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Influence of Recycled PET Particle Size on the Improvement of Sandy Subgrades for Flexible Pavements

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Abstract **-** This study evaluates the influence of recycled PET particle size on enhancing sandy subgrades for flexible pavements. A soil classified as poorly graded sand with silt and gravel (SP-SM) was treated with crushed PET in proportions of 2%, 5%, and 7% to examine its impact on load-bearing capacity. Modified Proctor and CBR tests were conducted to analyze changes in the soil's mechanical properties, revealing that adding 5% PET increased the CBR Index to 15.2% at 95% MDS, an 83.1% improvement compared to natural soil. However, with a 7% PET addition, the CBR was 9.6% at 95% MDS and 15.8% at 100% MDS, showing a decrease in load-bearing capacity likely due to excessive particle interference within the soil matrix. These findings highlight that both PET dosage and particle size are critical for optimizing subgrade performance. This research provides an innovative and sustainable solution for reinforcing granular soils in pavement structures, supporting the reuse of plastic materials in civil engineering applications.

Keywords**:** soil improvement, recycled PET, sandy subgrade, flexible pavements, load-bearing capacity.

1. Introduction

Sandy soils, characterized by their low cohesion and bearing capacity, often exhibit a reduced friction angle, which directly impacts their use as subgrade in pavements. This composition limits the stability and strength of the subgrade, increasing its susceptibility to deformations that compromise structural integrity and reduce the service life of flexible pavements [1]. To mitigate these issues, the incorporation of shredded PET into the subgrade is proposed as an innovative alternative to optimize the mechanical properties of sandy soil.

Previous studies have extensively documented the benefits of recycled PET as a reinforcement material, particularly in sandy soils. Experimental investigations have demonstrated that the addition of shredded PET, with particle sizes ranging between 4.750 mm (No. 4 sieve) and 0.075 mm (No. 200 sieve), in proportions of 5%, 10%, and 15%, enhances the California Bearing Ratio (CBR) of sandy soils. Results showed a maximum increase of 52% in the CBR when 10% PET was used compared to natural soil. This improvement was attributed to the PET particles facilitating interaction between the soil and reinforcement, enhancing both cohesion and internal friction of the material [2]. This empirical evidence confirms the effectiveness of PET as a stabilizing agent, improving the mechanical behavior of the soil and promoting environmentally sustainable construction practices.

Experimental studies have corroborated the effectiveness of recycled PET as a reinforcement in sandy soils through triaxial and plate load tests. The inclusion of different PET proportions resulted in significant improvements, evidenced by a 23% increase in the internal friction angle and a 35% increase in load-bearing capacity [3]. Results demonstrated that PET not only enhanced soil strength but also reduced settlements and favorably modified the failure mechanism, transitioning from brittle to ductile behavior [3].

Additional research evaluated the impact of PET in sandy soils through unconfined compression and drained triaxial tests. Results showed that the addition of 0.5% by weight of PET increased unconfined compressive strength by 70% and strength in drained triaxial tests by 40% [4]. This improvement was attributed to the action of PET fibers as discrete reinforcements, redistributing stresses and increasing the soil's energy absorption capacity. Additionally, the fibers improved ductility, making the soil more resistant to sudden failure under load [4].

Parallel experimental studies have strongly corroborated the efficacy of recycled PET as a reinforcement material in sandy soils. Laboratory results demonstrated that the optimal incorporation of PET strips (20 mm in length at 1.5%) led to substantial increases in mechanical properties, evidenced by a 92.8% increase in unconfined compressive strength and a 66.4% increase in cohesion, as well as more ductile behavior under high stress levels [5]. This effectiveness was further validated through dynamic tests on a shaking table and cyclic direct shear tests, which confirmed that PET strips (0-1%) optimize deformability and energy absorption under low pressures, while increasing stiffness under high pressures due to the stretching and sliding mechanisms of the fibers working mainly in tension [6].

This study proposes evaluating a soil classified as poorly graded sand with silt and gravel (SP-SM), corresponding to an A-1-b (0) classification according to AASHTO, which is considered an excellent subgrade material. This soil will be modified by incorporating shredded PET in proportions of 2%, 5%, and 7%. The experimental characterization will include standardized tests for particle size distribution, moisture content, modified Proctor, and California Bearing Ratio (CBR), conducted under ASTM and MTC guidelines. Furthermore, the study offers an innovative approach by analyzing how the particle size of recycled PET influences the improvement of granular soils, thereby contributing to the solution of specific geotechnical problems.

2. Materials and Method

2.1. Materials

- **Granular Soil**

The study material corresponds to a granular soil classified as poorly graded sand with silt and gravel (SP-SM). This soil was selected due to its deficient geotechnical characteristics, which require optimization for its application as subgrade in pavement structures.

- **Shredded Polyethylene Terephthalate (PET)**

The granulometry of the recycled shredded PET used as reinforcement material shows a distribution where 79.13% corresponds to particles retained on the No. 20 sieve (0.85 mm), 15.23% on the No. 40 sieve (0.425 mm), and a residual fine fraction of 3.51% retained on the No. 60 sieve, with smaller percentages in subsequent sieves. This specific granulometric characterization was selected to evaluate its influence on the mechanical behavior of the modified soil.

2.2. Methodology

An experimental design was employed to evaluate the effect of shredded recycled Polyethylene Terephthalate (PET) particle size on the mechanical properties of granular soils used as subgrade.

A representative soil sample was extracted from a depth of 1.5 meters through a test pit (C-01) located on Av. Huayna Capac, in the district of San Juan de Lurigancho, Lima. Physical characterization tests revealed, through granulometric analysis (ASTM D6913) [3], a composition of 40.15% gravel, 50.32% sand, and 9.53% fines. Atterberg limits (ASTM D4318) [4] classified the soil as non-plastic (NP), while the natural moisture content (ASTM D2216) [5] was 3.5%. The soil was classified according to the Unified Soil Classification System (USCS) (ASTM D2487) [6] as SP-SM (poorly graded sand with silt and gravel) and according to AASHTO (ASTM D3282) [7] as A-1-b (0).

The recycled PET used, with a density of 1.38 g/cm³, exhibited a granulometric distribution where 79.13% of particles were retained on the No. 20 sieve (0.85 mm), followed by 15.23% retained on the No. 40 sieve (0.425 mm), and a reduced presence of fines corresponding to 3.51% on the No. 60 sieve (0.25 mm), with smaller percentages on subsequent sieves. This specific particle size distribution, along with the irregular shape and rough surfaces of the shredded PET, was strategically selected to enhance mechanical interaction with soil particles and evaluate its effectiveness as an improvement material.

The selected PET percentages (2%, 5%, and 7%) are based on the research of Ortega and Capcha (2023), who demonstrated significant improvements starting at 2%. This percentage was maintained as the minimum value, the maximum was increased to 7% to explore new limits, and 5% was established as an intermediate point to analyze the improvement trend.

For the Modified Proctor tests (ASTM D1557) [8], 24,000 grams of base soil were used, incorporating 480 g, 1,200 g, and 1,680 g of PET for the respective dosages. This phase determined the maximum dry density and optimum moisture content for each soil-PET mixture. The California Bearing Ratio (CBR) tests, conducted according to ASTM D1883 [9], used 15,000 grams of base soil with additions of 300 g, 750 g, and 1,050 g of PET for the established percentages. For each CBR test, three specimens were prepared, compacted at different energies (56, 25, and 12 blows per layer), and their behavior was evaluated under both natural and saturated conditions after four days of immersion.

3. Results

The results obtained from the tests conducted on soil samples improved with shredded PET in different proportions (2%, 5%, and 7%) to evaluate bearing capacity are presented in the following tables and graphs. These results allowed the assessment of the soil's bearing capacity using the CBR Index, as well as the dry density and optimum moisture content through the Modified Proctor test.

3.1 Results of the modified proctor test

The results of the Modified Proctor test show the maximum dry unit weight and the optimum moisture content for both the natural soil and the soil improved with different proportions of PET. These parameters are essential to understand how the addition of PET affects the soil's compaction properties.

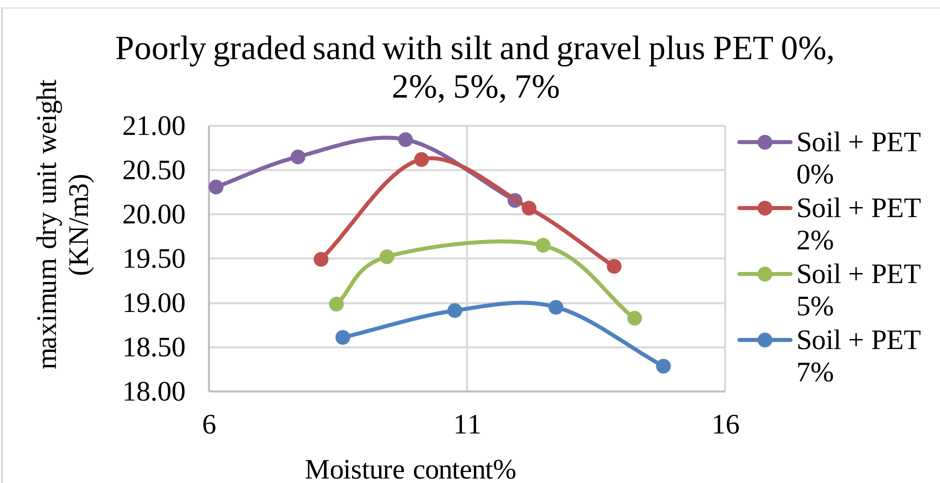

Fig. 1: Compaction curve graph of the natural soil mixture with the inclusion of recycled PET in percentages of 2%, 4% and 7%.

Table 1: Compilation of the modified proctor test of the soil without pet and with the inclusion of pet at 2%, 5% and 7%

Sample	Modified Proctor Test		
	Maximum Dry Density		Optimum Moisture Content (%)
	KN/m3	g/cm3	
Natural soil	20.86	2.126	9.5
2% PET	20.61	2.101	10.2
5%PET	19.86	2.024	11.1
7%PET	18.99	1.936	12

3.1 CBR index for natural soil and soil improved with pet

The CBR Index values obtained for the untreated soil and the soil improved with shredded PET in dosages of 2%, 5%, and 7% are presented. The results showed an improvement in the soil's bearing capacity with the incorporation of PET, confirming the positive influence of this material on the soil's mechanical performance.

Table 2: Compilation of the cbr test of the soil without pet and with the inclusion of pet at 2%, 5% and 7%

Sample	CBR (95% of MDS and 0.1" penetration)	CBR (100% of MDS and 0.1" penetration)
Natural soil	8.3%	13.2%
2 % PET	12.6%	19.9%
5% PET	15.2%	22.8%
7% PET	9.6%	15.8%

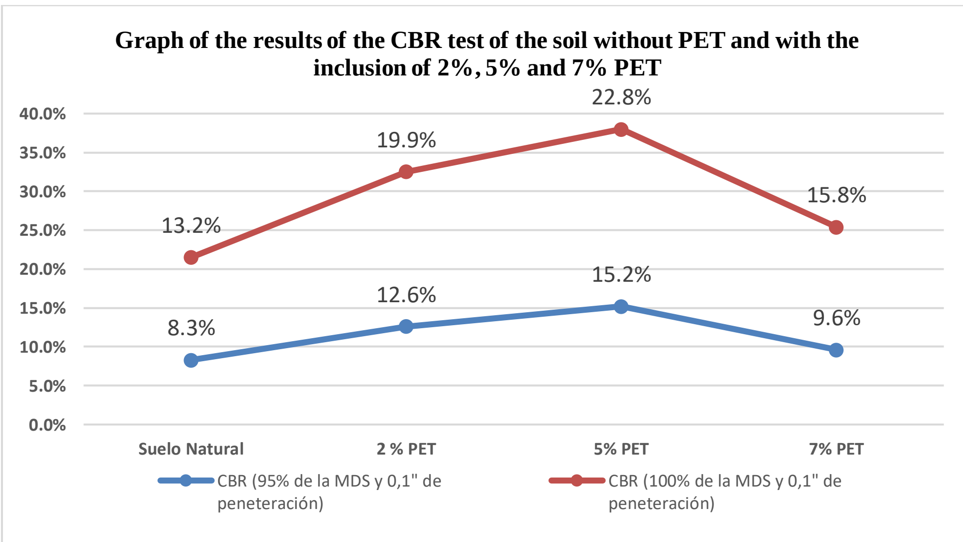

Fig. 2: Graph of the results of the CBR test of the soil without PET and with the inclusion of 2%, 5% and 7% PET

4. Analysis of results and validation

The laboratory tests systematically validated the effect of shredded recycled PET on subgrade soil improvement. The Modified Proctor test results showed a decreasing trend in maximum dry density as the percentage of PET increased, starting at 2.126 g/cm³ for natural soil and decreasing to 1.936 g/cm³ with the addition of 7% PET. This reduction is primarily attributed to the lower specific density of PET (1.38 g/cm³) compared to soil particles. Simultaneously, a progressive increase in optimal moisture content was observed, ranging from 9.5% in natural soil to 12% with the maximum PET addition, indicating a higher water demand to achieve optimal compaction of the composite material.

4.1 Influence of particle size distribution in shredded pet

A key factor influencing the results of this study, compared to the reference article, is the particle size distribution of the PET used. In this study, the shredded PET exhibited a specific gradation that may have favored better interaction and interlocking with soil particles, resulting in significantly higher CBR values with only 7% addition. Conversely, the article by Suthar et al. (2024) does not report details on the PET's particle size distribution, which may have required a higher addition percentage (up to 10%) to achieve relatively lower maximum CBR values. This suggests that careful selection of the size and shape of shredded PET particles is crucial when stabilizing soils with this recycled material. Optimizing the PET particle size distribution could yield more pronounced mechanical improvements with less material addition, offering significant technical and economic benefits. Future studies should evaluate the effect of varying PET particle size ranges on the performance of reinforced soil to determine the optimal distribution that maximizes stabilization efficiency.

4.2 Comparison of results with the reference article

When comparing the results of this study with the reference article by Suthar et al. (2024), significant differences in CBR values are observed. While the article achieved a CBR of 6.8% with 5% PET and 8.0% with 10% PET, this study obtained much higher results with only 7% PET, reaching 9.6% CBR at 95% MDD and 15.8% CBR at 100% MDD.

These differences may be attributed to variations in the base soil characteristics and, primarily, to differences in the size and shape of the PET particles used in each study. The article notes that as PET content increases, dry density decreases, a trend also observed in this study. These notable differences in mechanical performance may partly stem from variations in the base soil characteristics used in each study. However, a key factor likely influencing the results was the differences in the size and shape of the PET particles employed.

4.3 Final remarks on the effect of shredded pet in subgrade soil

The study results revealed that incorporating shredded PET significantly impacts the mechanical properties of subgrade soil, with an optimal 5% PET content maximizing CBR improvement, reaching a value of 15.2% at 95% MDD, representing an 83.1% increase compared to natural soil. This improvement is attributed to various mechanisms, including the reinforcement effect of PET particles and their contribution to better stress distribution within the soil matrix. However, significant limitations were observed when PET content exceeded 5%, leading to reduced bearing capacity, dropping to 9.6% with 7% PET. This performance decline is associated with excessive interference from PET particles within the soil matrix, negatively impacting density and bearing capacity.

From a practical perspective, this improvement technique offers a sustainable solution for subgrade reinforcement while contributing to plastic waste reduction. However, its successful implementation requires rigorous dosage control and mixing processes to ensure uniformity and optimal performance of the improved material. The significant improvement in bearing capacity justifies this technique's implementation, provided specific quality control protocols are established and followed during field application.

5. Conclusion

- Adding 5% shredded PET was the most effective, achieving an 83.1% increase in the CBR Index compared to natural soil. This translates to a considerable improvement in the soil's bearing capacity.
- Increasing PET content to 7% resulted in reduced bearing capacity, attributed to excessive interference from PET particles in the soil, particularly evident at 100% MDD (Maximum Dry Density).
- The findings of this study align with those of Suthar et al. [1], who also reported significant improvements in CBR Index by incorporating recycled PET in proportions of 5%, 10%, and 15%.
- However, in this study, the optimal PET proportion was 5%, contrasting with the 10% identified by Suthar et al. [1]. This suggests that the ideal PET proportion may vary depending on the specific soil characteristics and particle size range used.
- Additionally, while Suthar et al. [1] used PET with a size range of 0.075 mm to 4.750 mm, this study focused on a single shredded PET sample with particles distributed in a similar range, emphasizing the importance of further exploring the impact of particle size.
- The results highlighted the need for proper dosage and careful selection of PET particle size to balance strength and compatibility, ensuring the improved soil's optimal performance.

- The technique used offers a sustainable solution by reusing plastic materials that would otherwise be discarded, contributing to more environmentally friendly road engineering practices aligned with sustainable development goals.
- This study demonstrated that incorporating recycled PET in sandy subgrades significantly improves the soil's mechanical properties, underscoring its relevance for flexible pavement applications.
- It is essential to investigate how variations in PET particle size affect mechanical behavior in different soil types.
- Exploring combinations of PET with other stabilizers is also suggested to identify synergies that optimize its effectiveness in subgrade improvement

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