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Tesis

Improvement and Optimization of Mechanical Properties in Tropical Soils Using Marble Filler and Cane Ash: A Sustainable Approach for the Junín Region

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Abstract This research analyzes the impact of the incorporation of marble filler and sugarcane ash in the stabilization of tropical soils, specifically in the Central Peruvian rainforest. These soils, characterized by their high plasticity and low bearing capacity, represent a significant challenge for civil engineering. Four proportions of marble filler (3%, 6%, 9% and 12%) and sugar cane ash (1%, 2%, 3% and 4%) are evaluated in order to determine the optimum combination to improve soil strength and stability. The tests performed included granulometric analysis, determination of the plasticity index, consistency limits and mechanical property tests, such as the modified Proctor compaction tests and the CBR index. The results reveal that the combination of 6% marble filler and 2% sugarcane ash improves the bearing capacity and reduces the plasticity of the soil, obtaining a plasticity limit of 9.44%, a modified Proctor of 2.112 kg/m^3 and a CBR of 13.57%. This approach, which takes advantage of industrial and agricultural by-products, represents a sustainable and economical alternative for soil stabilization in regions with similar characteristics, providing a viable solution for infrastructure development in areas with soils of complex properties.

Keywords Tropical Soil, Marble Filler, Soil Stabilization, Sugar Cane Ash, Bearing Capacity

1. Introduction

Detailed knowledge of the properties of soils has been a crucial issue for civil engineering globally. Soils play a fundamental role in the sustainability of infrastructure, providing support and stability to buildings, pavements and geotechnical works. Globally, the variability in the physical and chemical characteristics of soils has led to the need for continuous research to ensure their proper use and improvement [1]. In addition, the pressure exerted by climate change and urban development has increased the need for sustainable techniques to improve soil properties, reducing risks such as erosion and subsidence [2]. These efforts not only seek to ensure the safety of buildings, but also to minimize the environmental impact and maximize the durability of the works.

First world countries have led research in advanced techniques for soil stabilization, adapting innovative methodologies that improve their mechanical behavior. In Europe, for example, the use of stabilizers such as lime and cement has been optimized by using industrial and agricultural wastes, contributing to more sustainable construction [3]. In North America, recent research has explored nanomaterials and polymers to improve the cohesion and strength of expansive soils by reducing their susceptibility to moisture changes [4]. These practices have been made possible through the implementation of rigorous controls and standardized regulations, allowing precise identification of soil properties and their appropriate treatment for specific applications.

In Peru, geographic diversity translates into a significant variability of soil types, which presents challenges and opportunities for civil engineering. Accurate identification of geotechnical properties is crucial to mitigate risks associated with construction, such as slope instability and collapse of structures [5]. In this context, the development of improvement techniques that take advantage of local resources and waste materials represents a unique opportunity to address geotechnical challenges in a sustainable manner. Recent studies have shown that the use of additives such as agricultural ashes and residues from industrial processes can be an effective solution to improve the mechanical properties of soils in different regions of the country [6] [7].

The Peruvian rainforest, characterized by tropical soils of high plasticity and low bearing capacity, faces significant limitations for infrastructure development. These adverse conditions require innovative approaches adapted to local geotechnical characteristics [8]. Previous research has highlighted the effectiveness of using agricultural residues, such as sugarcane ash, and industrial by-products, such as marble dust, in improving the strength and cohesion of soils in this region [9] [10]. This approach not only contributes to the sustainable development of infrastructure in the rainforest, but also promotes the valorization of waste, reducing its environmental impact [11].

The main objective of this work is to evaluate the impact of the combined use of sugar cane ash and marble filler in the improvement of the mechanical properties of tropical soils characteristic of the Peruvian rainforest. The analysis will include the determination of critical parameters such as shear strength, cohesion and bearing capacity, following international standards such as ASTM (American Society for Testing and Materials) and AASHTO (American Association of State Highway and Transportation Officials). This study seeks not only to contribute to the technical knowledge on stabilization techniques, but also to propose practical and sustainable solutions that can be replicated in other regions with similar characteristics [12]. The importance of this research lies in its potential to contribute to the development of resilient infrastructure in challenging contexts, maximizing the use of available resources and reducing the environmental impact [13].

2. Materials and Methods

The research proposal focuses on an integral analysis of the improvement of the mechanical properties of soils in the Peruvian jungle, addressing both their initial characterization and the application of innovative stabilization techniques that respond to the geotechnical needs of the region. The analysis considers the evaluation of key parameters such as granulometry, plasticity and shear strength, complemented with laboratory tests to validate the effectiveness of the methodologies used, all with a sustainable approach and adapted to the environmental and cultural particularities of the territory of the impact of marble and cane ash filler composites. The research development process is shown in Figure 1.

The soil used in this research was extracted from the province of Satipo, in the Jun ń region of Peru, a representative area of the Central Rainforest characterized by tropical soils with high plasticity and low bearing capacity. Satipo was selected because of its challenging geotechnical conditions, typical of tropical soils, which require specific treatments for stabilization and improvement. The mineralogical composition and granular structure of the soil in this region make it an ideal case study to evaluate the impact of marble and cane ash filler composites [8]. Figure 2 shows the extraction site, which allows contextualizing the geographic and environmental conditions that influence the properties of the soil studied.

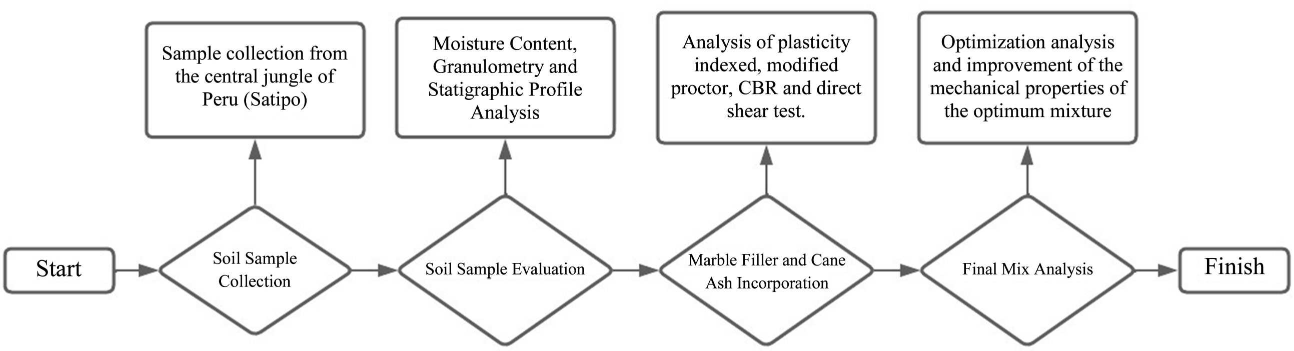

Figure 1. Research Development

Figure 2. Satipo Google Earth

A test pit is made at UTM coordinates 8755259m S and 538411m E, which ensures a precise geographical reference of the extraction, located in a representative area of the province of Satipo, in the region of Jun ń, Peru. The characterization of these soils and their stratigraphic profile is essential to establish the initial ground conditions and to evaluate the impact of the marble and cane ash filler compounds on their mechanical properties [9] [10]. This detailed analysis supports the relevance of the study in addressing the improvement of soils with complex and varied characteristics.

Figure 3 shows the stratigraphic profile of the extracted soil, classified according to the Unified Soil Classification System (USCS) as SM (silty soils or sand and silt mixtures) and SC (clayey sands or sand and clay mixtures). This analysis is carried out by means of a calicata of dimensions 1x1 meter, carefully excavated to a depth of 1.2 meters. This procedure allows a direct observation of the soil characteristics, facilitating its description and classification according to geotechnical standards. The test pit provides detailed information on the physical and mechanical properties of the soil in its natural state, an essential step to determine its behavior under different loading and treatment conditions.

The upper horizon, identified as SM, corresponds to silty sands, composed of sand and silt mixtures with the presence of gravel, located at a depth of 0.3 meters. This material presents characteristics that make it susceptible to deformation under load, which makes it a key component for analyzing the interaction with stabilizers. In the lower horizon, classified as SC, there are clayey sands, characterized by mixtures of sand and clay also with the presence of gravel, which extends from 0.3 to 1.2 meters deep. This stratum has a higher content of cohesive fines, which significantly influences its mechanical and stability properties.

2.1. Stabilizing Materials

Two main materials are used for soil stabilization in this study: marble dust and sugar cane ash. These materials are selected for their cementitious and pozzolanic properties, which have the potential to significantly improve the mechanical properties of the treated soil.

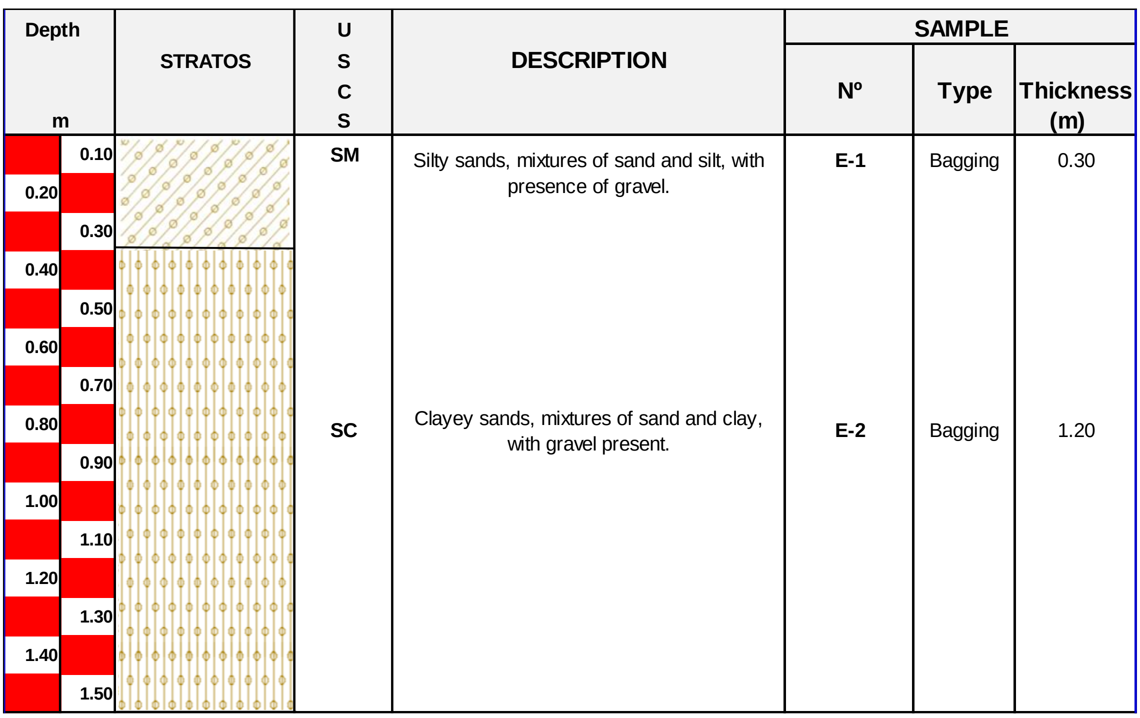

Figure 3. Soil Stratigraphic Profile of the Central Jungle - Satipo

2.1.1. Marble Filler

Marble filler is a by-product generated during the cutting and polishing process of marble blocks. This material is mainly composed of calcium carbonate ($CaCO_3$), silica, clays and alumina. Because of its cementitious properties, it is used to reduce plasticity and increase the mechanical strength of the soil [10].

In this study, marble powder obtained from the Instituto del Marmol quarry, located in Sicaya, Huancayo, Peru, is used. The proportions of marble filler considered correspond to 3%, 6%, 9% and 12% in relation to the weight of dry soil. The selection of the proportions of 3%, 6%, 9% and 12% marble filler and 1%, 2%, 3% and 4% sugar cane ash is justified on the basis of several technical and practical factors. These proportions are chosen based on previous studies indicating that moderate increases in the amount of additives significantly improve the mechanical properties of tropical soils, without compromising the economic viability of the process. In addition, the percentages selected correspond to ranges commonly used in soil stabilization research, where it is observed that, above certain thresholds, the benefits in terms of plasticity and bearing capacity tend to stabilize, suggesting that excessive doses are not necessary to achieve optimum performance. Thus, the aim is to identify the most efficient ratio in terms of cost-benefit and performance, avoiding waste of materials.

2.1.2. Sugar Cane Ash

Sugarcane ash is obtained as agricultural residue after the controlled burning of sugarcane plant waste. This material stands out for its high content of amorphous silica (SiO_2), which manifests pozzolanic properties when reacting with water and lime, promoting the formation of secondary cementitious compounds [9].

Prior to use, the sugarcane ash undergoes a screening process to ensure that the particles are less than 100 microns in size, thus maximizing its reactivity. In this study, ash proportions equivalent to 1%, 2%, 3% and 4% of the dry weight of the soil are used. The integration of this material seeks to improve the cohesion and strength of the treated soil, especially when combined with the marble filler, achieving a synergistic effect on the mechanical properties of the stabilized material. Figure 4 shows the marble filler, the ash powder and the soil from the central jungle of Peru.

Figure 4. Marble Filler and Ash Dust

2.2. Sample Preparation

Soil samples are air-dried until a constant moisture content is achieved, ensuring initial uniformity in the conditions of analysis. Subsequently, they are classified and the effects of different proportions of marble filler and sugar cane ash on their granular structure are evaluated. The procedures are performed in accordance with ASTM D6913, maintaining the technical precision required for geotechnical studies.

2.3. Soil Physical Characterization Tests

2.3.1. Granulometric Analysis

Particle size analysis is performed by sieving to determine the particle size distribution in the samples. This procedure evaluates the uniformity of the soil and the changes induced by stabilizers in its granular structure. Standard sieves are used, and the data obtained comply with ASTM D6913 specifications [14]. This analysis is essential to classify soil types and to understand the structural modifications caused by the incorporation of stabilizers.

2.3.2. Specific Gravity of Solids

The specific gravity of solids is measured using the pycnometer jar method in accordance with ASTM D854. This test provides the density of solid particles, an essential parameter for estimating soil properties such as dry density and void ratio. The determination of these parameters is critical for evaluating the viability and performance of stabilized soil in geotechnical applications [15].

2.3.3. Atterberg Limits and Moisture Content

Atterberg limits, including liquid limit, plastic limit and plasticity index, are determined according to ASTM D4318 specifications. These tests make it possible to evaluate the plasticity and cohesion of the soil as a function of moisture content, as well as the changes induced by stabilizers [16].

The plasticity index is calculated from the optimum moisture content of the soil and of each mixture, providing key information on the ability of the stabilized soil to maintain its cohesion and strength under varying conditions.

2.4. Soil Mechanical Properties Tests with Stabilizing Material

2.4.1. Soil Compaction (Standard and Modified Proctor Tests)

Standard and modified Proctor compaction tests are performed for each of the mixes containing different percentages of marble filler and cane ash. The objective of these tests is to identify the optimum ratio between moisture content and maximum achievable density for each mix. These tests, performed according to ASTM D698, allow evaluating the capacity of the stabilized soil to resist compressive stresses, which is essential to determine its suitability for supporting infrastructure applications, such as pavements and structures subjected to loads [17].

2.4.2. CBR (California Bearing Ratio)

The CBR test is performed to determine the bearing capacity of stabilized soil by simulating loading conditions representative of its performance as a subgrade in roads and foundations. This index measures the penetration resistance, providing an estimate of the capacity of the soil to support structural and vehicular loads. The test is performed according to ASTM D1883, applying a progressive load on a compacted sample. The CBR results obtained for each combination of materials are compared, allowing the determination of the optimum mix in terms of strength and performance, which ensures the effectiveness of the stabilized soil in its use in civil engineering [18].

Based on the tests carried out and the stabilizing materials selected, a series of mixtures of marble filler, sugarcane ash powder and tropical soil from the central jungle of Peru were made. The mixtures are prepared in different proportions of marble filler (3%, 6%, 9% and 12%) and sugarcane ash (1%, 2%, 3% and 4%), in order to evaluate the impact of each combination on the mechanical and geotechnical properties of the soil. These mixtures are subjected to laboratory tests to determine their bearing capacity, plasticity and other parameters to identify the optimum combination for soil stabilization in the region.

3. Results

Once the soil sample from the central jungle of Peru Satipo was collected, the corresponding tests were carried out independently to evaluate its characteristics and behavior. The tests performed include the determination of granulometry, plasticity limit, liquid limit, density and compactness, among others. These tests provide a detailed evaluation of the soil properties, which facilitates the identification of its suitability for construction projects and its possible improvement through stabilization with the selected materials.

3.1. Soil Physical Characterization Tests

The results obtained make it possible to accurately classify the soil and predict its behavior in engineering projects. Figures 5a and 5b correspond to laboratory tests performed on soil properties, Fig. 5a shows a particle size test, while Fig. 5b represents the specific gravity test.

(a) (b)

Figure 5. Soil Testing

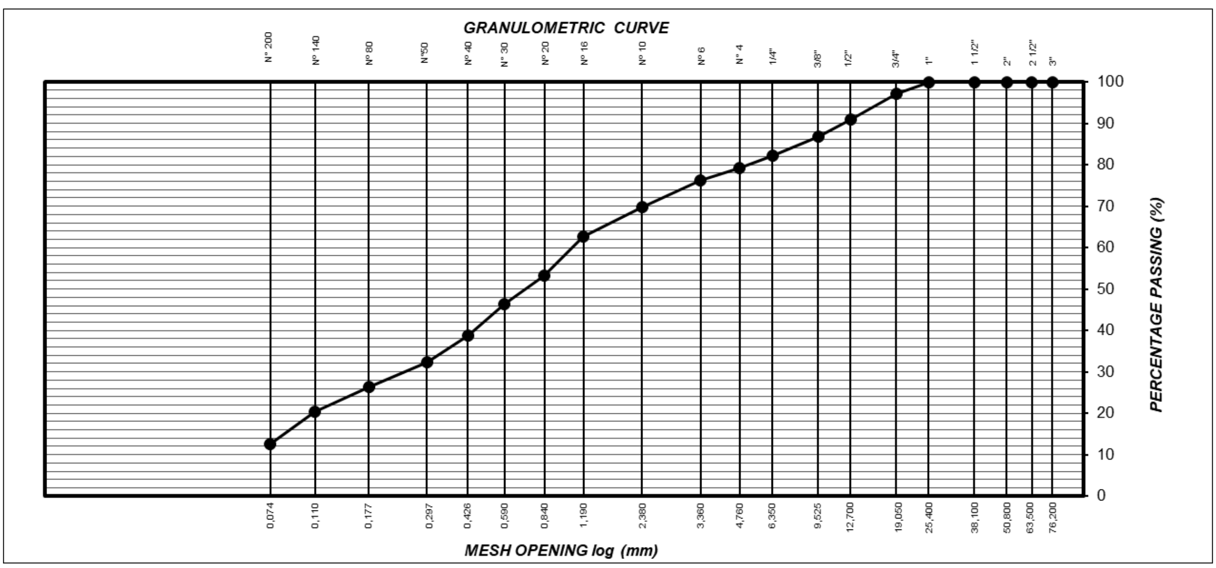

Figure 6. Granulometric curve

3.1.1. Granulometric Analysis

The results obtained from the granulometric analysis, carried out by sieving with standard sieves, indicate that the sample has 20.77% of 76.2 millimeters gravel, 66.77% of sand between sizes N°4 (4.75 mm opening) and N°200 (75 µm opening), and 12.46% of fines. These results allow classifying the soil under the USCS system as SC (cohesive soil) and under the AASHTO system as A-2-6 (0), which suggests that it is a low plasticity soil, suitable for certain engineering applications [19]. The granulometric curve obtained, shown in Figure 6, accurately illustrates the distribution of the different particle sizes.

3.1.2. Specific Gravity of Solids

The solids specific gravity test, performed at a temperature of 20 °C with a specific gravity of water of 0.99823, shows that the specific gravity value obtained for the soil sample is 1.99. The result indicates that the soil has a relatively low density compared to pure solids, which is relevant for evaluating its behavior in terms of compactness and stability [20].

3.1.3. Atterberg Limits and Moisture Content

The results obtained in the Atterberg Limits and Moisture Content test show a moisture content of 11.02%, which indicates the amount of water present in the soil in its natural state. As for the Atterberg limits [21] [22], the liquid limit is presented with a value of 36.35%, the plastic limit of 23.98% and the plasticity index of 12.37%.

3.2. Soil Mechanical Properties Tests with Stabilizing Material

3.2.1. Plasticity Index

Tests are carried out to determine the plasticity index in samples stabilized by incorporating marble filler (PDM) and sugar cane ash (CCA) in different proportions. The mixtures include combinations of soil with 3% PDM + 1% CCA, 6% PDM + 2% CCA, 9% PDM + 3% CCA and 12% PDM + 4% CCA.

Each mixture is analyzed in four replicates, obtaining an average plasticity index as the final result. In addition, a control sample without additives is included to compare the effects of stabilization. The results indicate that the plasticity index decreases progressively with increasing proportions of PDM and CCA. The control sample presents a plasticity index of 15.41%, while the stabilized mixtures show values of 12.34% for 3% PDM + 1% CCA, 9.44% for 6% PDM + 2% CCA, 7.58% for 9% PDM + 3% CCA and 4.83% for 12% PDM + 4% CCA as shown in Table 1.

Figure 7 shows the average plasticity indexes of each mixture represented in a bar graph, which clearly shows the decreasing trend of the values as the proportions of additives increase.

3.2.2. Modified Proctor

Compaction tests were carried out using the modified Proctor method to evaluate the maximum dry density of mixtures stabilized with marble filler (PDM) and sugar cane ash (CCA) in different proportions. The combinations studied include soil + 3% PDM + 1% CCA, 6% PDM + 2% CCA, 9% PDM + 3% CCA and 12% PDM + 4% CCA. Each mixture is analyzed in four replicates, obtaining an average dry density value for each case. Additionally, a control sample without stabilizers is included to establish a reference point.

The results obtained show that the dry density initially increases with the addition of PDM and CCA as shown in Table 2, reaching a maximum with the 6% PDM + 2% CCA mixture, which registers an average value of 2.112 kg/m³. The control sample presents a value of 1.812 kg/m³, while the other mixtures report values of 1.831 kg/m³ for 3% PDM + 1% CCA, 2.010 kg/m³ for 9% PDM + 3% CCA, and 2.037 kg/m³ for 12% PDM + 4% CCA. These data reflect that the 6% PDM + 2% CCA ratio is the most effective in improving soil dry density, highlighting its potential for compaction applications in civil engineering.

Figure 8 illustrates the dry density averages of each mix in a bar graph, allowing to visually observe the variations and the optimum compaction trend with the stabilizers.

Table 1. Plasticity index sample results

TESTS	SAMPLE 01	SAMPLE 02	SAMPLE 03	SAMPLE 04	AVERAGE
CONTROL SAMPLE	15.14%	15.78%	15.01%	15.69%	15.41%
SAMPLE + 3 % PDM + 1% CCA	12.24%	12.39%	12.04%	12.69%	12.34%
SAMPLE + 6 % PDM + 2% CCA	9.44%	9.17%	9.78%	9.37%	9.44%
SAMPLE + 9 % PDM + 3% CCA	7.24%	7.77%	8.19%	7.11%	7.58%
SAMPLE + 12 % PDM + 4% CCA	4.87%	5.01%	4.27%	5.18%	4.83%

Note: Marble Filler (PDM); Sugar Cane Ash (CCA)

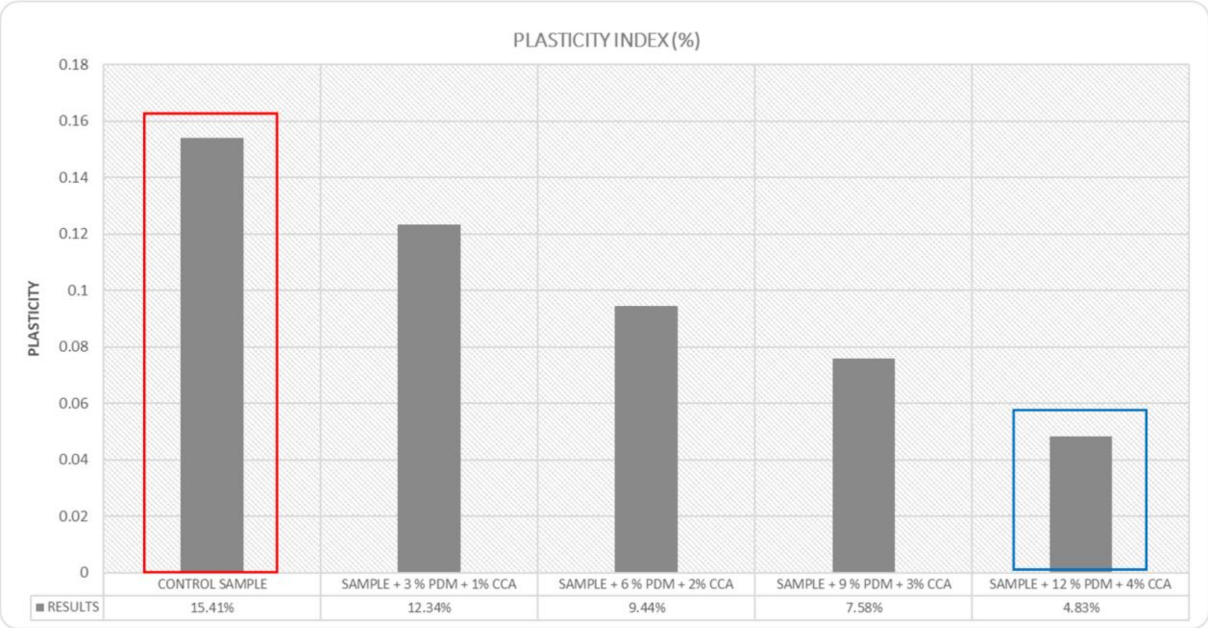

Figure 7. Plasticity Index

Table 2. Modified proctor sample results (kg/m^3)

TESTS	SAMPLE 01	SAMPLE 02	SAMPLE 03	SAMPLE 04	AVERAGE
CONTROL SAMPLE	1.854	1.734	1.812	1.848	1.812
SAMPLE + 3 % PDM + 1% CCA	1.832	1.851	1.821	1.818	1.831
SAMPLE + 6 % PDM + 2% CCA	2.135	2.124	2.052	2.137	2.112
SAMPLE + 9 % PDM + 3% CCA	1.965	1.972	2.055	2.046	2.010
SAMPLE + 12 % PDM + 4% CCA	2.038	1.993	2.067	2.050	2.037

Note: Marble Filler (PDM); Sugar Cane Ash (CCA)

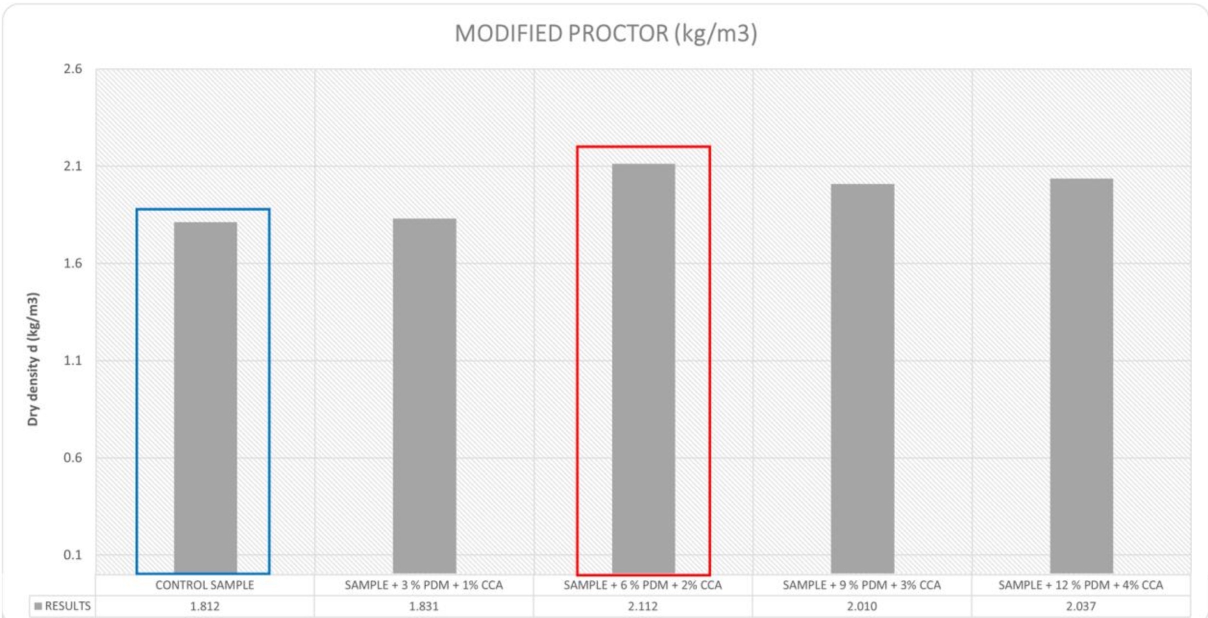

Figure 8. Modified Proctor results of dry density

3.2.3. CBR - Penetration Resistance

California Bearing Capacity Index (CBR) tests are conducted to evaluate the effect of soil stabilization by incorporating marble filler (PDM) and sugarcane ash (CCA) in different proportions. The combinations tested include soil + 3% PDM + 1% CCA, 6% PDM + 2% CCA, 9% PDM + 3% CCA and 12% PDM + 4% CCA, plus a control sample with no additives. Each mixture is evaluated in four replicates, obtaining an average for each ratio.

The results show that the incorporation of stabilizers improves the CBR of the soil, reaching the maximum value with the 6% PDM + 2% CCA mixture, which registers an average of 13.57%. The control sample, used as a reference, presents a CBR of 10.80%. For the other combinations, values of 11.71% were obtained with 3% PDM + 1% CCA, 11.44% with 9% PDM + 3% CCA, and 9.17% with 12% PDM + 4% CCA. These results highlight that the 6% PDM + 2% CCA ratio optimizes soil bearing capacity, while mixtures with higher amounts of stabilizers show a decrease in CBR as shown in Table 3.

While sample combinations with + 9 % PDM + 3 % CCA and with + 12 % PDM + 4 % CCA, a decrease in CBR due to the excess of marble filler and sugar cane ash can alter the internal structure of the soil, negatively affecting its mechanical properties. In particular, when high proportions of these additives are used, the mixture tends to become too dense, making proper compaction difficult. In addition, a high proportion of these materials can prevent optimal particle distribution, affecting the homogeneity of the mixture and reducing its ability to improve soil stability.

Figure 9 presents a bar chart illustrating the CBR averages obtained for each mix, allowing a visual comparison of the performance of the different proportions and their impact on the improvement of the stabilized soil.

Table 3. CBR sample results

TESTS	SAMPLE 01	SAMPLE 02	SAMPLE 03	SAMPLE 04	AVERAGE
CONTROL SAMPLE	10.25%	11.24%	10.47%	11.25%	10.80%
SAMPLE + 3 % PDM + 1% CCA	12.77%	12.65%	10.15%	11.25%	11.71%
SAMPLE + 6 % PDM + 2% CCA	13.16%	14.78%	12.86%	13.49%	13.57%
SAMPLE + 9 % PDM + 3% CCA	10.84%	11.22%	12.58%	11.11%	11.44%
SAMPLE + 12 % PDM + 4% CCA	9.78%	9.48%	8.13%	9.28%	9.17%

Note: Marble Filler (PDM); Sugar Cane Ash (CCA)

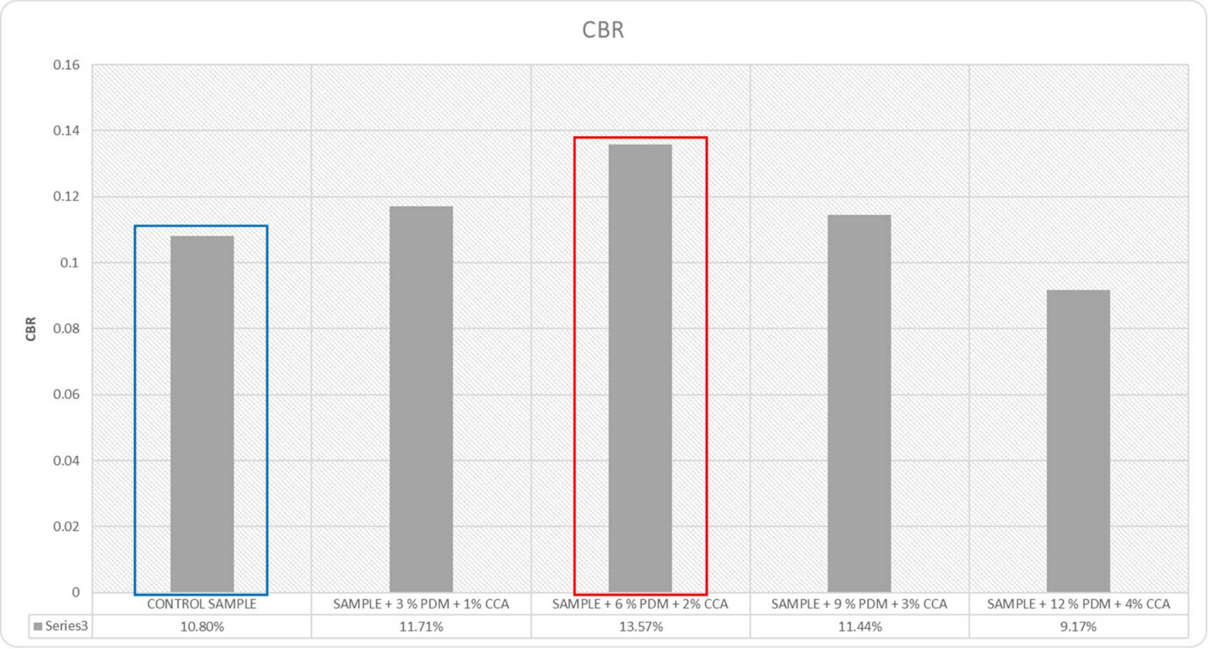

Figure 9. Average CBR test results for analyzed samples

3.2.4. Direct Shear Test

Direct shear tests were performed to evaluate the friction angle and cohesion of soil mixtures stabilized with marble filler (PDM) and sugarcane ash (CCA) in different proportions. The combinations tested included soil + 3% PDM + 1% CCA, 6% PDM + 2% CCA, 9% PDM + 3% CCA and 12% PDM + 4% CCA as shown in Table 4. A control sample without stabilizers was also included to establish a reference point. The results obtained show that both friction angle and cohesion increase with the addition of PDM and CCA. The mixture with 6% PDM + 2% CCA reached the highest value for friction angle (27.59 °) and cohesion (52.76 Kpa), indicating a significant improvement in soil strength and stability. The control sample presented a friction angle of 25.21 ° and a cohesion of 24.81 Kpa. Other mixes showed varied results, with the 3% PDM + 1% CCA mix achieving a friction angle of 26.12 ° and a cohesion of 36.87 Kpa, while the 9% PDM + 3% CCA mix showed a friction angle of 26.63 ° and a cohesion of 42.95 Kpa. These results suggest that the 6% PDM + 2% CCA mix is the most effective in improving both friction angle and cohesion, highlighting its potential for improving soil stability in civil engineering applications.

Table 4. Direct Shear Test

DESCRIPTION	FRICTION ANGLE (°)	COHESION (Kpa)
Control sample	25.21	24.81
Sample + 3% PDM + 1% CCA	26.12	36.87
Sample + 6% PDM + 2% CCA	27.59	52.76
Sample + 9% PDM + 3% CCA	26.63	42.95
Sample + 12% PDM + 4% CCA	25.92	33.05

Note: Marble Filler (PDM); Sugar Cane Ash (CCA)

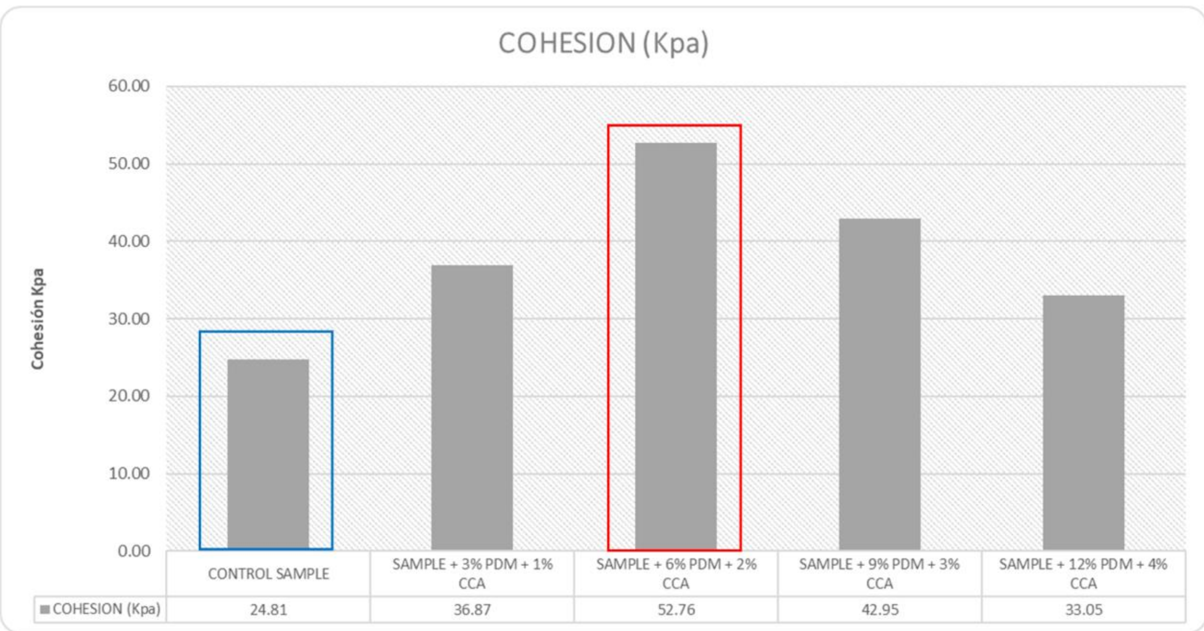

Figure 10. Average CBR test results for analyzed samples

Figure 10 illustrates the average values of the friction angle and cohesion for each mix in a bar graph, allowing for a visual observation of the variations and the trend of improvement in soil stability with the addition of stabilizers.

4. Discussion of Results

Current research on the stabilization of tropical soils with marble filler (PDM) and sugarcane ash (CCA) aligns with the growing focus in civil engineering on employing industrial and agricultural by-products to improve soil properties. Similarly, the study entitled "Soil stabilization with rice husk ash and sugarcane bagasse ash" highlights the use of wastes as sustainable alternatives to reduce reliance on conventional stabilizing agents such as cement and lime, which present increasing costs and greater environmental impacts [23].

A notable difference between the two studies is in the effects on stabilized soil properties. While the work on CPA and CACA reports a decrease in the maximum dry density and an increase in the optimum moisture content, the present investigation shows that the optimum combination of 6% PDM and 2% CCA increases the maximum dry density to 2.112 kg/m^3, according to the modified Proctor test. This result indicates that PDM and CCA not only improve soil stability, but also increase its compactability, which reinforces its applicability to support structural loads.

Both studies share the goal of minimizing the environmental impacts associated with the disposal of industrial and agricultural wastes, demonstrating that these materials can be effectively reused for soil stabilization. However, the current research extends this approach by including PDM, a by-product of the marble industry, thus diversifying the options for sustainable materials in this field.

Furthermore, the results of this research are comparable to the study "Stabilization of lateritic soils for road application using lime and cow bone ash". While the comparative study focuses on lateritic soils and uses cow bone ash (CBA) together with lime as stabilizers, the present research employs marble filler (PDM) and sugar cane ash (CCA) for tropical soils, also achieving significant improvements in mechanical properties [24].

In terms of bearing capacity ratio (CBR), the study on CBA and lime shows an optimum increase at 8% stabilizer addition, highlighting its effectiveness for road applications. In comparison, the mixture of 6% PDM and 2% CCA in the present investigation achieves a maximum CBR value of 13.57%, evidencing its ability to increase soil strength and provide better mechanical performance against loads.

In conclusion, the stabilization of tropical soils through the combined use of marble filler (PDM) and sugarcane ash (CCA) has shown significant improvements in soil mechanical properties, such as plasticity index, maximum dry density and bearing capacity. The incorporation of PDM reduces soil plasticity by interacting with clay particles, while CCA, with its high amorphous silica content, favors the formation of additional cementitious compounds, improving soil cohesion and strength. The optimum combination of 6% PDM and 2% CCA achieved a notable reduction in the plasticity index (9.44%), a dry density of 2.112 kg/m^3 in the modified Proctor test and a bearing capacity of 13.57% in the CBR test. These results show that stabilization of tropical soils with these additives is effective in improving bearing capacity and soil stability for pavement and foundation applications in areas with high plasticity soils and low bearing capacity.

Comparing these results with previous studies, such as the use of rice husk ash and sugarcane bagasse for soil stabilization [23], and the use of lime and cow bone ash for lateritic soils [24], differences in stabilization mechanisms are observed. In the study [23], the use of agricultural residues as sustainable alternatives is highlighted, but without significant improvement in maximum dry density, as was achieved with the combination of PDM and CCA in this study. In addition, [24] on stabilization of lateritic soils with lime and bone ash showed an increase in bearing capacity, but the response of lateritic soils to stabilizers such as PDM and CCA could differ due to their lower clay content. This contrast highlights the need to adapt stabilization techniques to the specific characteristics of each soil type, which broadens the possibilities of applying these methods in different geotechnical contexts.

5. Conclusions

From the results obtained, it is concluded that the incorporation of marble filler (PDM) and sugarcane ash (CCA) in the stabilization of tropical soils significantly improves their mechanical and physical properties. In particular, the combination of 6% PDM + 2% CCA optimizes the plasticity index, increases the maximum dry density obtained in the modified Proctor test (2,112 kg/m^3) and improves the bearing capacity index (CBR) up to 13.57%. These improvements make the soil more suitable for pavement and foundation applications, addressing the challenges associated with its high plasticity and low bearing capacity [25].

Therefore, it shows its importance in the area of civil engineering, as it offers a sustainable and economical alternative for soil stabilization in regions with complex characteristics. Furthermore, this technique uses industrial and agricultural by-products, promoting sustainability and reducing the environmental impact related to the use of conventional stabilizing materials. This approach is particularly relevant in infrastructure contexts in developing countries, where conventional resources may be limited.

This research proposes to engineers worldwide to evaluate the use of alternative materials such as marble filler and sugar cane ash in soil stabilization projects. The applied methodology demonstrates the technical feasibility of incorporating these additives in different proportions to improve soil properties, encouraging replication of the study in other regions with soils of similar characteristics.

Future lines of research are oriented towards the evaluation of the durability of soils stabilized with these materials under moisture and drought cycles, the analysis of their impact on soil permeability and the study of their long-term behavior under dynamic loads. It is also recommended to investigate the combined use of other industrial and agricultural by-products, as well as to evaluate the implementation of these techniques in large-scale infrastructure projects.

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