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Utilization of Plastic Waste in Reinforcing Sandy Soil for Sustainable Engineering Applications

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Abstract. Large quantities of polyethylene terephthalate (PET) plastic are discarded into the environment during production, application, and disposal. Although current clean-up strategies aim to mitigate the adverse impacts of PET pollution, efforts struggle to keep up with the escalating amount of PET waste. This accumulation of PET waste poses significant threats to ecosystems worldwide. One recycling method for PET plastic waste involves its utilization in soil reinforcement applications within civil engineering. By incorporating PET plastic waste to reinforce poor-quality sands, sustainable construction practices can be promoted in civil engineering infrastructures, addressing multiple aspects of sustainability, including engineering, economic, social, and environmental considerations. The experimental work conducted in this research involved sieve analysis, proctor compaction test, California Bearing Ratio (CBR) test, and direct shear box test. The sand was reinforced with varying percentages of PET plastic waste flakes, namely 5, 10, and 15 %, with respect to the weight of the soil sample taken for the test, and laboratory tests were performed on the samples. Including PET plastic flakes enhanced various soil properties, such as shear strength and friction angle. It also improved the CBR value of the composite, making it suitable for pavement construction. The reduction in dry density further supports the application of the composite in lightweight structures. In conclusion, the geotechnical material obtained from the soil-PET plastic waste composite can be utilized in various geotechnical projects, including landfills and slope stabilization.

Keywords: polyethylene terephthalate, plastic waste, soil reinforced, sustainable construction.

1 Introduction

Polyethylene terephthalate (PET) is a widely used thermoplastic polyester with various applications. It is primarily utilized in fibers, accounting for more than 60 % of its usage, while bottle production contributes approximately 30 % to global demand [1].

While the sustainable approach of reducing, reusing, and recycling is in practice, it does not effectively address the issue of abandoned PET waste. Research has indicated that reinforcing poor-quality soil with PET plastic waste can enhance the performance and durability of structures [2].

The application of plastic waste in soil stabilization has shown improvements in the foundation layers of pavements [3]. This approach reduces waste quantities and recycles them to enhance soil properties [4].

After adding PET, previous experiments have significantly enhanced soil mixtures' strength and friction angle, although the cohesive properties have decreased [5]. The soil strength parameters of the composite were evaluated by varying the percentage of finely crushed PET flakes in the mixture. This article analyzes the behavior of soil-PET composite based on a series of laboratory tests.

The literature review section highlights previous research observations and findings on the impact on shear strength, bearing capacity, and California Bearing Ratio. Additionally, the article presents test results and observations obtained from laboratory-reinforced soil samples.

By analyzing these results with previous findings, conclusions are drawn regarding applying soil-PET composites and prospects in geotechnical engineering.

2 Literature Review

Engineering has witnessed significant advancements by incorporating fibers into the soil for reinforcement. Numerous researchers have conducted studies on the topic of fiber-reinforced soil, and this section provides a summary of select published research in this field.

Gray and Ohashi [6] studied the mechanics of fiber reinforcement in sand. The tests performed for the study were direct shear tests on dry sand reinforced with natural fibers, synthetic fibers, and metal wires. The results demonstrated increased shear resistance directly proportional to the fibers oriented at a 60° angle to the shear surface. These findings have significant implications for solving problems such as stabilizing sandy soil, coarse-textured soils in granitic slopes, and stabilizing dunes and beaches with pioneer plants.

In another study, Park and Tan [7] investigated the suitability of composite walls constructed using soil-polypropylene plastic. It was observed that the composite walls improved stability, reducing earth pressure and wall settlement. The inclusion of short fibers in reinforcing the soil enhanced wall stability, resulting in decreased earth pressures and displacements. The combination of short-fiber soil with geogrid had even more significant effects.

Consoli et al. [8] studied sand reinforcement using fibers. Uniformly graded quarzitic sand, polypropylene, and fibers (0.05 % by dry sand weight) were added. The physical properties of the sand were determined through specific gravity tests and particle size distribution tests.

Acharyya et al. [9] studied the improvement of undrained shear strength in clayey soil by blending it with PET bottle strips to form a composite. The clayey soil samples were prepared by mixing them with 10 and 20 % sand, and PET shreds with lengths ranging from 5 to 15 mm and a width of 5 mm were used. The fiber percentage ranged from 0.5 to 2.0 % by weight of the soil. Tests such as Atterberg limit tests, compaction tests, unconfined compressive strength tests, and direct shear tests were carried out to determine the physical properties of the soil and soil-fiber composite. Tests performed on the strips focused on width, thickness, tensile strength, and density. The results revealed that the unconfined compressive strength of the soil-fiber composite increased up to 1.0 % as the percentage of PET inclusion increased.

Akbulut et al. [10] investigated the behavior of clayey soils reinforced with scrap tire rubber and synthetic fibers. The clayey soil was reinforced with 2.0 % by weight of scrap tire rubber and 0.2 % by weight of polyethylene and polypropylene fibers with diameters of 1mm and lengths ranging from 5 to 60 mm. The research findings demonstrated a significant improvement in the strength and dynamic behavior of clayey soils after reinforcement with fibers.

Benson and Khire [11] conducted a study using strips of reclaimed high-density polyethylene (HDPE) as reinforcing fibers in sand. The fiber contents ranged from 1 to 4 %. The results of California bearing ratio (CBR), resilient modulus, and direct shear tests demonstrated that reinforcing sand with HDPE strips enhanced its resistance to deformation and increased its strength. The study suggests that HDPE strips can be utilized in highway construction and other light-duty geotechnical applications. Also, Consoli et al. [8] examined the engineering behavior of uniform fine sand reinforced with PET fibers and rapid-hardening Portland cement. Test results showed that PET fiber reinforcement improved the peak and ultimate strength of both cemented and uncemented soil, reducing the cemented sand's brittleness.

Tang et al. [12] analyzed the strength and mechanical properties of short polypropylene (PP) fibers combined with cement-stabilized clayey soil. The results indicated that fiber reinforcement in uncemented and cemented soil increased the unconfined compressive strength, shear strength, and axial strain on the verge of failure. However, it also resulted in a decrease in stiffness and a loss of post-peak strength, making the cemented soil more ductile.

Sadek et al. [13] investigated the shear strength of fiber-reinforced sand by adding coarse or fine sand and using nylon fishing wires as reinforcement fibers. Adding 1 % nylon fibers by dry sand's weight increased the composite's shear strength. The ductility of the composite increased by 37.0 % for coarse sand and 46.8 % for fine sand. The test results indicated that adding fibers positively affected the sand mixtures' shear strength parameters (angle of internal friction and cohesion).

Ranjan et al. [14] studied the behavior of plastic fiber-reinforced sand composite. The addition of discrete plastic fibers with fiber contents ranged from 1 % to 4 % (by weight) to poorly graded fine sand. The results of various tests indicated that the critical confining stress decreased with an increased aspect ratio of the plastic fiber. Additionally, the shear strength of the plastic fiber-reinforced sand mixture increased with higher fiber content and aspect ratio. The practical significance of these findings is the recommended use of the composite for ground improvement in embankments and subgrades.

Ramini et al. [15] conducted a series of small-scale laboratory tests to investigate the effectiveness of soil-filled PET bottles for soil reinforcement. The findings indicated an improvement in bearing capacity for all reinforcement configurations, with a notable increase correlated to bottle size. Adding a PP belt resulted in further enhancements, surpassing the performance of a single layer of geogrid across all three bottle sizes. Additionally, the incorporation of an extra layer of geogrid over the reinforced zone led to a stiffer response and higher bearing pressure at significantly lower displacement.

Haider et al. [16] observed a substantial increase in soil strength, ranging from 28 to 91 %, with the introduction of cement-PET shreds. Substituting cement with cement-PET shreds also resulted in a reduction in accumulated mass loss (ALM). Small-strain stiffness initially decreased throughout twelve wetting and drying cycles, eventually stabilizing at a consistent value in subsequent cycles. The ratio of porosity to binder was utilized as an indicator for CBR, ALM, and the maximum shear modulus, with the latter suggested as a measure of durability.

Ferreira et al. [17] conducted a study on soil properties with added fibers, revealing that fiber inclusion improved the stress-strain behavior, demonstrated by greater absorbed strain energy in the reinforced soil. PET reinforcement reduced vertical and horizontal deformation, altering the soil failure mechanism. Settlement reduction in fiber-reinforced sand was found to be dependent on stress magnitude, decreasing by approximately 81 % for stresses above 300 kPa. For instance, settlement decreased from 125.3 mm in unreinforced sand to 23.6 mm with fiber insertion at 400 kPa. A 375.7 % enhancement was observed in bearing capacity at the maximum comparable settlement, increasing from 240 to 1142 kPa. In addition to enhancing our understanding of soil-PET mixtures, these results promote sustainable engineering applications, such as embankments, shallow foundations, and retaining wall layers.

3 Research Methodology

3.1 Formation of the soil-PET composite

The materials used in this research work include sandy soil, water, and PET plastic waste flakes. Soil: The soil material used in this research was medium-dense, clean quartz sand consisting of round-shaped particles ranging between 0.075 and 1.180 mm. Several tests were conducted on the soil, including particle size distribution, compaction, CBR, and direct shear box tests. This research used plastic waste flakes made of PET as reinforcing material. These flakes were obtained from a factory that uses recycled PET plastic bottle flakes to manufacture geosynthetic products such as geotextiles. The PET plastic waste flakes used in the study had different colors, and their sizes ranged from 0.075 to 4.750 mm.

Table 1 provides an overview of the various laboratory tests conducted on the sand, PET flakes, and the sand-PET plastic waste composite.

Table 1 – Laboratory tests with their methods and references

Material	Test	Standard
Unreinforced sand	Particle size distribution	ISO 11277:2020
	Compaction	IS:2720-8:1983
	CBR	IS:2720(Part 16):1987
	Direct shear box	IS:11229:1985
PET	Particle size distribution	ISO 11277:2020
	Compaction	IS:2720-8:1983
	CBR	IS:2720(Part 16):1987
Sand-PET plastic waste composite	Direct shear box	IS:11229:1985

To accomplish the objectives of this study, laboratory experimental work was conducted following the procedures outlined in the Indian Standard (IS) codes.

Initially, tests were performed on the soil without any reinforcement to establish a baseline. Subsequently, the soil was reinforced by incorporating different percentages of PET plastic waste concerning the soil weight taken for the test, and experiments were carried out on the soil-PET plastic waste composite and the unreinforced sample. A comparative analysis of the results obtained from these tests served as the basis for evaluating the properties and potential applications of the composite. The formation of the soil-PET composite is depicted in Figure 1.

Figure 1 – Compacted Sand-PET plastic waste composite

As mentioned earlier, the research utilized the primary materials of sandy soil, water, and PET plastic waste. Particle size distribution tests were conducted on both the sandy soil and PET plastic waste flakes, and the results are presented in the following section. Atterberg limit tests were also performed, indicating that the soil specimen exhibited a non-plastic behavior. The subsequent section will discuss the outcomes of these tests and explore the potential application of the soil-PET plastic waste composite.

3.2 Grain size distribution

A grain size analysis was conducted to examine the distribution of soil particle sizes. This analysis provides information about the range of particle sizes in the soil and the distribution pattern of different-sized particles. The same range of IS sieve sizes was used for the soil and PET plastic waste. The results of the particle size distribution for the sand and PET plastic waste flakes can be seen in Figure 2.

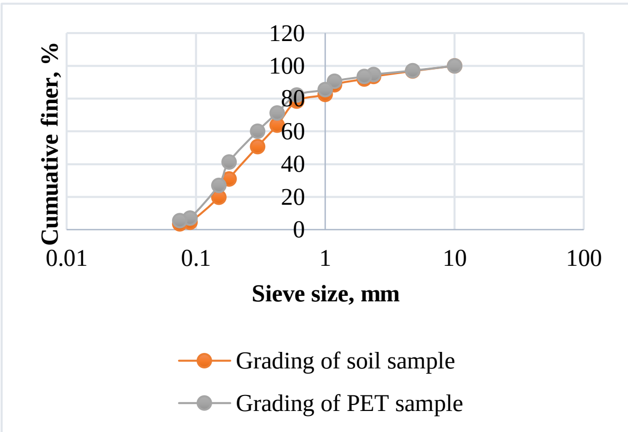

Figure 2 –Particle size distribution of sand and PET plastic waste flake

Figure 2 displays the particle size distribution curves for the soil and PET plastic waste flake samples. The soil specimen exhibited particle sizes ranging from 4.750 to 0.075 mm, with a zero-value gravel percentage, a sand percentage of 96.5 %, a silt percentage of 3.5 %, and a zero-value clay percentage. It also shows that the soil specimen has a mean particle size (D50) of 0.295 mm, D60 of 0.381 mm, D30 of 0.169 mm, and D10 of 0.111 mm. These values yield a coefficient of uniformity (Cu) of 3.45 and a coefficient of curvature (Cc) of 0.69.

The grain size analysis indicates that the soil classification is poorly graded soil. The distribution of grains indicates that the soil sample primarily consists of a high percentage of sand and lacks fines. The PET plastic waste consists of smooth and flaky particles ranging between 0.075 and 4.750 mm, which exhibit a similar particle size distribution as the sandy soil sample. However, due to the different nature of the materials, achieving a perfect bond between the PET plastic waste and sandy soil posed a challenge.

When the two materials were mixed, it was observed that the resulting composite had a uniformly graded particle size distribution, as both the sand and PET plastic waste fell within the same size range. This uniform grading of the composite was attributed to the absence of fines in the mixture. This substitution of some percentage of sand with PET plastic waste in the mixture not only reduces construction costs as the volume of sand used is replaced by PET plastic waste, decreasing a considerable proportion of sand used, but also provides an alternative in areas where an adequate supply of sand is not available but plastic waste is abundant. The chemical bond between PET plastic waste and sand is an area that warrants further investigation and study.

4 Results

4.1 Compaction analysis

The compaction test followed the guidelines specified in IS:2720(Part 7). The test aimed to establish the relationship between dry density and moisture content by plotting a maximum dry density (MDD) graph against optimum moisture content (OMC). Initially, the compaction test was performed on the unreinforced soil sample (zero-value PET plastic waste), and subsequently, it was conducted on soil samples reinforced with increasing proportions by soil weight of PET plastic waste, namely 5, 10, and 15 %.

The results of the compaction test are presented in Figure 3.

increases in the sand-PET plastic waste composite, the MDD of the composite decreases. This is because the sand particles are denser than the PET plastic waste particles. The compaction test results for the unreinforced sand showed a MDD of 1800 kg/m^3 at an OMC of 12 %, which is similar to the MDD of the compacted unreinforced sand.

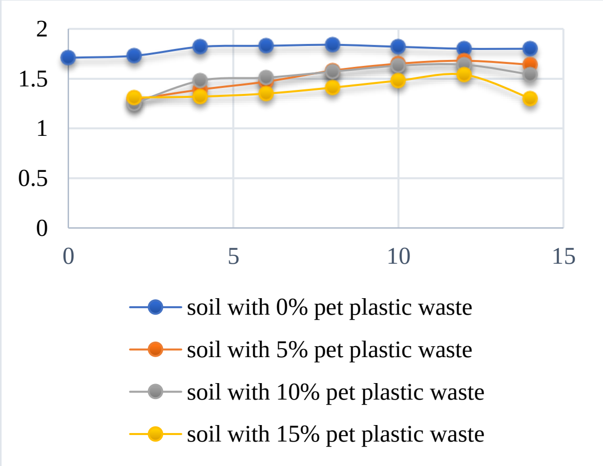

Figure 3 – Relationships between MDD and OMC

Figure 4 illustrates the relationship between MDD and the percentage of PET plastic waste added to the sand.

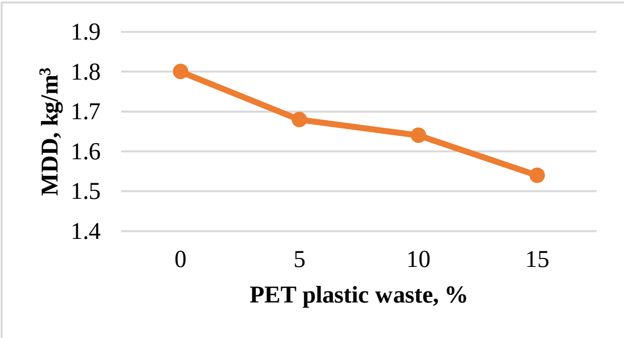

Figure 4 – Relationship between MDD and PET plastic waste

Generally, as the percentage of PET plastic waste

When the sand was reinforced with 5 % PET plastic waste, the sand-PET plastic waste composite exhibited an MDD of 1650 kg/m^3 at 11.2 % OMC. Notably, there was a negligible difference in the OMC between the unreinforced sand and the sand-PET plastic waste composite with 5.0 % PET plastic waste. However, there was a decrease of 6.7 % in the MDD value of the sand-PET plastic waste composite with 5.0 % PET plastic waste compared to the unreinforced sand. Adding 10.0 % PET plastic waste to the sand resulted in a sand-PET plastic waste composite with an MDD of 1640 kg/m^3. Comparing the data of the sand-PET plastic waste composite with 10.0 % PET plastic waste to the sand-PET plastic waste composite with 5.0 % PET plastic waste, there was a reduction of 2.4 % in the MDD. This suggests that adding 5.0 % PET plastic waste made the sand-PET plastic waste composite lighter with 10.0 % PET plastic waste. When the sand was reinforced with 15.0 % PET plastic waste, the composite yielded a MDD of 1540 kg/m^3. This represents a decrease of 16.8 % in the MDD compared to the unreinforced sand.

Analyzing the data between the sand-PET plastic waste composite with 15.0 % PET plastic waste and the sand-PET plastic waste composite with 10.0 % PET plastic waste, there was a decrease of 6.1 % in the MDD.

As the percentage of PET plastic waste increases in the sand-PET plastic waste composite, the composite becomes lighter in weight, as evidenced by the compaction test results. Such a composite can be applied in projects that require lower MDD of the soil. The findings indicate that the compacted soil composite becomes denser due to the expulsion of air voids, reducing the air volume associated with the addition of plastic waste and reducing the composite density.

4.2 CBR analysis

The CBR values measure soil strength and bearing capacity, specifically for the design of pavement base and sub-base layers. The laboratory experiment on poorly graded uniform sand soils reinforced with PET plastic waste aimed to establish a correlation between CBR and the percentage of PET plastic waste. This correlation facilitates the formulation of conclusions about the practical implications of using this composite material.

Figure 5 illustrates the CBR values obtained from the compaction tests conducted on the four tested specimens, each compacted at their respective optimum moisture content.

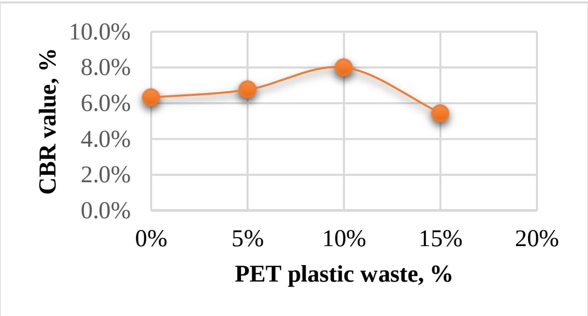

Figure 5 – Relationship between PET plastic waste and CBR

The tests followed the guidelines outlined in IS:2720(Part 16):1987. Adding PET plastic waste by soil weight at different percentages (0, 5, 10, and 15 %) to reinforce the poorly graded uniform sand led to corresponding CBR values of 6.3, 6.8, 8.0, and 5.5 %, respectively.

It is observed that the unreinforced sand specimen and the sand-PET plastic waste composite specimen reinforced with 5.0 % PET plastic waste have similar CBR values of 6.3 %. This indicates that adding 5.0 % PET plastic waste to the poorly graded uniform sand has a negligible effect on the CBR value. This can be attributed to the lack of fines in the composite and the limited bonding between the sand particles and the flaky PET plastic waste flakes.

Notably, an increase in the percentage of PET plastic waste in the composite generally increases the CBR value. The incorporation of PET plastic waste increased the CBR value for the composite up to 10.0 % by weight of PET plastic waste, but there was a reduction in value for the 15.0 % inclusion. No significant change was observed for the 5.0 % by weight of soil addition, likely due to the scarcity of fines and less bonding between the PET plastic flakes and soil particles at this stage. With a further increase in percentage, the CBR value improved as bonding increased with compaction. An increase of 15.5 % in CBR value was noted for the 10.0 % wt. addition of PET plastic flakes in the soil. This indicates that the higher CBR value enhances the reliability of the composite for flexible pavement design, reducing the amount of soil mass required. However, additional PET plastic flakes reduced the CBR value due to forming a dispersed structure at the same optimum water content. The optimal percentage of PET plastic flakes for this study was found to be 10.0 % by weight of soil.

4.3 Shear strength analysis

The direct shear box test was conducted on the soil samples reinforced with different percentages of PET plastic waste.

In this test, the soil samples were subjected to varying normal stresses of 100, 200, and 300 kPa. The shear stresses at failure were determined to assess the soil's ability to withstand stress before reaching the point of failure. In the direct shear test, shear parameters such as the angle of internal friction and cohesive intercept were determined.

Figure 6 illustrates the relationship between shear stress and normal stress under different conditions. Comparing the friction angle between the sand-only sample (38.5°) and the sand-15.0 % PET plastic waste composite (41.1°), there was a 6.3 % increase in the friction angle.

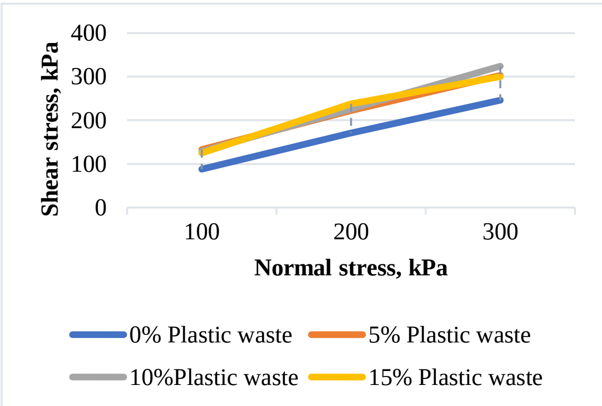

Figure 6 – Relationship between shear stress and normal stress

This increase can be attributed to the improved interlocking of particles in the sand-15 % PET plastic waste composite. However, it is essential to note that there was a decrease of 7.4 % between the sand-10 % PET plastic waste composite (44.4°) and the sand-15 % PET plastic waste composite (41.1°). This decrease could be attributed to the excessive presence of PET plastic waste beyond the optimum level for soil reinforcement. This excessive amount may have reduced the bonding properties of the composite, resulting in a decrease in the friction angle and, consequently, a reduction in the shear strength of the composite [18]. Another factor to consider is the smooth surface of the PET plastic waste flakes, which may have hindered their interaction with the sand particles during compaction [19].

5 Discussion

Research on the reinforcement of sand with PET plastic waste is still in its early stages. Initial findings suggest that the composite material can be introduced to the soil to enhance the bearing capacity of soil in foundation layers and determine the CBR for road construction. The addition of PET plastic waste flakes to the sand reduced composite weight by 6.8, 12.5, and 16.8 % for PET plastic waste concentrations of 5, 10, and 15 by sand mass, respectively. It was observed that the sand-PET plastic waste composite generally exhibited lower densities compared to unreinforced sand. Consequently, the lightweight nature of the composite makes it suitable for structures that require weight-sensitive materials. The inclusion of PET plastic waste increased the CBR value for the composite up to 10 % by weight of PET plastic waste, but there was a reduction in value for the 15 % inclusion. No significant change was observed for the 5 % by weight of soil addition, likely due to the scarcity of fines and less bonding between the PET plastic flakes and soil particles at this stage. With a further increase in percentage, the CBR value improved as bonding increased with compaction. An increase of 15.5 % in CBR value was noted for the 10.0 % wt. addition of PET plastic flakes in the soil. This indicates that the higher CBR value enhances the reliability of the composite for flexible pavement design, reducing the amount of soil mass required. However, additional PET plastic flakes reduced the CBR value due to the formation of a dispersed structure at the same optimum water content. The optimal percentage of PET plastic flakes for this study was found to be 10 % by weight of soil. A similar pattern in the relationship between CBR and PET plastic waste percentage was also observed in the study conducted by Ashraf et al. [20]. The test results showed that CBR values increased from 1.967 to 2.479 with 0.6 % of plastic for soil mixed with waste plastic strips and then decreased with further additions. It was also observed that there was a reduction in the CBR value from 1.967 for plain soil to 1.687 when adding 0.2 % plastic, which follows a similar pattern to the above study.

However, due to the lack of cohesiveness between the sand and PET plastic waste flakes, a perfect bond was not achieved in the sand-PET plastic waste composite. To address this issue, it is recommended to introduce cohesive soil, such as clay particles, to fill the voids in the composite. This would enhance the interaction between the composite constituents, resulting in a more homogeneous material capable of sustaining heavier loads. The limited number of specimens tested, consisting of four categories with PET plastic waste inclusion percentages of 0, 5, 10, and 15 %, is insufficient to draw conclusive results. The experimental results obtained by Kanwar and Shukla [21] showed that introducing 1.0 % plastic waste material, with an aspect ratio of 3, significantly enhanced both the shear strength and the CBR of the Campus soil. The research also indicated that using plastic waste strips as a stabilizing agent for sub-grade material in flexible pavement construction, particularly for highway sub-base construction, could substantially reduce the thickness of the base course in road pavements.

Additionally, the study demonstrated that including plastic waste improves flexible pavement properties, including the CBR value. Farah and Nalbantoglu's study [22] noted that blending sand with 0.50 % and 0.75 % plastic waste increased the peak and critical friction angles. Adding waste bottle plastic chips to the sand enhanced its shear strength. The optimal proportion of plastic chips was determined to be 0.75 %. The peak and critical internal friction angles increased as the percentage of plastic chips rose to the threshold of 0.75 %. However, when plastic chips were included in amounts beyond 0.75 %, there was a decrease in the peak internal friction angle.

Consequently, the reinforcing effect of plastic waste on the sand's shear strength diminished. This study also increased the friction angle of the sand-only sample from 38.5° to 41.1° for the sand-15.0 % PET plastic waste composite. It is important to note a 7.4 % decrease between the composite of sand and 10.0 % PET plastic waste (measuring 44.4°) and the composite of sand and 15.0 % PET plastic waste (measuring 41.1°). With an increase in the percentage of PET plastic flakes, the soil becomes overly reinforced, leading to a decrease in value due to the segregation of the soil-PET plastic composite in the presence of a more significant number of plastic flakes.

Further studies can be conducted to analyze the engineering behavior of the sand-PET plastic waste composite using different percentages of PET plastic waste inclusion. By increasing the number of specimens, more robust conclusions can be drawn, and the results can be correlated with the findings of this research. The potential of using the composite as construction blocks or bricks should also be considered. Investigating the thermal and sound properties of the composite would provide insights into its suitability for constructing residential houses. Stabilizing the composite with chemical compounds like cement or lime could enhance its shear strength and CBR values [23]. However, it is essential to note that this approach may incur higher costs. It is crucial to highlight that this study was conducted solely in a laboratory setting to analyze the engineering behavior of the sand-PET plastic waste composite. Thus, it is highly recommended that field trials be conducted to assess the performance of the composite under real-world conditions.

The lifespan of infrastructures where the sand-PET plastic waste composite is applied ranges from 20 to 80 years. To ensure the product's sustainability, properly handling composite waste is crucial to avoid negative effects on society, the economy, and the environment. Therefore, it is recommended that when an infrastructure reaches its lifespan, the composite wastes should be recycled and integrated into other construction materials to create new infrastructure. This practice would make the proposed composite more sustainable, mitigating risks for future generations and reducing project costs.

The direct shear box, compaction, and CBR tests were conducted to evaluate the applications of unreinforced sand and sand-PET plastic waste composite. The data obtained from these tests were analyzed to assess the suitability of the soil composite in various fields. These tests provide valuable insights into the behavior and properties of the composite material, assisting in determining its potential applications. By considering the results of these tests, the performance of the soil composite can be evaluated in terms of shear strength, compaction characteristics, and load-bearing capacity, allowing for informed decisions regarding its utilization in various engineering fields. The inclusion of PET plastic waste in the sand specimen enhances the shear strength of the composite, leading to an increased bearing capacity of the soil. This results in a reduction in the width of the foundation, making construction more cost-effective. However, it should be noted that excessive inclusion of PET plastic waste can decrease the shear strength of the sand-PET plastic composite, necessitating a more comprehensive foundation and increasing costs [6]. Therefore, reinforcing sand with PET plastic waste flakes can improve the bearing capacity of sandy soil and reduce the required foundation width, resulting in cost savings compared to using unreinforced sand [17]. PET plastic waste, in this manner, also contributes to environmental sustainability by reusing the waste material and reducing the amount of plastic sent to landfills. Further improvements in the particle grading and stabilization of the composite could enhance its shear strength.

Furthermore, exploring the potential application of the composite in construction materials, such as in the production of bricks or blocks, shows promise. To analyze the behavior of soil reinforced with PET plastic waste, the CBR test was conducted as part of this research. The findings suggest that the sand-PET plastic waste composite material may find application in flexible pavement, cycle paths, or footpath design, as the obtained CBR values indicate suitability for these purposes. Based on this study's results (including 5, 10, and 15 % PET plastic waste flakes by weight in the sand), the CBR values were increased to 6.8, 8.0, and 5.5 %, respectively. For instance, in the case of poorly graded sandy soil in the subgrade layer, unreinforced sand with a CBR value of 6.3 % and the 5.0 % sand-PET plastic waste composite with a CBR value of 6.76% are suitable. The 10 % sand-PET plastic waste composite with a CBR value of 8 % is suitable for poorly graded and well-graded sandy soils in the subbase layer.

Similarly, the 15 % sand-PET plastic waste composite with a CBR value of 5.5 % is suitable for both categories of sandy soil in the subgrade layer. This suggests that the sand-PET plastic composite could potentially serve as a material for the subgrade layer in flexible pavement construction. However, conducting field trials and evaluating its performance in real-world conditions is advisable before considering widespread application for subgrade material in major road projects. Biotechnical stabilization, also known as bio-stabilization, is a method employed to control soil erosion and protect slopes. It involves using mechanical structures and biological elements such as plants [24].

The technique is commonly employed for slope stabilization, riverbank protection, and reinforcing embankments along railways and highways. The sand-PET plastic waste composite, studied in this research with a PET plastic waste content of 15 % by weight, shows potential for use as a material for slope stabilization. It can be employed with tree planting on the slope surface, ensuring the tree roots are positioned beneath the composite layer in soil rich in organic matter. This approach enhances slope stability by combining the mechanical reinforcement provided by the composite with the biological reinforcement from the plant roots. The sustainability of a system is gauged by its ability to maintain functionality over time, which necessitates that the system's capacity surpass its demands. This principle applies to various systems, encompassing social, economic, environmental, and engineered systems. Achieving sustainability in a project involves integrating these diverse systems to guarantee long-term viability [25].

6 Conclusions

Ensuring the sustainability of a structure is imperative, considering the depletion of natural resources attributed to urbanization. To overcome this challenge, it is essential to introduce new eco-friendly materials and advocate for the reuse of waste materials.

We can promote sustainable construction practices by employing PET plastic waste to reinforce low-quality sands. This approach aligns with sustainability principles, encompassing engineering, economic, social, and environmental considerations.

Prioritizing sustainability should be integral at every project stage, commencing from the initial planning and design phases, continuing through the construction process, and extending throughout the operational lifespan of the infrastructure. Integrating sustainability into all facets of the project can minimize the long-term environmental, economic, and social impacts, culminating in a more sustainable and resilient infrastructure.

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