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Exploring the Feasibility of Using Recycled PET Strips with Palm Leaf Ash for Sustainable Soil Stabilization

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Abstract: This research paper addresses the urgent environmental concern of waste management by focusing on sustainable consumption by utilizing waste plastic and palm leaves to stabilize soil in geotechnical engineering. The study examines the impact of incorporating recycled polyethylene terephthalate (PET) strips and palm leaf ash (PLA) into clayey sand to enhance its engineering properties. The investigation involved mixing varying proportions of recycled PET strips (10 mm, 20 mm, and 30 mm in length) with clayey sand, ranging from 0% to 2% by weight of the soil with a 0.5% increment for PET strips. Similarly, PLA was mixed with the clayey sand at proportions ranging from 0% to 12% by weight of the soil with a 3% increment. The strength parameters of lateritic soil were analyzed through the execution of unconfined compressive strength (UCS), triaxial, and California bearing ratio (CBR) tests. The optimum mixture was determined to be 2% recycled PET strips with a length of 30 mm and 12% PLA by weight of the soil. This specific combination exhibited significantly improved strength parameters for the lateritic soil, highlighting its potential for sustainable soil stabilization in geotechnical applications.

Keywords: recycled polyethylene terephthalate (PET) strips; palm leaf ash (PLA); soil stabilization; particle size; mechanical properties; sustainability

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1. Introduction

Modern engineering techniques place a strong emphasis on sustainability, highlighting the necessity for environmentally sound solutions that reduce resource use and waste production [1]. There are now major environmental concerns across the globe as a result of the tremendous industrialization and urbanization of recent years [2–5].

Wei and Zimmermann [6] estimated that one million plastic bottles are purchased globally every minute and that this figure may increase by 20% by 2021, potentially causing an environmental issue. The manufacture of plastic has increased from 15 million tons in the 1960s to 311 million tons in 2014 and is predicted to triple by 2050. Because of its prevalence and harmful effects on the environment, polypropylene waste is one such waste item that has drawn attention. Because it is non-biodegradable, it is difficult to dispose of, which results in landfills and ecosystem degradation [7–9]. In addition, Weiland, et al. [10] encouraged the use of local resources in engineering projects and included a major reduction in waste generation as one of their targets. Researchers and engineers, however, are looking at methods to use waste materials in geotechnical and building applications for sustainable soil stabilization. Recycled polyethylene terephthalate (PET) is also one such waste product that has the potential to stabilize soil [11,12].

In this context, recycled PET is used to create three-dimensional grid-like structures. To increase the stability and strength of the soil, these geogrids are mixed into the soil. The soil particles are efficiently contained by the PET interlocking structure, which also restricts their lateral mobility and prevents erosion. This confinement lessens the possibility of soil settlement and subsidence while simultaneously improving load distribution and load-bearing capacity in a sustainable way [13]. Conversely, the synergistic impact of incorporating recycled PET alongside complementary binding agents such as lime, ash, and cement serves to enhance soil strength through the improvement of interlocking mechanisms among soil particles. This, in turn, contributes to the increase in both cohesive properties and the angle of friction within the soil [14–17].

According to Koohmishi and Palassi [18], the effects of utilizing PET and adding lime support the idea that the stabilizing effects of lime on the strength of soil are more significant. The maximal strength of reinforced clayey soil is demonstrated by the small amount of 1.5% PET. Regarding the combined influence of PET fibers and fly ash, the ratios span from 0% to 1.6% of the soil's weight for PET fibers, incrementing in 0.4% intervals. Similarly, for fly ash, the ratios range from 0% to 20% of the soil's weight, increasing in 5% increments. [19]. A similar study conducted by Dandin and Kulkarni [15] analyzed the synergistic impact of fly ash and PET waste on subgrade soil, revealing a substantial 10% enhancement in the California bearing ratio (CBR) value. Sengul, et al. [20] investigated the performance of PET fibers with fly ash when introduced to clayey soil. The study revealed a significant increase in soil strength, ranging from 3 to 21%, through the collaborative influence of these materials. These combinations play a pivotal role in enhancing the soil's mechanical characteristics. The study conducted by UNIYAL [21] demonstrates an enhancement in load bearing capacity of soil through the incorporation of recycled PET strips with crushed pieces of plastic. As indicated in Silveira, et al. [22] study, incorporating cement along with PET strips into lateritic soil results in an enhancement of the soil's strength and durability. Kumar and Mishra [23] research shows that PET strips, when treated with sodium hydroxide and utilized at an optimal mixture of 1.5%, lead to a notable enhancement in both the CBR and unconfined compressive strength (UCS) values. While the utilization of recycled PET contributes to enhanced soil stability when integrated with other substances, it is worth noting that there exists a research gap concerning the combined impact of recycled PET and leaf ash on soil stabilization. This study fills the gap by conducting UCS, triaxial, and CBR tests to evaluate the mechanical characteristics of the amended soil mixture with recycled PET strips and palm leaf ash (PLA).

2. Materials and Methods

The following section provides a comprehensive explanation of the materials employed and the testing methodologies outlined in this study.

2.1. Materials' Properties

The soil that was used in this study was obtained in Multan, Pakistan. The soil was crushed into a fine powder and sieved using a 4.75 mm sieve. To the soil, a certain quantity of recycled PET strips strengthened with PLA were added to improve the soil's geotechnical properties.

2.1.1. Soil

Clayey sand, sourced from the Multan region in Pakistan, was obtained for analysis. The soil's physical properties were assessed following American Society for Testing and Materials (ASTM) guidelines as shown in Table 1, and the classification of the soil type was performed using the Unified Soil Classification System (USCS) and the American Association of State Highway and Transportation Officials (AASHTO) guidelines. The particle size distribution curve of soil is shown in Figure 1.

2.1.2. Recycled PET Strips

The recycled PET bottles were gathered from material recycling facilities and thoroughly cleaned with water to remove any contaminants. The bottle's neck and base were cut off and the uneven and unevenly shaped parts were removed. From two separate water bottle brands that are commonly available in the local market, Nestle and Dasani, recycled PET bottle strips were made into 10 mm, 20 mm, and 30 mm lengths. Nestle and

Dasani bottle brands had average thicknesses of 0.18 mm and 0.16 mm, respectively. Only a fraction of the recycled PET bottle can be fully utilized into recycled PET bottle strips due to the limitations of the plastic bottle's form and structure. The physical properties of recycled PET strips are shown in Table 2.

Table 1. Properties of selected soil sample.

Properties	Value	Specifications
Soil Classification (AASHTO)	A-2-6 (0)	ASTM D3282 [24]
Soil Classification (USCS)	SC	ASTM D2487 [25]
Percent fines (%)	15	ASTM D7928 [26]
Percent Sand (%)	85	ASTM D7928 [26]
Maximum dry unit weight (kN/m^3)	19.8	ASTM D698 [27]
Specific gravity, GS	2.64	ASTM D854 [28]
Liquid limit	18	ASTM D4318 [29]
Plastic limit	NP	ASTM D4318 [29]
Plasticity index	NP	ASTM D4318 [29]
Optimum moisture content (%)	11	ASTM D698 [27]

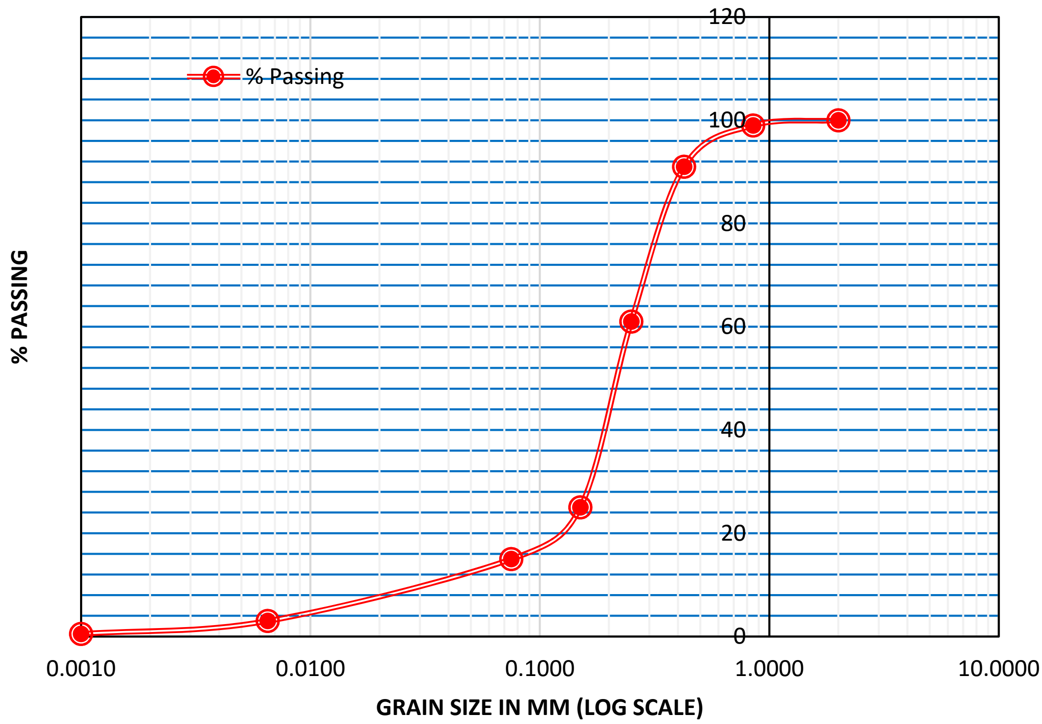


Figure 1. Particle size distribution curve for soil sample.

Table 2. Physical properties of recycled PET strips.

Parameters	Value Range (Unit)
Melting temperature	250–270 (°C)
Intrinsic viscosity	0.7–0.85 (dL/g)
Glass transition temperature	65–135 (°C)
Tensile strength	57.5–73.2 (MPa)
Tensile modulus	2.5–4.2 (GPa)
Flexural strength	96–125 (MPa)
Flexural modulus	2.3–3.2 (GPa)
Impact strength	13.2–34.7 (J/m)

2.1.3. Palm Leaves Ash

Dried palm leaves were collected and burned within a temperature range of 100–150 °C to create ash. This process preserves the essential nutrients present in the leaves, converting them into ash. The chemical composition of selected PLA is shown in Table 3. Silica (SiO_2) is a significant component of PLA, often ranging from 50% to 80% [30]. By improving the capacity of soils to bond, silica is known to help them become more cohesive and stable. In sand, abrasive soils that lack cohesiveness, this property is crucial. The pH range of PLA, which is between 9 and 11, also points to a sizable alkaline character [31]. The presence of calcium oxide (CaO) and potassium oxide (K_2O) in the ash is thought to be the cause of this alkalinity. By neutralizing soil acidity, the alkaline properties of PLA can aid in promoting soil stability and reducing the negative impacts of acidic conditions on soil. PLA also contains several macro- and micronutrients, including phosphorus (P), calcium (Ca), magnesium (Mg), and potassium (K), all of which are necessary for soil stabilization. When PLA is added to the soil, these nutrients can be released, increasing the soil's overall strength. Additionally, PLA's microscopic particle size distribution makes it easier for it to link with soil particles effectively, which enhances soil aggregation and stability. By filling up the spaces between the soil particles, the ash particles can increase compaction and reduce soil porosity [32]. The gradation curve of PLA is shown in Figure 2.

Table 3. Chemical composition of PLA.

Parameters	Percentage (%)
SiO_2	71.16
Al_2O_3	1.37
Fe_2O_3	1.14
MgO	2.91
CaO	9.21
Na_2O	1.73
K_2O	3.04
SO_3	0.08
P_2O_5	1.49
MnO	0.04
TiO_2	0.96
LOI	3.28
Others	3.59

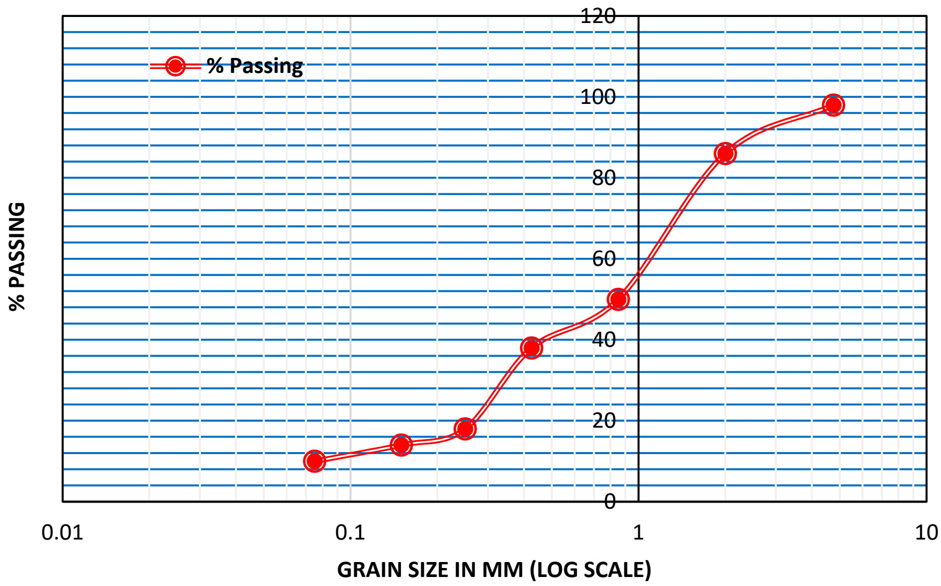


Figure 2. Particle size distribution curve for PLA.

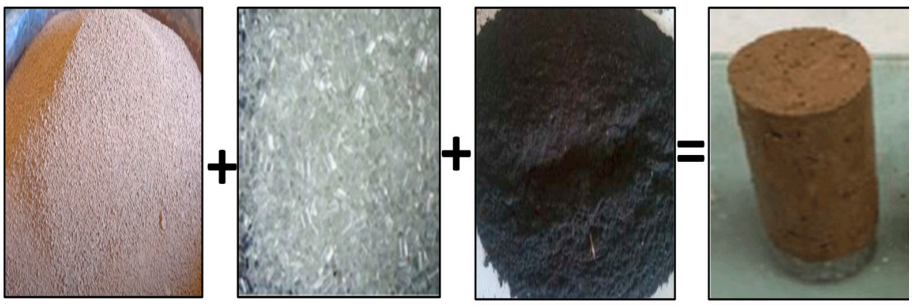
2.2. Preparation of Samples

In a lab, the mixture of dry clayey sand and recycled PET strips was created in accordance with the specifications, together with PLA, as shown in Table 4. After that, the prepared combinations were put into plastic bags for later use. Water was applied in the desired amounts to the mixes that have been further blended at the optimum moisture content to create a homogenous mixture. The study investigates the impact of recycled PET strips ranging from 0 to 2% and PLA ranging from 0 to 12% on the clayey sand. The analysis focuses on three parameters: UCS, shear strength parameters, and CBR to analyze soil improvement.

Table 4. Soil samples reinforced with different content of recycled PET and PLA.

SN	Weight-Based Ratios of Soil Combinations	Designation	Soil (%)	Recycled PET Strips (%)	Palm Leaves Ash (%)	Total (%)
Recycled PET strip length 10 mm						
1	Soil + recycled PET strips 0% + PLA 0%	SP1	100	0	0	100
2	Soil + recycled PET strips 0.5% + PLA 3%	SP2	96.5	0.5	3	100
3	Soil + recycled PET strips 1% + PLA 6%	SP3	93	1	6	100
4	Soil + recycled PET strips 1.5% + PLA 9%	SP4	89.5	1.5	9	100
5	Soil + recycled PET strips 2% + PLA 12%	SP5	86	2	12	100
Recycled PET strip length 20 mm						
7	Soil + recycled PET strips 0.5% + PLA 3%	SP6	96.5	0.5	3	100
8	Soil + recycled PET strips 1% + PLA 6%	SP7	93	1	6	100
9	Soil + recycled PET strips 1.5% + PLA 9%	SP8	89.5	1.5	9	100
10	Soil + recycled PET strips 2% + PLA 12%	SP9	86	2	12	100
Recycled PET strip length 30 mm						
12	Soil + recycled PET strips 0.5% + PLA 3%	SP10	96.5	0.5	3	100
13	Soil + recycled PET strips 1% + PLA 6%	SP11	93	1	6	100
14	Soil + recycled PET strips 1.5% + PLA 9%	SP12	89.5	1.5	9	100
15	Soil + recycled PET strips 2% + PLA 12%	SP13	86	2	12	100

The physical composition of the soil sample under consideration is depicted in Figure 3a. Figure 3b, in contrast, depicts the recycled PET strips sourced from plastic bottles. Figure 3c illustrates the physical composition of PLA, whereas Figure 3d depicts the soil reinforced with PET strips and PLA.



(**a**) (**b**) (**c**) (**d**)

Figure 3. Mixing of (**a**) clayey sand, (**b**) recycled PET, and (**c**) palm leaf ash to make (**d**) the soil-reinforced sample.

2.3. Tests Performance

2.3.1. Unconfined Compressive Strength

The study used the ASTM D2166 [33] guidelines to test UCS on lateritic soil samples mixed with recycled PET strips and PLA. Before the UCS tests, standard Proctor compaction tests were carried out to determine the optimum water content (OWC) using ASTM D698. Reinforced soil specimens, each measuring 50 mm in diameter and 100 mm in height, were tested to examine the variability in the UCS properties for both lateritic soils. The UCS tests were performed at different curing periods of 7, 14, and 28 days. Cylindrical specimens were prepared by compacting the soil–strip mixtures reinforced with palm leaf ash at their respective OWC levels. The specimens were then subjected to unconfined compression testing, where a vertical load was applied until failure occurred. The maximum load and corresponding deformation were recorded for each test. By assessing the UCS properties of the lateritic soils with waste strip additions over different curing periods, the study aimed to understand the potential engineering applications and the effects of recycled PET strips reinforced with PLA on soil strength characteristics. The apparatus of UCS is shown in Figure 4a.

(**a**) (**b**) (**c**)

Figure 4. Test apparatus for (**a**) UCS, (**b**) triaxial, and (**c**) CBR.

2.3.2. Triaxial Test

In this study, a series of unconsolidated undrained (UU) triaxial compression tests were conducted on remolded reinforced specimens to see how they behaved under different confining pressures (shown in Table 5), which were equal to 250 cm, 500 cm, and 750 cm of depth in an embankment according to ASTM D4767 [34]. The specimens were modified with different quantities of PET strips, ranging from 0.0% to 2%, and PLA, ranging from 0% to 12% of the wet soil weight. Confining pressure values (σ_c) were applied to replicate effective vertical stresses (σ_v), specifically 58.45, 123.90, and 182.20 kPa. The specimens had a height-to-diameter relationship (h/d) of approximately 2.43, with a diameter of 35 mm and a height of 85 mm. Moreover, all specimens were fabricated with an OMC of 11%. The apparatus of the triaxial test is shown in Figure 4b.

Table 5. Values of confining pressure.

Depth (cm)	Effective Vertical Stress (σ_v), kPa	Confining Pressure (σ_c), kPa
0	0.00	0.00
250	58.45	58.45
500	123.90	123.90
750	182.20	182.20

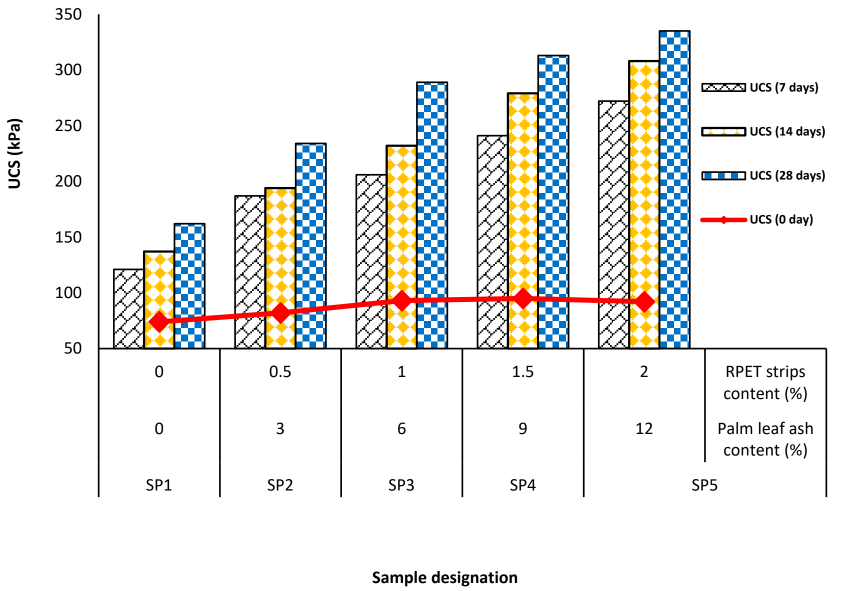
2.3.3. California Bearing Ratio

According to ASTM D1883 [35], the CBR test was conducted. Five equal layers of the combined mixture were layered into the 150 mm in diameter and 180 mm in height cylindrical mold, and each layer was compressed with tamping equipment at a loading rate of 1.25 mm per minute. According to the established standard technique and recommendations, soil samples for both unreinforced and reinforced soil were prepared. The soaked and unsoaked samples underwent the CBR test. Accordingly, the CBR values were established. On clayey sand under both soaked and unsoaked conditions, CBR experiments were conducted with and without recycled PET strips and PLA. The mixes' ideal moisture content was used to prepare the test specimens. The samples were submerged in water for 96 h before testing in a wet environment. The CBR value of soil–recycled PET reinforced with PLA mixtures was achieved by dividing the loads corresponding to 3 and 5.5 penetration by the standard loads of 1375 and 2060 kg, respectively. Accordingly, the CBR values were established. The apparatus of the CBR test is shown in Figure 4c.

3. Results and Discussion

3.1. Influence of Recycled PET strips with PLA on UCS of Soil

In Figure 5, the UCS values of clayey sand are shown for the reinforcement of recycled PET strips combined with PLA at different times (0 days, 7 days, 14 days, and 28 days). The addition of recycled PET strips and PLA has been found to result in a notable increase in the UCS value of the clayey sand. Optimal combinations of strip content and length, along with PLA, were identified for each soil based on the UCS results.



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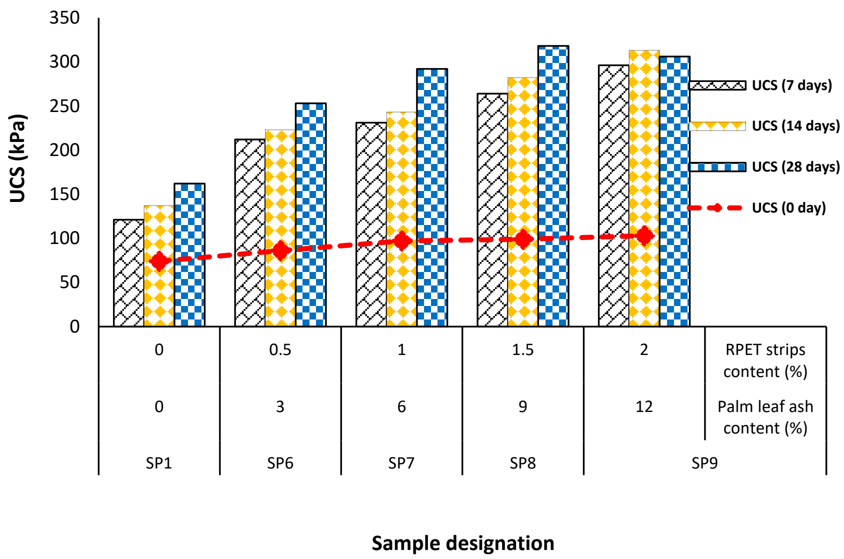

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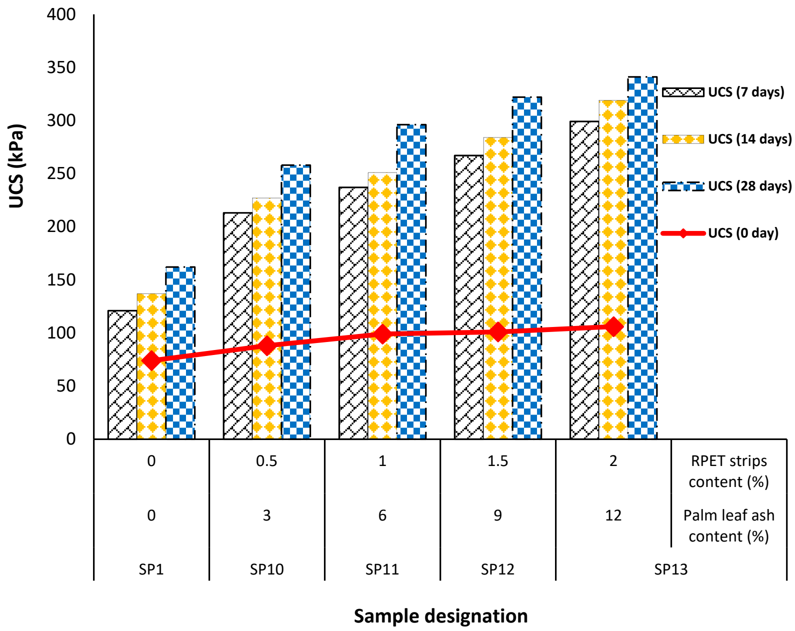


(**c**)

Figure 5. Influence of recycled PET strips with PLA on UCS of soil: (**a**) 10 mm recycled PET strip length, (**b**) 20 mm recycled PET strip length, (**c**) 30 mm recycled PET strip length.

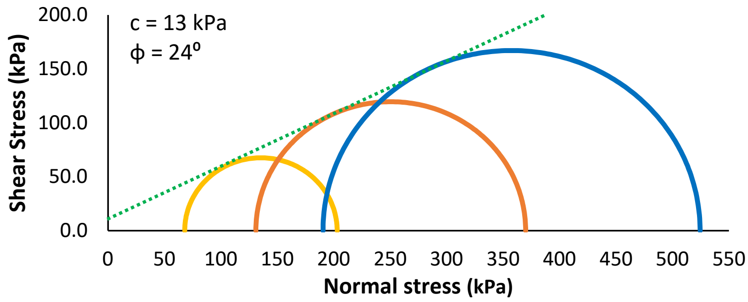
Figure 5a illustrates the UCS values for clayey sand reinforced with 10 mm-long recycled PET strips, varying in content from 0% to 2% and PLA content ranging from 0% to 12%. The most substantial improvement was observed in the SP4 soil sample (consisting of 1.5% recycled PET strip content and 9% PLA) at 0 days, showing a remarkable 28% increase in UCS compared to the initial value. After 7 days, the most significant improvement in UCS value was observed in the SP5 soil sample, with the UCS value increasing by 3.7 times from its initial value of 74 kPa at 0 days. This improvement was achieved by adding 2% of the 10 mm-long strip content and 12% palm leaf ash. Furthermore, at both 14 days and 28 days, the maximum improvement was again observed in the SP5 soil sample, with the UCS value increasing by 4.1 times and 4.5 times, respectively, compared to the initial UCS value of 74 kPa for the SP1 soil sample at 0 days.

Figure 5b presents the results of UCS testing for clayey sand reinforced with 20 mm-long recycled PET strips, with varying content ranging from 0% to 2% and PLA content ranging from 0% to 12%. The most notable improvement was observed in the SP9 soil sample at 0 days, showing a remarkable 39% increase in UCS compared to its initial value. At 7 and 14 days, the most substantial enhancement in UCS was again seen in the SP9 soil sample, with UCS values increasing by 4 times and 4.2 times, respectively, compared to the initial value of 74 kPa at 0 days. Additionally, at 28 days, the maximum improvement was observed in the SP8 soil sample, with the UCS value increasing by 4.3 times compared to the initial UCS value of 74 kPa for the SP1 soil sample at 0 days.

In Figure 5c, the UCS values for clayey sand reinforced with 30 mm-long recycled PET strips, with varying content from 0% to 2% and PLA content ranging from 0% to 12%, are illustrated. The most substantial improvement was observed in the SP13 soil sample at 0 days, showing a remarkable 43% increase in UCS compared to the initial value. After 7, 14, and 28 days, the most significant improvement in UCS value was witnessed in the SP13 soil sample, with UCS values increasing by 4 times, 4.3 times, and 4.6 times, respectively, compared to the initial value of 74 kPa (SP1) at 0 days. The findings align with prior research exploring the combined impact of PET with additional binding agents in soil. The conclusions of Silveira, Lodi, Correia, Rodrigues and Giacheti [22] substantiate the augmentation of UCS within lateritic soil through the incorporation of recycled PET strips within cement-reinforced soil. Furthermore, it was observed that an increase in strip length from 10 mm to 30 mm results in a corresponding increase in UCS values, attributed to the interlocking mechanisms. Another study conducted by Kumar and Mishra [23] highlights that employing 5mm strip lengths and progressively raising the strip content from 0 to 4% with sodium hydroxide leads to an increase in the UCS value in soil. A study carried out on clayey soil illustrates that employing a content of 0.8% PET strips (18mm in length) leads to an enhancement in the UCS value [36]. Bozyigit, Bulbul, Alp and Altun [16] conducted a comparable study on kaolin clay stabilized with cement, investigating the influence of recycled PET strips. The study noted that higher proportions of cement and PET strip content led to an increase in the UCS value.

3.2. Influence of Recycled PET Strips with PLA on Shear Strength Parameters of Soil

Figure 6 displays the Mohr circles at 10% of the strain for the unconsolidated undrained (UU) triaxial tests conducted on both unreinforced and recycled PET-reinforced soil specimens. These figures provide valuable insights into the effects of the PET strip length content (specifically 30 mm) and PLA content on the apparent internal friction angle (φ) and cohesion (c), respectively. In Figure 6, the yellow color corresponds to a confining pressure of 58.45 kPa, whereas the orange color indicates a confining pressure of 123.9 kPa. Additionally, the blue color is indicative of a confining pressure of 182.2 kPa. Upon careful observation of the figures, it becomes evident that as the strip content and PLA content increase, there is a noticeable trend of increasing apparent internal friction angle and cohesion in the soil. By introducing 2% PET strips (at a length of 30 mm) and 12% palm leaf ash to the unreinforced soil, there is an increase in the apparent cohesion, rising from 13 kPa (unreinforced soil) to 18.5 kPa (SP13 soil sample). It becomes evident that the apparent cohesion of the soil undergoes a significant enhancement of approximately 1.42 times by adding 2% PET strips (at a length of 30 mm) and 12% palm leaf ash to the unreinforced soil. Enhancing the cohesion of reinforced soil samples results in improved compactness and stability of its structure. This enhancement aids in preventing the separation of soil particles and enables a more effective distribution of forces throughout the sample [37].



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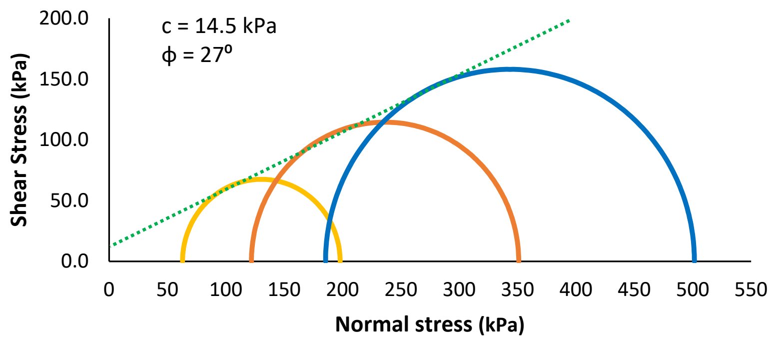

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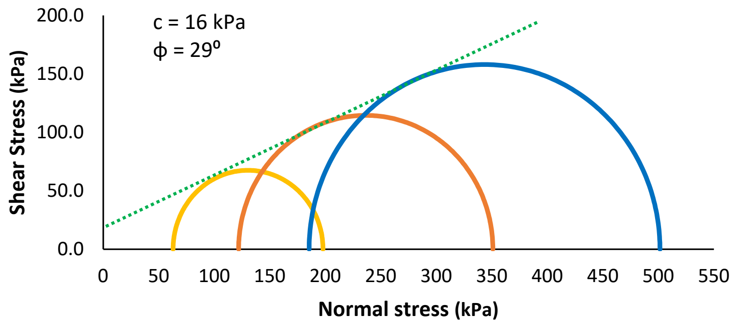

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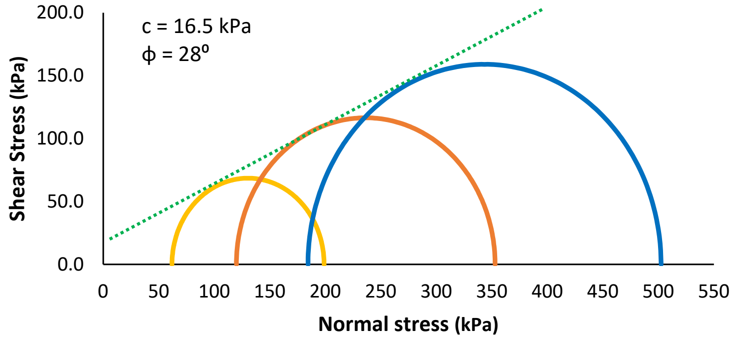

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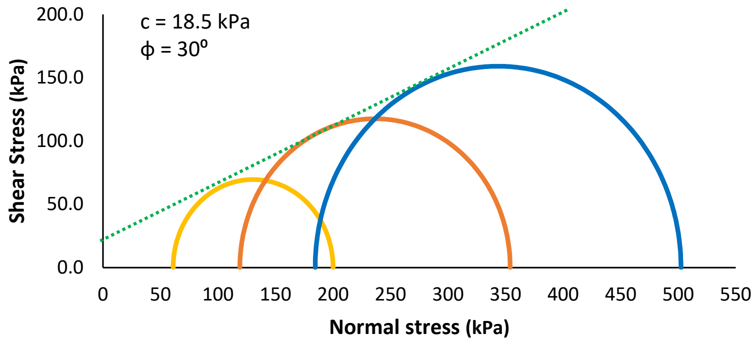


(**e**)

Figure 6. Influence of recycled PET strips with PLA on shear strength parameters of soil samples: (**a**) S1, (**b**) S10, (**c**) S11, (**d**) S12, (**e**) S13. Where yellow color shows confining pressure: 58.45 kPa; orange color shows confining pressure: 123.90 kPa; blue color shows confining pressure: 182.20 kPa.

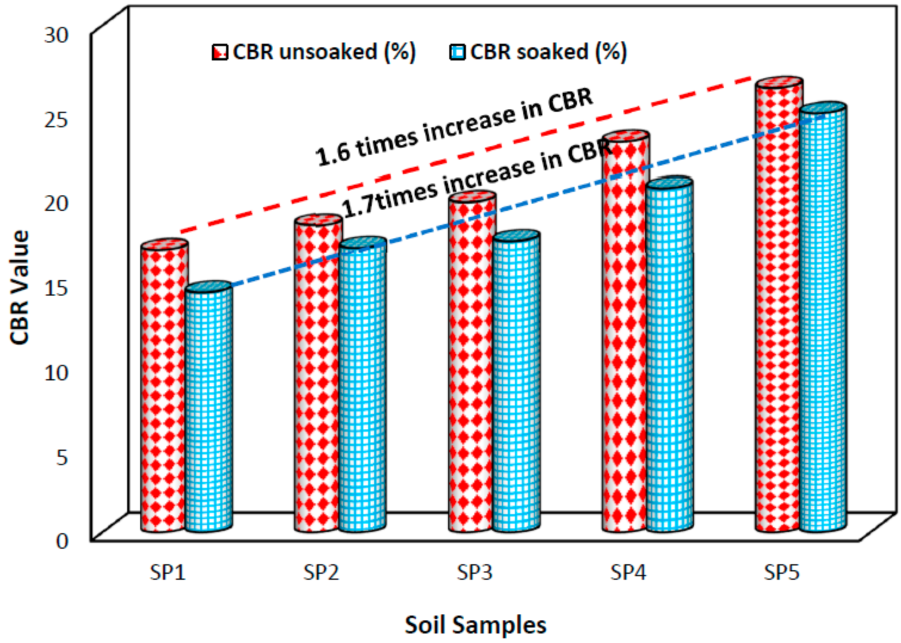
It has been noted that the frictional angle of the unreinforced soil was 24°. Upon incorporating 2% PET strips (measuring 30 mm in length) and 12% palm leaf ash into the unreinforced soil, the frictional angle increases to 30°. This change reflects a 1.25 times increase in frictional angle in the reinforced soil. An increase in the internal friction of soil implies that, under shear loads, the soil is less susceptible to internal movement [38].

Previous research has identified a similar soil response, where the addition of PET strips up to 1.5% in content and lengths of up to 30 mm leads to an increase in both cohesion and the frictional angle of the soil [39]. The experimentation conducted on expansive clay soil similarly demonstrates that the optimal enhancement in both cohesion and frictional angle values is achieved by employing a PET strip content of 2%, coupled with a length of 20 mm [40]. Muntohar, et al. [41] research findings indicated that increasing the PET content along with rice husk ash from 0.4% to 0.8% resulted in an increase in cohesion within the silty soil.

3.3. Influence of Recycled PET Strips with PLA on CBR Value of Soil

The CBR tests were conducted following the ASTM D1883 guidelines. The mixture of soil and reinforcements was filled into a cylindrical mold with a diameter of 15 cm and a height of 18 cm, compacted in five layers using a tamping device with a loading rate of 0.125 cm per minute. Both un-reinforced and reinforced soil samples were prepared according to standard procedures.

CBR tests were performed on both unsoaked and soaked samples, and the results are plotted in Figure 7. The findings indicate that the addition of recycled PET strip content in combination with PLA leads to an increase in the CBR value for both soaked and un-soaked samples, signifying an improvement in soil strength.



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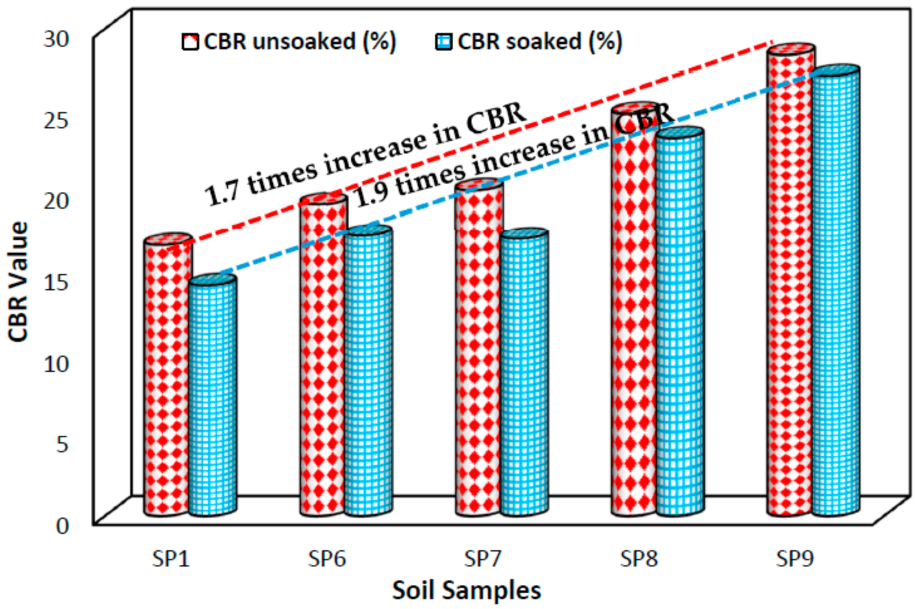

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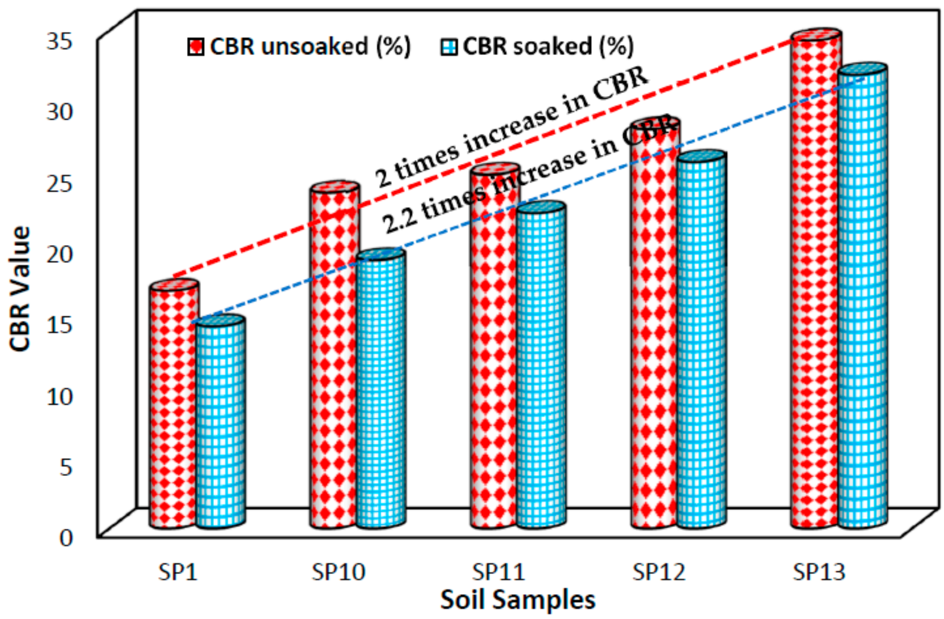

(**c**)

Figure 7. Influence of recycled PET strips with PLA on CBR value of soil samples: (**a**) 10 mm PET strip length, (**b**) 20 mm PET strip length, (**c**) 30 mm PET strip length.

In Figure 7a, the CBR values of soil reinforced with 10 mm recycled PET strip content and PLA are presented. The CBR value of the unreinforced soil was 16.7% under unsoaked conditions. It has been observed that an increase in the content of recycled PET strips (10 mm in length), by increments of 0.5%, and PLA by increments of 3%, leads to a corresponding improvement in the CBR value. On average, the CBR value shows an increase of 2.4% for unsoaked samples. The most significant enhancement was observed in the SP5 (2% PET + 12% PLA) sample, displaying a 1.6 times increase in CBR after the soil was reinforced under unsoaked conditions. On the other hand, the CBR value of the unreinforced soil was 14.2% under soaked conditions. It has been observed that an increase in the content of recycled PET strips (10 mm in length), by increments of 0.5%, and PLA by increments of 3%, leads to a corresponding improvement in the CBR value. On average, the CBR value shows an increase of 2.6% for soaked samples. The most significant enhancement was observed in the SP5 (2% PET + 12% PLA) sample, displaying a 1.7 times increase in CBR after the soil was reinforced under soaked conditions. The improvement in CBR values under unsoaked and soaked conditions indicates improvement in the load bearing capacity of soil.

In Figure 7b, the CBR values of soil reinforced with 20 mm recycled PET strips and PLA are depicted. Through the incremental addition of PET strips (20 mm in length) by 0.5% and PLA by 3%, the CBR value increased by 2.3% under unsoaked conditions. The most significant enhancement, reaching 1.7 times that of the unreinforced soil, was observed in the SP9 sample (2% PET + 12% PLA) under unsoaked conditions. On the other hand, through the incremental addition of PET strips (20 mm in length) by 0.5% and PLA by 3%, the CBR value increased by 2.4% under soaked conditions. The most significant enhancement, reaching 1.9 times that of the unreinforced soil, was observed in the SP9 sample (2% PET + 12% PLA) under soaked conditions. This observation further demonstrates that increasing the strip length from 10 mm to 20 mm results in an increase in the CBR value of the soil.

In Figure 7c, the CBR values of soil reinforced with 30 mm recycled PET strips and PLA are shown. The most significant enhancement, a two-times increase in CBR value compared to unreinforced soil, was observed in SP13 under unsoaked conditions. Additionally, the highest improvement, with a 2.2 times increase in CBR value relative to unreinforced soil in SP13, was evident under soaked conditions. The Choudhary, et al. [42] study demonstrated that extending the length of PET strips from 12 mm to 36 mm led to an increase in CBR, from 41% to 54% by increasing the contact area with soil, while keeping the PET strip content unchanged. Another study indicates that raising both the PET strip and fly ash content results in a higher CBR value for soil. This increase is attributed to fly ash enhancing the bonding with the soil matrix, while the PET strips contribute to load-bearing capabilities [43,44]. Amena [45] research reveals that increasing the waste brick powder content up to 40% and incorporating PET strips at a content of 0.75% leads to an increase in the CBR value of expansive soil. A similar study indicates that by introducing up to 20% marble content and increasing the PET strip content to 0.75%, there is a notable increase in the CBR value of the soil. This phenomenon is attributed to the enhancement of the soil's bonding capacity, which subsequently improves its ability to withstand and bear loads effectively [46].

4. Interaction Mechanism between Recycled PET, PLA, and Soil

The interaction mechanism between PET strips, PLA, and soil particles is shown in Figure 8. It involves several critical activities that work in concert to improve the soil's qualities. A connected network can be made within the soil matrix by using longer recycled PET strips. By increasing the length of recycled PET strips, axial loads are dispersed over a larger area of the soil volume. This lessens the likelihood of localized stress concentrations and helps to distribute the applied load evenly [47]. The strips' longer length dissipates the load, lowering the possibility of early failure and raising overall compressive strength. It can also provide additional lateral confinement to the soil sample during the UCS test. This confinement mimics the effect of lateral support, resulting in improved compressive strength and stability [37]. As PLA is added, the soil becomes denser and more compact by filling up the spaces and gaps between soil particles. Furthermore, the chemical components of the ash encourage cementation by fostering cohesion and adhesion between soil particles and reinforcing materials. The mixed materials also have the ability to absorb and hold water, which helps to maintain the proper soil moisture levels necessary for the best compaction and stability. PET strips and PLA improve the soil's shear resilience, reducing the likelihood of sliding and deformation. Additionally, the addition of PET strips promotes soil particle stability and durability over the long term by reducing deterioration. Overall, this interaction mechanism provides a useful strategy for soil stabilization, erosion management, and various building projects, enhancing the soil's long-term performance and mechanical strength.

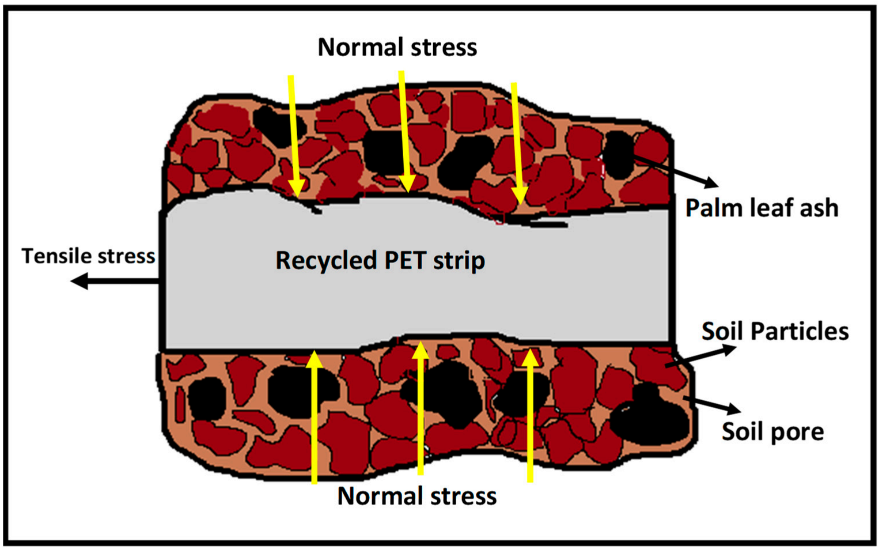

Figure 8. The interaction mechanism between PLA, PET strips, and soil particles.

5. Conclusions

As a result, the sustainable approach of enhancing the engineering properties of soil using a combination of recycled PET strips and PLA demonstrates a promising and environmentally responsible solution to challenges regarding soil stability by improvements in shear strength, cohesion, compaction, and load-bearing capacity of the stabilized soil. Furthermore, it sheds light on the construction industry by showcasing how the synergistic utilization of recycled materials and natural stabilizers can effectively tackle concerns associated with soil stability and construction practices, all the while adhering to sustainable approaches. The outcomes of this study highlight the possibility of combining waste products, such as PET strips and palm leaf ash, to enhance soil properties. The main outcomes are given below.

- Reinforcing SC soil with recycled PET strips of 10 mm, 20 mm, and 30 mm lengths, ranging from 0% to 2% content for PET and 0% to 12% for PLA, resulted in notable improvements in UCS. The SP4 sample exhibited the most significant increase of around 28% in UCS with 10 mm strips at day 0. Subsequently, SP5 demonstrated the highest enhancements after 7, 14, and 28 days. Using 20 mm PET strips, the SP9 sample showed a remarkable 39% enhancement on 0 days, with notable UCS increases at 7 and 14 days, while SP8 displayed substantial improvements after 28 days. For 30 mm PET strips, the initial 43% increase in UCS was most prominent in the SP13 sample, followed by significant improvements at 7, 14, and 28 days.
- At a strain of 10%, it was noted that the apparent cohesion of the soil increased by around 1.42 times when comparing unreinforced soil to soil containing 2% PET strips (30 mm in length) and 12% palm leaf ash (referred to as S13). Similarly, the apparent friction angle also exhibited an increase of roughly 1.21 times in the same comparison.
- Significant improvements in CBR values were witnessed through the CBR test. With a 10 mm PET strip length, the CBR value increased by 1.6 times in unsoaked and 1.7 times in soaked conditions for SP5 soil, compared to unreinforced soil. Increasing the strip length to 20 mm led to a 1.7 times increase in unsoaked and a 1.9 times increase in soaked conditions for SP9 soil. Further, transitioning from 20 mm to 30 mm strip length resulted in a 2 times increase in unsoaked and 2.2 times increase in soaked conditions for SP13 soil, relative to unreinforced soil.

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