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Experimental study of high plasticity clays reinforced with mixtures of plastic waste and lime in flexible pavement subgrades

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ABSTRACT: The amount of plastic waste in the environment is increasing steadily, leading to the rise in the use of improper disposal methods such as open burning. Consequently, associated environmental and pollution issues are observed. This situation is exacerbated by the absence of a deeply ingrained recycling culture in Peru and the limited implementation of circular economy principles. Using controlled compaction or soil stabilization through the addition of stabilizing agents such as cement, lime, fly ash, bitumen, tar, etc., improves the capacity of weak subsoil. However, these additions are not always viable or economical. Consequently, this study aims to experimentally evaluate mixtures of residual polyethylene terephthalate (PET) plastics with lime in tropical clays from Pucallpa, located in eastern Peru, to enhance their mechanical properties and thus promote the use of PET plastics in subgrades. A crushed PET layer of width of 1–2 mm at 2.5% by weight is used in the study experiments. Tests are conducted for evaluating physical characterization, modified Proctor compaction, California Bearing Ratio (CBR), unconfined compression, and resilient modulus. The results indicate that the addition of low PET content to clays improves their mechanical behavior; thus, it is concluded that the PET-lime mixture can be used in flexible pavement subgrades.

KEYWORDS: Clay, lime, PET, resilient modulus, soil reinforcement.

1. INTRODUCTION

Currently, the production of solid waste, especially plastic waste, is adversely impacting the environment. To resolve this issue, research and development of plastic alternatives and plastic waste reuse are being pursued, particularly in the field of geotechnical engineering, such as in the works of Peddaiah (2018), Hassan et al. (2021), Mishra & Kumar (2023), among others.

The presence of clay soil in the subgrade of a pavement can cause deformations that affect the quality of the pavement, leading to issues such as sinkholes or cracks in the road. These complications are mainly attributed to the high plasticity of clay soil, its sensitivity to moisture changes, and its expansive behavior. Clays are soils that mainly comprise fine and highly cohesive particles; thus, during pavement construction processes, it is challenging to manipulate and compact these soils. However, these difficulties can be overcome through appropriate soil stabilization using various methods, which, if implemented appropriately, can enable soils to acquire valuable and useful long-term properties.

The inclusion of PET in these soils emerges as a promising alternative, given that PET is an inert, resistant material with good chemical stability; more importantly, it enhances the mechanical properties of soils for soil stabilization purposes. Its application in road construction and design primarily aims to improve the load-bearing capacity, shear strength, and soil deformability of soils, resulting in increased road durability. Furthermore, crushed PET presents advantages such as resistance to chemical degradation and water absorption.

By using crushed PET, the need to extract and utilize natural materials for enhancing the mechanical properties of soils is reduced, implying less resource exploitation and a decrease in associated environmental impacts. Additionally, the use of this recycled material contributes to appropriate management of plastic waste, promoting circular economy principles and reducing the amount of plastic waste disposed in landfills.

In contrast, soils that have undergone chemical stabilization, wherein chemical additives such as hydrated lime (1%-8%) are used as stabilizers for clayey soil, respond positively when combined with soils reinforced with PET (hereinafter referred to as "PET-reinforced soils"). The use of lime as a stabilizer chemically transforms PET-reinforced soils into usable soils, improving their mechanical properties such as compression strength and load-bearing capacity, while also reducing their plasticity index, thus enhancing resistance to atmospheric agents, and reducing permeability.

In this context, this study aims to experimentally evaluate the mechanical behavior of clayey soil extracted from the city of Pucallpa, Callería district and compare it with two mixtures: mixture 1 (clay + 2.5% PET) and mixture 2 (clay + 2.5% PET + 1.5% lime). The percentage of crushed PET was chosen based on previous research (Álvarez et al., 2019; Hassan et al., 2021; Mishra & Kumar, 2023), that used percentages below 4% and yielded optimal results for percentages between 2%–3%, while the percentage of hydrated lime was chosen based on the recommended CE-020 standard. The purpose of this study was to determine whether there is an improvement in soil behavior due to the integration of PET and lime that can be applied in the design of road subgrades, thus contributing to relevant knowledge for assisting future road works in the region.

2. MATERIALS

2.1. Clay

The clay selected for this study is sourced from the central east region of Peru, specifically, from the Amazon rainforest, Ucayali department, city of Pucallpa, Callería district, Coronel Portillo province. The study area is located on a river terrace used for agriculture, at an altitude of 154 meters above sea level, and experiences a warm tropical climate throughout the year. The term "Pucallpa" comes from Quechua words "puca" and "allpa," that translate to "red earth." This name is due to the distinctive color of the predominant clayey soils in the region, that have a pH of 5.11. The soils exhibit a reddish hue due to the minerals present in their composition. The acidity of these soils is evidenced by the presence of aluminum oxide ($Al2O3$), while its coloration is due to iron oxide ($Fe2O3$) (López & Quevedo, 2022). Samples were dried to facilitate the disintegration process for physical characterization and PET-lime mixture analyses.

2.2. PET

The crushed PET used was obtained from non-biodegradable plastic, primarily from bottles, that are currently reintegrated into various economic processes for reuse as raw material. Despite being an inert material, the crushed material may contain biological residues and/or contaminants that could affect soil quality. Consequently, the polymer was washed before use. Subsequently, the crushed PET ranging from 1-2 mm (in fiber and powder forms) was used at a concentration of 2.5% by weight relative to the dry weight.

2.3. Lime

Hydrated lime, containing Road Lime (CaO), is a non-regulated product known for its highly alkaline pH, ranging between 11 and 12. In terms of its chemical properties, its purity is maximum at 39.9%, with a calcium carbonate ($CaCO3$) percentage of <25.00%. Additionally, it contains silicon dioxide ($SiO2$) in a concentration of <12.00%, magnesium oxide (MgO) < 2.00%, aluminum oxide ($Al2O$) below 0.05%, and iron oxide ($Fe2O$) in quantities less than 0.05%. Regarding its physical properties, the retained particle size on a #70 sieve (212 µm) is maximum at 20.0%, and its specific gravity is 2.15 g/cm^3. It is worth noting that, due to its Road Lime content (40% purity), only the fraction of lime that effectively reacts with the clayey soil was used in the research. Figure 1 depicts the clay, crushed PET, and lime used for the tests

2.4. Mixtures

The clayey soil was mixed in two different proportions: the first included only 2.5% PET and the second included a mixture of 2.5% PET and 1.5% lime. Table 1 summarizes the materials used for each mixture

Table 1: Soil and Mixtures Characteristics.

Material	Clay (%)	PET (%)	Lime (%)
Clay	100	0	0
Mixture 1	97.5	2.5	0
Mixture 2	96	2.5	1.5

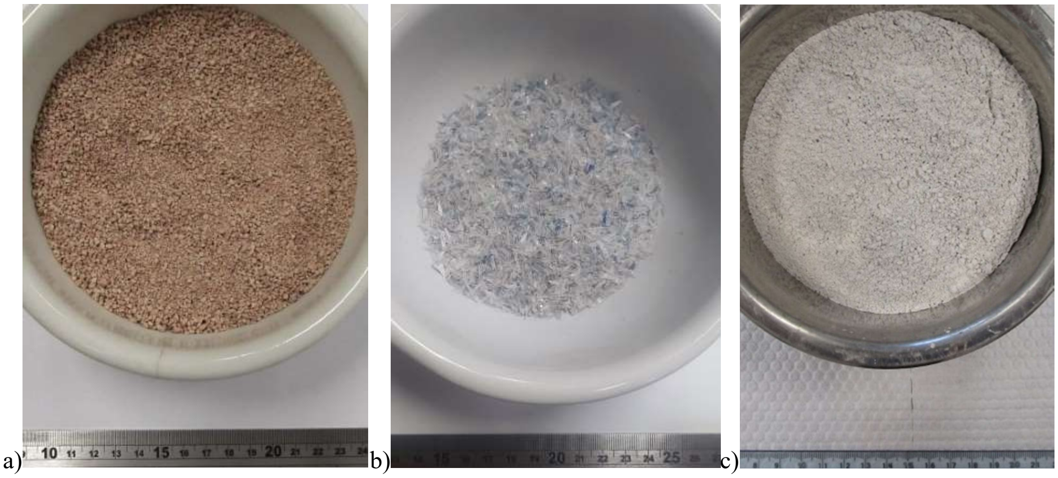

Figure 1: a) Clay from Pucallpa, b) Crushed PET and c) Hydrated lime.

3. EXPERIMENTAL PROCEDURE

The Atterberg limits were determined according to ASTM D4318, while the specific gravity of solids (Gs) was measured following ASTM C128. Additionally, a granulometric analysis was conducted following ASTM D422.

Modified Proctor compaction tests were performed on the natural soil and the soil samples containing the different mixtures in accordance with ASTM D1577. Method A was used, that employs a soil with a maximum nominal particle size of 4.57 mm and a compaction energy of 26996 kN-m/m³, achieved using a standard 2.5 kg hammer dropped from a height of 304.8 mm. This method results in a controlled effort simulating compaction conditions that the soil would experience in the field under static or dynamic loads. It allows for obtaining a compaction curve showing how the dry density of the soil varies with different moisture content levels.

The California Bearing Ratio (CBR) value is a mechanical parameter expressing the ability of a compacted soil to withstand axial loads. Initially, it involves determining the ratio between the pressure required to produce a piston penetration in the compacted sample and comparing it to the pressure required to produce the same penetration (in inches) in a granulometrically stabilized crushed stone according to ASTM D1883. The test for obtaining the CBR was conducted on the three study samples to determine the optimal size and dosage of PET as a subgrade reinforcement material. The samples were compacted in the laboratory at the optimal moisture content and different compaction levels. This method involved preparing three compacted soil samples with different compaction energies of five layers of soil compacted with 12, 25, and 56 blows per layer. Subsequently, the molds were clamped, disassembled, and reassembled in reverse. Subsequently, they were submerged in water for a period of 4 days (96 hours) to determine their expansion using a dial gauge tripod. Finally, the sample was removed from the water for drying, and pressure was applied to the penetration piston using the CBR press, recording the readings of the penetration pressure curve.

The CBR is commonly used in roadworks in Peru, where pavement thickness design based on traffic is determined based on this value. However, for determining the pavement thickness, the resilient modulus value is the most appropriate methodology to be used because it considers the actual cyclic loads to which the soil is subjected.

Currently, the most commonly used test procedure used to determine the resilient modulus (Mr) of base and subgrade pavement materials is the American standard AASHTO T 307-99, that uses variable confinement stresses. Monzón (2012) reported that samples compacted statically, compared to those compacted by the kneading technique, generated higher Mr values. Therefore, a HiKOKI vibratory hammer was used to perform the resilient modulus test by the cyclic triaxial equipment UTM 30-PV70B12/I12 manufactured by the company IPC Global, with dimensions of 2750 × 920 × 900 mm.

The resilient modulus is one of the main mechanical input parameters for characterizing fine and coarse granular materials and for designing pavements using mechanistic-empirical design methods. Tanimoto and

Nishi (1970) introduced the term resilient modulus as the ratio between the magnitude of cyclic deviator stress in triaxial compression ($q = \sigma1 - \sigma3$) and the recoverable (elastic) axial deformation.

Unconfined compressive strength tests were conducted on samples at a one percent per minute axial strain rate according to ASTM D2166. This test was used to determine the ultimate load that a soil could withstand under conditions of axial load without lateral confinement. This ultimate load indicated the shear strength of the soil samples and provided a conservative estimate of the maximum load that could be applied before soil collapse or failure occurs.

4. RESULTS AND DISCUSSION

4.1. Soil Characterization

For the clay, it was found that the Liquid Limit (LL) was 58, Plastic Limit (PL) was 25, and Plasticity Index (PI) was 33, verifying that the clay had high compressibility according to the plasticity chart. For Mixture 2, that contained lime, a decreasing trend in PI was observed from the obtained results. The inclusion of lime in the clay produced a change in the internal structure of the sample because lime accelerated the drying process of the clay, resulting in a reduction in plasticity.

Table 2 shows the results of the variation in the specific gravity of solids (Gs) and Atterberg limits, namely, LL, PL, and PI, of the natural soil, Mixture 1, and Mixture 2. An increase in the values of Gs and PI was observed in Mixture 2 as compared to that of the natural soil, while these values decreased in Mixture 1.

It is observed that the Gs value of Mixture 1 (2.5% PET), the Gs value decreased by 8.46% as compared to that of the natural soil; this can be attributed to the lower density of PET as compared that of the natural soil. Meanwhile, in Mixture 2 (that contained only 2.5% PET and 1.5% lime) increased by 1.15% as compared to that of the natural soil because lime acts as a binding material, promoting the interlocking of soil particles.

Figure 2 shows the particle size distribution of the natural soil, PET, and lime obtained through sieving and sedimentation tests (only for clay). According to the Unified Soil Classification System, the soil is a highly compressible clay (CH), with the following particle distribution: 10.2% sand, 38.7% silt, and 51.1% clay. The classification according to AASHTO is A-7-6 (33), that is considered a soil with poor behavior, making it ineligible for application in pavements.

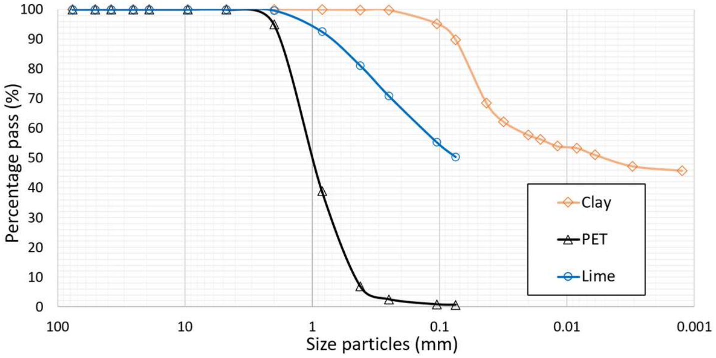

Figure 2: Particle Size Distribution.

Table 2: Specific Gravity and Atterberg Limits Results.

Material	G_s	LL	LP	IP
Clay	2.60	58	25	33
Mixture 1	2.38	69	24	45
Mixture 2	2.63	33	21	12

4.2. Modified Proctor

The results of the compaction tests are presented in Figure 3. The observed trend for both mixtures during the Proctor test revealed that an increase in the optimum moisture content led to a decrease in the dry density of the material.

The natural soil exhibited a higher degree of compaction than Mixture 1 and Mixture 2. The dry density value of the natural soil, Mixture 1, and Mixture 2 was 1.791 g/cm3, 1.758 g/cm3, and 1.698 g/cm3, respectively. The optimum moisture content of the natural soil, Mixture 1, and Mixture 2 was 15.7%, 17%, and 18.30%, respectively. These soil moisture-density curves revealed that an increase in moisture content led to a decrease in dry density, as shown by the trend line in Figure 3.

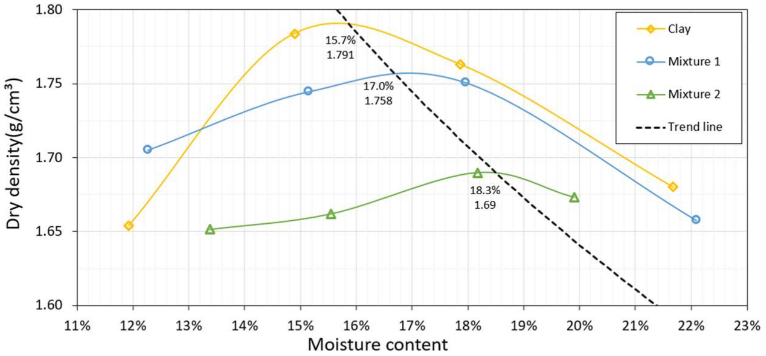

Figure 3: Compaction Test Curves.

4.3. CBR Index

Figure 4 depicts the results of the CBR test on the three soil samples with different compaction energies (55, 25, and 12 blows) for penetrations of 0.1" and 0.2". In Figure 4a, the evolution of expansion over time is represented, with minimum expansions of 6.5%, 4.6%, and 1.37% for the natural soil, Mixture 1, and Mixture 2, respectively, with a compaction energy of 56 blows per layer. It is noteworthy that Mixture 2 (2.5% PET and 1.5% lime) shows the lowest expansion at 0.39%. The inclusion of lime reduces the soil's plasticity through chemical reactions, counteracting expansion and improving stability. In contrast, the crushed PET.

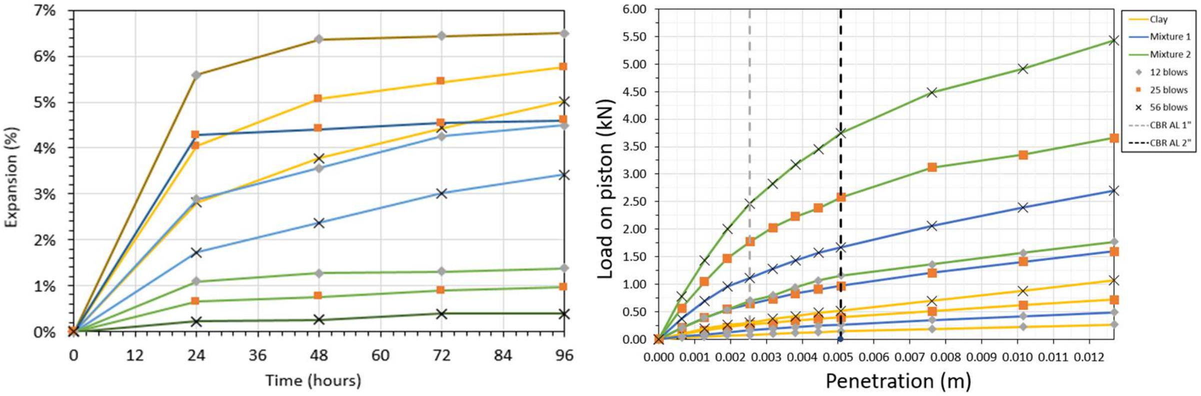

Figure 4: a) Expansion Evaluation and b) Stress vs. Penetration.

In Figure 4b, the CBR values obtained for a penetration of 0.1" (0.254 mm) for the samples are shown, being 2.25, 8.39 and 18.50 for the natural soil, Mixture 1, and Mixture 2, respectively. Additionally, it is observed that as the compaction energy increased (number of blows per layer), greater interlocking between soil particles was encouraged. This increased interaction between particles led to further reduction in soil expansion, further reinforcing its stability and structural resistance.

4.4. Resilient Modulus

Figure 5 presents the results of the resilient modulus test for the tested samples. The resilient modulus (Mr) test applied pressure variations every five cycles, with constant values of 41.4, 27.6, and 13.8 kPa, generating different Mr values that needed to be averaged. For the clay, values of 128.56, 130.96, and 138.31 MPa were obtained; for Mixture 1 (2.5% PET), the values were 146.41, 144.86, and 142.51 MPa; and, for Mixture 2 (2.5% PET and 1.5% lime), the values were 221.04, 213.12, and 220.56 MPa. These values are averaged to obtain a reference data. The resulting averages for the natural soil, Mixture 1, and Mixture 2 were 132.61, 144.59, and 218.24 MPa, respectively

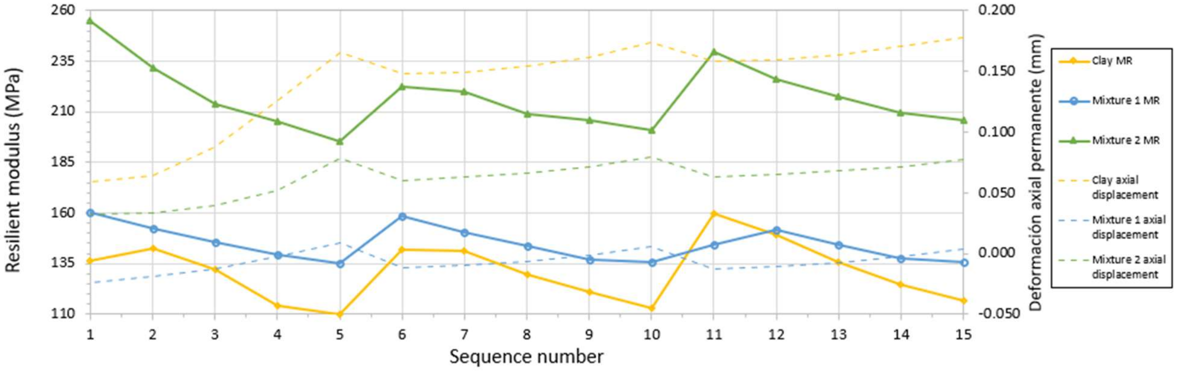

Figure 5: Variation of Mr and Deformation.

The representation of Mr is performed using trend lines, as it is not an exact value but rather a range of values that vary within a bounded range according to different variables. Thus, to observe the improvement in soil properties, the trend shows how the increase in these curves depends on the type of additive used. The highest value of Mr for different confinement pressures was obtained in Mixture 2 (2.5% PET and 1.5% lime), within a range of 210–230 MPa, as shown in Figure 6a.

Similarly, the same trend is observed regarding the improvement of Mr properties for the deviator stress; however, there is a decrease in the obtained values, as shown in Figure 6b. This is because the deviator stress directly influenced the vertical load applied through the automated piston. Consequently, greater visible deformation occurred in the tested sample, both externally (manifested in cracks and fissures) and internally (affecting the behavior and internal properties of the sample, as shown in Figure 7), that reduced the Mr values.

There was an increase of 9.04% in the Mr value for Mixture 1 and an increase of 64.57% in the Mr value for Mixture 2 as compared to that of the natural soil.

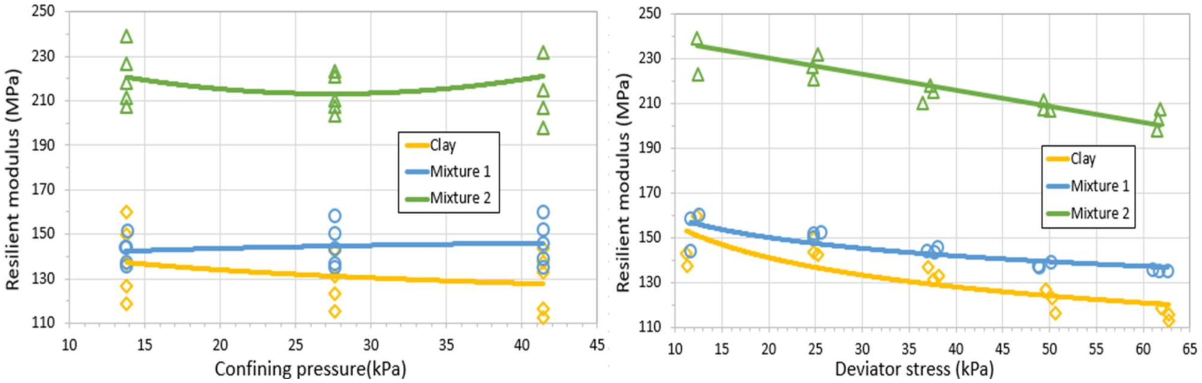

Figure 6: a) Variation of Mr vs. Confining Pressure and b) Variation of Mr vs. Shear Stress.

Figure 7: Cracks and fissures with mixture 2.

4.5. Unconfined Compressive Strenght

The unconfined compression test was repeated three times to improve the reliability of the results by averaging, as shown in Figure 8a. The values of the unconfined compression strength (qu) obtained for the natural soil, Mixture 1, and Mixture 2 were 414.5, 616.3, and 355.8 kPa, respectively, with a maximum strain (ε) of 1.82%, 4.8%, and 3.41% for each sample. From these values, the value of undrained cohesion (cu) could be extrapolated, that represented half the value of unconfined compression. Finally, the unconfined shear strength (qs) was indirectly calculated, represented by the last point on the graph when the test was completed. In the case of Mixture 1, the increase in strength occurred due to the stiffness and hardness provided by the PET, that acted as mechanical reinforcement within the clay structure when subjected to compression. In contrast, in Mixture 2, there was a reduction in strength because the drying effect of lime reduced the workability of the specimens, resulting in accelerated material failure as compared to that of Mixture 1.

In Figure 8b, the results in the Mohr circle are presented, facilitating the visualization of the value at which the failure envelope occurs. This value relates the maximum values of shear and normal stress, that is useful for assessing the sensitivity of clay behavior. The average values obtained for the natural soil, Mixture 1, and Mixture 2 were 207 kPa, 308 kPa, and 178 kPa, respectively. According to Skempton and Northey (1953), the values correspond to a “sensitive” sensitivity for the natural soil and Mixture 1, while considering the value for Mixture 2, the sensitivity is termed “insensitive”.

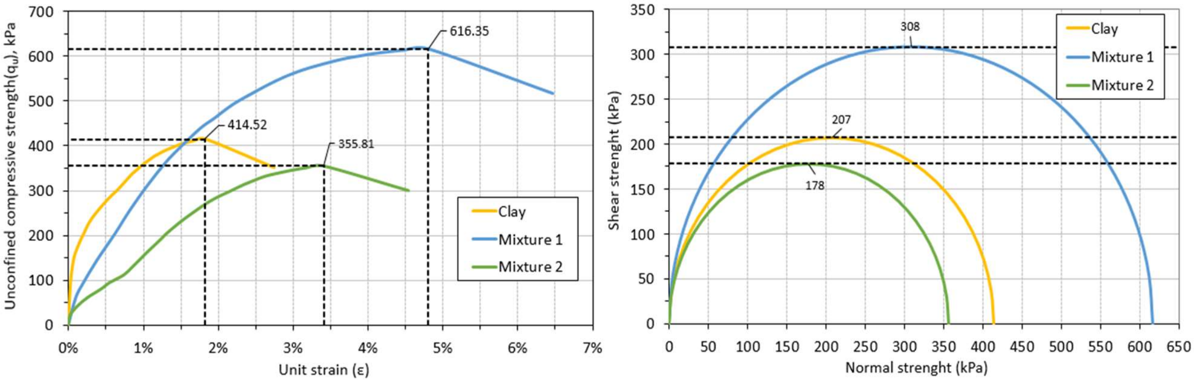

Figure 8: a) Unconfined Compressive Strength and b) Mohr-Coulomb Circles

5. CONCLUSIONS

The results lead to the conclusion that the addition of low-content crushed PET (approximately 2.5%) to a highly plastic clayey soil from the tropical city of Pucallpa modifies its properties and can be used as an alternative material for flexible pavement subgrades. Thus, mixtures of PET and the natural soil and that containing the natural soil, PET, and lime represent an alternative for stabilizing clayey soils for constructing rural roads.

Both mixtures exhibited a considerable improvement in the mechanical behavior of the soil, increasing the Mr value, consequently leading to a reduction in subgrade thickness in pavement design.

The evaluation of Mixtures 1 and 2, comprising different proportions of PET and lime, revealed that Mixture 2 (2.5% PET and 1.5% lime) exhibited the highest values in terms of the CBR, along with a notable reduction in soil expansion. Additionally, it achieved the highest penetration strength compared to other mixtures. Mixture 2 also excelled in the resilient modulus test, showing the highest values of resilient modulus in each loading sequence, as well as in shear stress and confining pressure evaluations. In contrast, Mixture 1 (2.5% PET) proved to be the next best option, suggesting that its application carries comparative advantages with respect to the natural soil, although not as pronounced as those provided by the addition of lime to the natural soil. However, it is important to note that these trends were not reflected in the unconfined compression test.

For cases where there are no confining stresses, it is recommended to use purely physical stabilization (via PET) instead of physicochemical stabilization (via PET and lime), due to the higher q_u values. Consequently, direct mechanical improvement is achieved without the need for additional chemical reaction processes. The reduction in the values for unconfined compression strength evaluated for samples with lime does not reflect improvement values as in the other properties and tests, as there is a considerable reduction in the natural soil binder due to particle agglomeration and reduction in its moisture content.

Finally, using recycled polymers (PET) as subgrade improvement provides added value because it represents a good solution for its disposal and, consequently, for mitigating the significant negative impact it currently has on the environment.

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