the relatively high-water absorption and water-retention capacity of the fibers. Palm fibers are coarse, porous organic fibers rather than fine-grained particles. Their lignocellulosic structure contains hydrophilic functional groups that facilitate water absorption and retention within the fiber structure. Consequently, an increasing amount of mixing water is required to wet and partially saturate the fibers, in addition to the water needed for lubrication and rearrangement of the soil particles during compaction. The reduction in MDD of soil sample is because of partial substitution of heavier soils with lightweight PF.

As can be seen from Table 5, the MDD value increases with an increase in the percentage of TA. The observed increase may be associated with the combined effect of particle rearrangement and improved packing of the soil–PF matrix. The fine TA particles may have occupied some of the void spaces between the soil and palm-fiber particles, resulting in a denser packing structure under compaction. While with the increase in the percentage of TA, the OMC of the soil continuously decreases. This is due to the decrease in the percentage of clay in the soil due to the substitution by TA. The addition of TA replaces a portion of the highly water-demanding clay fraction with relatively coarser and less water-absorbing particles. Consequently, the specific surface area and the amount of water required to coat the soil particles and facilitate lubrication during compaction are reduced. In addition, the fine TA particles can modify the soil fabric by promoting particle rearrangement and reducing the volume of micropores that retain water. Therefore, less water is required to achieve the maximum compacted state as the TA content increases.

Table 5. Influence of TA on (MDD) and (OMC) of clayey soil treated with optimum of PF

% TA with optimum Palm Fiber	MDD (kN/m ³)	OMC (%)
0.8 % PF+ 1% TA	16.8	28
0.8 % PF+ 3% TA	17.3	20
0.8 % PF+ 5% TA	18.0	19

4.3. Unconfined Compressive Strength Test

Cylindrical compacted samples with maximum dry unit weight (MDD) and optimal moisture content (OMC) were subjected to unconfined compression tests. Fig. 5 shows the test setup for the UCS test.

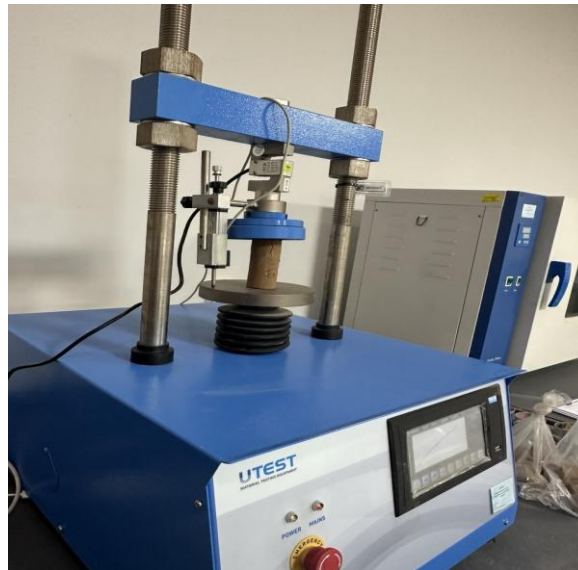


Fig. 5. Test setup for unconfined compressive strength

Table 6 provides specific results from these tests. As shown in Fig. 6 and mentioned by reference, it is clear that the unconfined compressive strength increases as the amount of palm fiber increases [21].

Table 6. Influence of PF on unconfined compression strength

PF %	Unconfined Compression Strength(kPa)
0	60
0.2	62
0.4	70
0.6	80
0.8	83

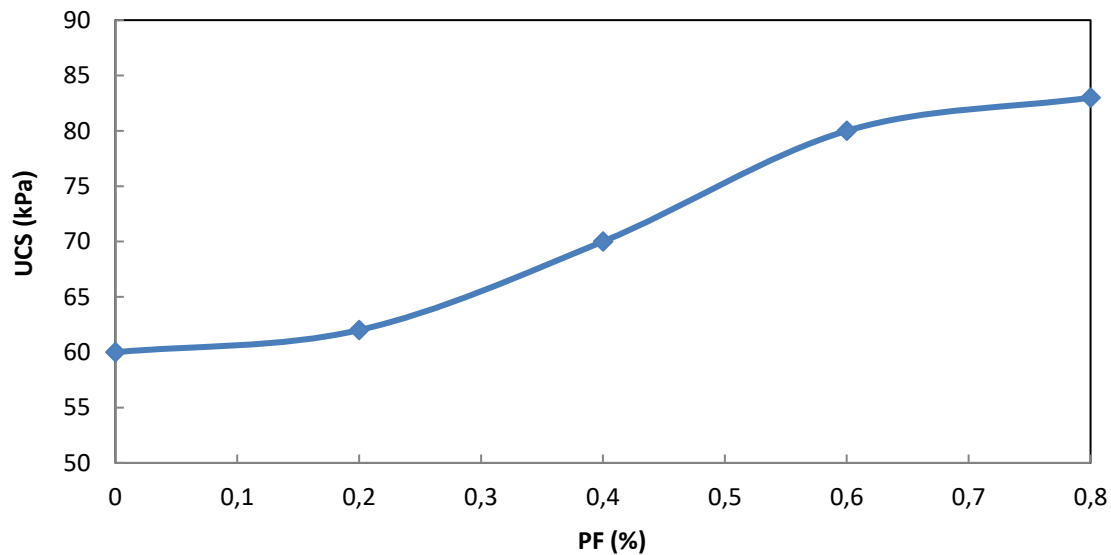


Fig. 6. The relationship between different percentage of PF and unconfined compressive strength values

It can be seen from Table 7 that the addition of Tire ash increased the UCS of the soil samples for the optimum Palm Fiber percentage. These behaviors were also observed by researchers for different materials lime, volcanic ash, rice husk ash, sugarcane straw ash, scrap tire rubber and synthetic fibers [22].

The pronounced improvement in UCS obtained with the hybrid palm fiber–tire ash (PF+TA) treatment can be attributed to the complementary mechanisms produced by the two additives. Tire ash primarily modifies the soil matrix through particle rearrangement, void filling, and improvement of interparticle contact. Depending on its chemical composition, reactive mineral phases in the ash may also contribute to physicochemical bonding between the soil constituents. Such effects can produce a denser and more resistant soil matrix. In contrast, palm fibers provide a discrete reinforcement mechanism. The fibers are randomly distributed within the soil and interact with the surrounding particles through friction and mechanical interlocking. Under axial loading, the fibers bridge developing cracks and potential shear surfaces, transfer tensile stresses, and restrict relative displacement of soil particles. Previous investigations of palm-fiber-reinforced clay have demonstrated that these mechanisms can increase UCS and change the failure behavior from relatively brittle to more ductile [23].

Table 7. Influence of TA on (UCS) strength of clayey soil treated with optimum of PF

% TA with optimum Palm Fiber	Unconfined Compression Strength(kPa)
0.8 % PF+ 1% TA	120
0.8 % PF+ 3% TA	142
0.8 % PF+ 5% TA	170

5. Conclusions

The main conclusions of the present study could be summarized as follows:

- The addition of PF to the clayey soil reduced the liquid limit (LL) and plasticity index (PI) while raising the plastic limit (PL). Moreover, the addition of TA to the 0.8% PF mixture results further suppressed soil plasticity, reducing the PI to 5.5%. This demonstrates that hybrid PF–TA treatment successfully converts highly swell-prone clay into a more stable, workably inert soil matrix.
- The Optimum Moisture Content (OMC) increased progressively with increasing palm fiber (PF) content, rising from 19.5% for the untreated clayey soil to 27.6% at the highest PF

content. In contrast, the Maximum Dry Density (MDD) showed a decreasing trend with increasing PF content. This behavior can be attributed to the relatively low density, low specific gravity and high-water absorption capacity of the palm fibers. Conversely, adding TA counteracted this effect by increasing MDD and reducing OMC, indicating enhanced structural packing and reduced water demand for field compaction.

- While the unconfined compressive strength (UCS) increases with an increase in the palm fiber content alone from 60 kPa to 83 kPa (a 38.33% increase), the hybrid blend of 0.8% PF and 5% TA achieved a peak UCS of 170 kPa—representing a 183.33% strength enhancement relative to untreated clay. This synergism combines discrete fiber tension-bridging with ash-induced matrix densification. The addition of tire ash increases the UCS of the soil samples at the optimum Palm Fiber percentage.
- The proposed hybrid stabilization method (PF+TA) offers compelling practical advantages for geotechnical field applications, particularly regarding environmental sustainability and cost-efficiency. Utilizing waste palm fibers and tire ash directly mitigates environmental landfill burdens by recycling abundant agricultural and industrial byproducts into high-value construction materials. Economically, replacing traditional, carbon-heavy chemical stabilizers (such as cement or lime) with these readily available waste materials substantially lowers subgrade preparation and soil stabilization costs for infrastructure projects.
- Practical Engineering & Environmental Implications The proposed hybrid stabilization technique offers a viable, eco-friendly alternative to traditional cementitious binders (e.g., lime or cement) for pavement subgrades and foundation beds. Recycling regional agricultural waste (palm fibers) and industrial waste (tire ash) reduces landfill burdens while lowering material costs in subgrade preparation. The resulting soil matrix exhibits improved bearing capacity and reduced moisture susceptibility, making it highly suitable for sustainable geotechnical infrastructure projects.
- Future research should evaluate long-term durability under diverse environmental conditions. Additionally, microstructural and mineralogical investigations using advanced techniques, such as XRD and SEM, are recommended to better understand the reaction mechanisms. Investigating the impact of PF and TA on other geotechnical properties, such as consolidation and hydraulic conductivity, is also suggested.

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