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Eco-Efficient Stabilization of Fine-Grained Soils Using *Eucalyptus globulus* Leaves to Improve Strength and Bearing Capacity

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Abstract Soil stabilization is a critical challenge in civil engineering, particularly in regions with fine-grained soils prone to volumetric changes and reduced bearing capacity. In Peru's central highlands, unstable subgrades pose significant risks to infrastructure durability, making the development of sustainable reinforcement techniques essential. This study evaluates the effectiveness of *Eucalyptus globulus* leaves (EL) as a natural soil stabilizer, considering their availability and potential for improving mechanical properties. Dry and crushed EL, passing through No. 40 and No. 4 sieves, were incorporated into two soil types using an experimental design. Laboratory tests included Atterberg limits—liquid limit (LL), plastic limit (PL), and plasticity index (PI)—as well as unconfined compressive strength (UCS) and California Bearing Ratio (CBR), following standardized procedures. For the soil in Sa ños Chaupi (Sch), the LL increased with 5% EL inclusion. UCS values improved with a 2% EL increment, rising from 1.54 kg/cm ² to 4.073 kg/cm ². Similarly, CBR resistance increased by 2% and 3% EL, reaching values from 6% to 15.4%. However, both UCS and CBR showed a decline with 5% EL incorporation. Similar trends were observed in Parco (Pa). These findings demonstrate that *Eucalyptus globulus* leaves can enhance soil strength, particularly at optimal dosages of 2% to 3%. Their application as a natural stabilizer presents an eco-friendly alternative to conventional methods, reducing environmental impact while improving soil performance for construction purposes in the region.

Keywords Fine Soils, *Eucalyptus globulus*, Leaves, Stabilization, Construction

1. Introduction

The stability of fine-grained soils is a critical factor in the durability and functionality of civil engineering projects. In regions with expansive or low-strength soils, volumetric changes caused by moisture variations lead to structural failures, including cracking, settlement, and reduced bearing capacity. The central highlands of Peru, where infrastructure development is growing, present significant challenges due to soil instability. Studies have shown that fine-grained soils, particularly those with high clay content, are susceptible to large volume changes, emphasizing the need for stabilization techniques to enhance their mechanical properties [1–4]. Traditional soil classification systems, such as those based on particle size distribution, are often inadequate for fine-grained soils, as their behavior is primarily influenced by mineralogy and plasticity [5,6]. Consequently, evaluating soil stabilization methods that improve strength and reduce deformation susceptibility is essential for long-term infrastructure sustainability.

Historical approaches to soil reinforcement have utilized a variety of natural and synthetic materials [7]. The Great Wall of China, for instance, incorporated wooden columns, compacted soil, and natural binders, demonstrating the longstanding practice of improving soil stability through material inclusion [8,9]. More recently, research has explored the effectiveness of organic additives, such as starches derived from potatoes, cassava, corn, and rice, as well as lignin-based compounds, for enhancing soil performance. These studies have reported reductions in plasticity index by 10% to 60%, which is crucial for subgrade strength [10]. Natural fibers, including rice husk fiber (RHF) and sawdust fiber (SD), have been evaluated as sustainable alternatives, achieving CBR increases from 14% to 36% and unconfined compressive strength (UCS) improvements from 121 kPa to 335 kPa when properly treated with chemical agents such as citric acid [11].

Among the various reinforcement materials, *Eucalyptus globulus* leaves (EL) have emerged as a potential eco-friendly stabilizer due to their high lignin and cellulose content [12]. Previous studies on bagasse fiber and lime addition have demonstrated significant improvements in soil compressive strength and shrinkage reduction, particularly when hydrated lime is combined with organic fibers in controlled proportions [13]. Furthermore, alkaline-activated mixtures incorporating steel slag and sugarcane bagasse ash have been shown to increase CBR values from 1.78% to 10.62%, reinforcing the viability of bio-based stabilizers for expansive soils [14]. Research on fine-grained soil classification highlights the importance of sedimentation and spectrophotometry in determining particle size distribution [15], UCS values of treated expansive soil increased with increasing bagasse [13], further validating the role of natural additives in modifying soil behavior [16]. In this context, the use of EL as a soil stabilizer remains an area of limited study, warranting further investigation into its mechanical benefits and environmental advantages.

The objective of this study is to evaluate the effectiveness of *Eucalyptus globulus* leaves as a natural reinforcement for fine-grained soil stabilization in two distinct soil types. By conducting experimental tests on Atterberg limits, UCS, and CBR, this research aims to determine the optimal dosage of EL to improve soil strength while maintaining environmental sustainability. The findings will contribute to the development of sustainable soil stabilization methods that minimize ecological impact and enhance the performance of subgrade materials in road construction.

2. Materials and Methods

2.1. Soil Collection and Characterization

The soils used in this study were collected from two distinct locations in the central highlands of Peru: Saños Chaupi (Sch), El Tambo district, Huancayo, and Parco (P), Jauja district. Soil samples were extracted from a depth of 1.5 meters below ground level to ensure consistency in sample quality. The collected soils were classified and tested according to Peruvian Technical Standards (NTP) to evaluate their basic resistance parameters, detailed in Table 1.

Table 1. Natural Soil Properties in the study area

No	Parameter	Symbol	Soil Sch	Soil P
1	Soil Classification	SUCS	CL	CL
2	Specific Gravity	Gs	2.53	2.6
3	Liquid Limit (%)	LL	29-33	36.08-44.80
4	Plastic Limit (%)	PL	14.08-19	20.82-21.71
5	Plasticity Index (%)	PI	10-15.62	14.37-23.98
6	Maximum Dry Density (g/cm^3)	MDD	1.87	1.9
7	Optimum Moisture Content (%)	OMC	12.5	13
8	Unconfined Compressive Strength (Kg/cm^3)	UCS	1.54-2.85	1.22-2.68
9	California Bearing Ratio (%)	CBR	5.7-7.3	12.4

Table 2. Physical Properties of *Eucalyptus globulus* Leaves

Property	Mean	Standard Deviation	Maximum	Minimum
Moisture Content (%)	77.05	1.934	78.59	73.61
Green Density (g/cm^3)	1.09	0.03	1.13	1.06
Air-Dry Density (g/cm^3)	0.62	0.015	0.64	0.6

2.2. Natural Fiber (*Eucalyptus globulus* Leaves)

Eucalyptus globulus leaves (EL) were selected as a natural reinforcing material due to their availability and promising properties for soil stabilization. The genus *Eucalyptus*, belonging to the Myrtaceae family, comprises around 700 species and varieties, primarily distributed across tropical and subtropical regions. Globally, over eighteen million hectares are planted with *Eucalyptus* species, known for their significant height, often exceeding 45 meters, and considerable diameter, sometimes surpassing 6 meters [2]. The leaves used in this study were sourced from mature *Eucalyptus globulus* trees, characterized by high moisture content (94.57% to 138.99%), green density (0.990 to 1.150 g/cm^3), and air-dry density (0.576 to 0.805 g/cm^3). The basic density ranges from 0.440 to 0.580 g/cm^3, making them suitable for enhancing soil properties [17]. The leaves were dried at 105 ℃ for 24 hours to achieve optimal moisture removal, ensuring the efficacy of reinforcement. Additionally, *Eucalyptus globulus* leaves contain bioactive compounds, including 41 polyphenols, which contribute to their structural integrity and potential for use as a soil stabilizer [18,19]. The measured physical properties of the *Eucalyptus globulus* leaves used for stabilization are detailed in Table 2.

To ensure uniformity in the reinforcement process, the leaves were oven-dried at 105 ℃ for 24 hours before use. The mass loss due to drying was recorded at different time intervals to analyze moisture evaporation. Table 3 illustrates the variation in mass of the *Eucalyptus globulus* leaves over the monitored drying time.

Table 3. Mass Variation of *Eucalyptus globulus* Leaves Over Drying Time

Drying Time (hours)	Mass (g)
0	262.21
24	216.94
48	216.34
72	215.83

2.3. Research Design

This study employed an experimental research design to evaluate the effectiveness of *Eucalyptus globulus* leaves in enhancing soil mechanical properties. Two types of soil were tested with varying percentages of EL (2%, 3%, and 5%) as reinforcement.

2.4. Sample Preparation

Soil samples were oven-dried at 105 ℃ for 24 hours, followed by manual crushing to ensure uniformity. The *Eucalyptus globulus* leaves were similarly dried, cleaned, and manually crushed using a small mill. Both soil types (Sch and P) were sieved using No. 40 and No. 4 meshes to standardize particle sizes for testing. Soil samples were oven-dried at 105 °C for 24 hours, followed by manual crushing to ensure uniformity. The *Eucalyptus globulus* leaves were similarly dried, cleaned, and manually crushed using a small mill. To balance workability and reinforcement effectiveness, soil was sieved through mesh No. 40 to achieve a fine, cohesive texture, while leaf particles were retained by mesh No. 4 to maintain sufficient fiber length for effective interlocking and tensile resistance [20].

2.5. Laboratory Testing

The following laboratory tests were conducted by NTP standards: Atterberg Limits: Determined using soil passing through the No. 40 sieve, focusing on liquid limit (LL), plastic limit (PL), and plastic index (PI). Unconfined Compressive Strength (UCS): Samples were molded into 69 mm x 140 mm specimens and tested to evaluate the maximum compressive strength. California Bearing Ratio (CBR): Performed as per AASHTO T-180D standards to assess subgrade strength.

2.6. Data Analysis

The results from each test were analyzed using descriptive statistics to determine the meaning, standard deviation, and variability in soil properties. Comparative analysis was conducted to evaluate the effectiveness of *Eucalyptus globulus* leaves at different inclusion rates. Statistical significance was assessed through ANOVA, with a p-value < 0.05 considered significant.

3. Results and Discussion

3.1. Effect of *Eucalyptus globulus* Leaves on Atterberg Limits

The Atterberg limits were used to characterize the behavior of fine soils, the clay fraction being important, considering that its behavior varies over time. Figure 1 shows variations in PI, decreasing with 2% reinforcement. In research with natural fibers such as Diss, a reduction in soil plasticity is also observed [21]. Introducing sugarcane bagasse ash to the soil also reduces its plastic behavior [22].

3.2. Effect of *Eucalyptus globulus* Leaves on Unconfined Compressive Strength (UCS)

Tests revealed that incorporating *Eucalyptus globulus* leaves initially improved soil strength, but beyond an optimal dosage, performance decreased. In Sa ños Chaupi (Sch, C-1), the unreinforced soil had a UCS of 2.85 kg/cm^2

The addition of 2% EL produced the highest UCS value (4.073 kg/cm ²), showing a statistically significant increase compared to all other reinforcement levels ($p < 0.05$). However, higher dosages (3% and 5%) resulted in significantly lower strengths than the optimal 2% EL treatment, although still higher than the unreinforced condition. The complete results of the Unconfined Compressive Strength (UCS) tests across all reinforcement percentages for both soil types are summarized in Table 4.

This trend was also observed in excavation points C-2 and C-3. In Parco (P), the maximum UCS was likewise obtained at 2% EL reinforcement (3.675 kg/cm ²), with significant differences compared to the unreinforced soil and the 5% EL ($p < 0.05$). The 3% EL level in Parco showed intermediate values, significantly lower than 2% EL but higher than 0% and 5% EL. The two-way ANOVA confirmed significant effects of reinforcement percentage, site, and their interaction ($p < 0.05$), reinforcing the conclusion that 2% EL is the optimal level for both locations (Figure 2). This performance is attributed to improved internal cohesion and reinforcement [23]. However, excessive organic material disrupts soil structure, reducing its bearing capacity. This aligns with studies on *Diss* fibers [21], sisal fibers [15], and rice husk fibers [11,24], where moderate fiber content enhanced UCS, but excessive amounts weakened.

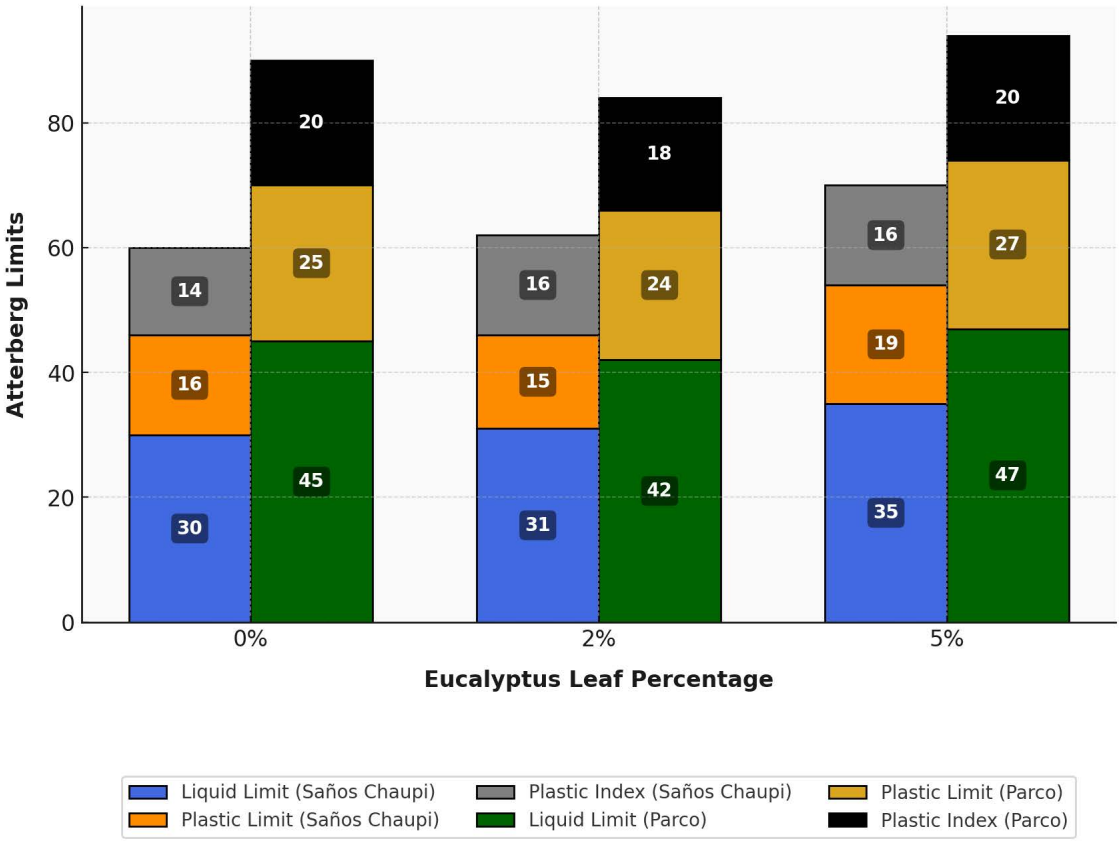

Figure 1. Variation of Atterberg limits for Safios Chaupi and Parco soils with *Eucalyptus globulus* leaf incorporation (0 %, 2 %, 5 %). Values (in %) correspond to Liquid Limit, Plastic Limit, and Plasticity Index, indicating plasticity changes with increasing fiber content

Table 4. Unconfined Compressive Strength (UCS) of Soil Samples with *Eucalyptus globulus* Leaves

Reinforcement (%)	Unconfined Compressive Strength (kg/cm ²)	
	Sch	P
0	2.85^{c}	2.682^{b}
2	4.073^{g}	3.675^{e}
3	3.847^{f}	3.07^{d}
5	3.114^{d}	2.279^{a}

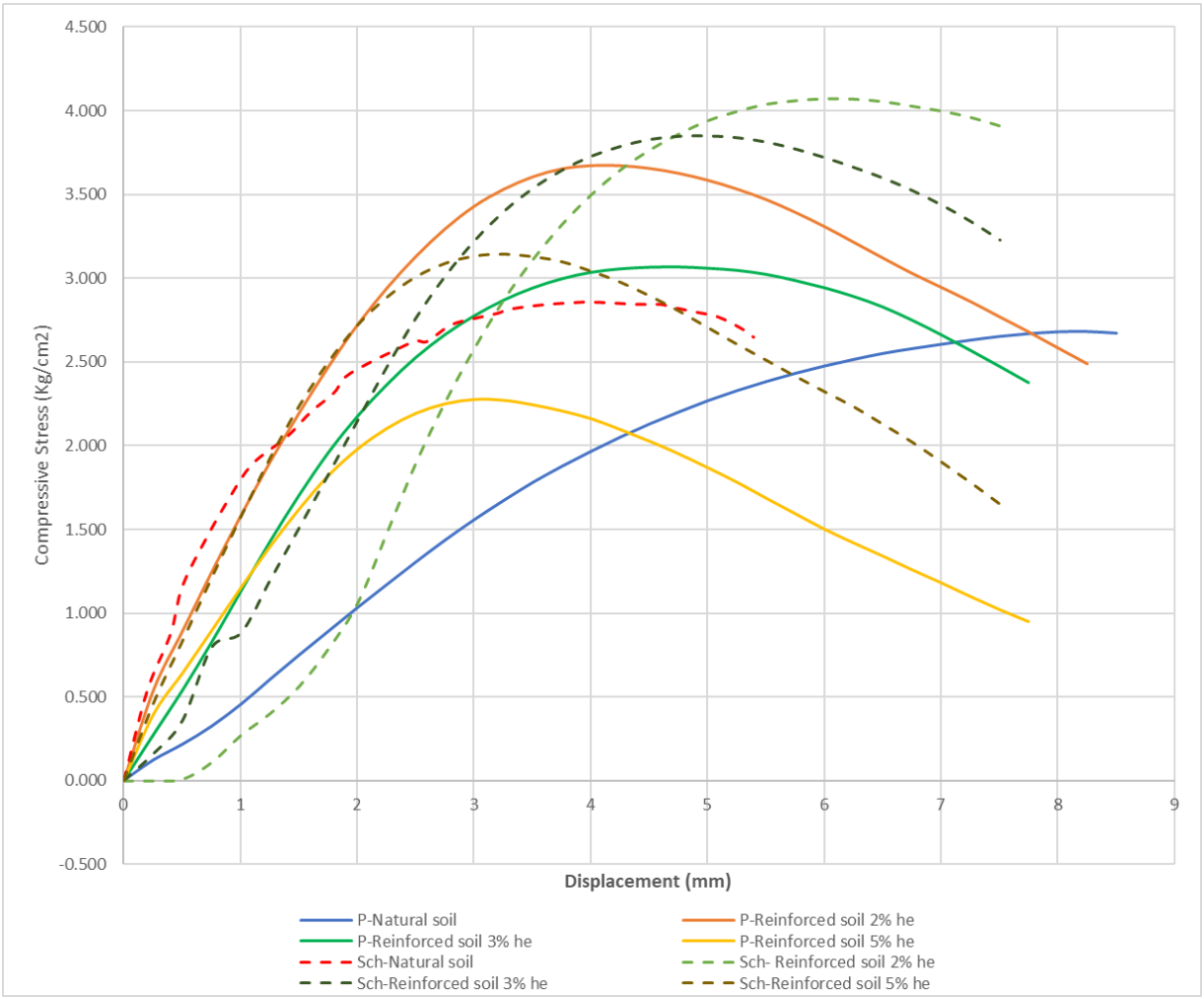

Figure 2. Stress-Strain Behavior of Soil with and without *Eucalyptus globulus* Leaves in Sa ños Chaupi and Parco

Figure 3. Post-failure condition in UCS tests: (A) Non-reinforced specimens (69 mm; 140 mm) with brittle fracture; (B) Eucalyptus leaf–reinforced specimens (69 mm; 140 mm) showing EL fiber-induced interlocking

Figure 3 presents two sets of soil specimens subjected to unconfined compressive strength (UCS) testing to evaluate their mechanical behavior: (A) Non-reinforced specimens with diameters of 69 mm and 140 mm, exhibit typical failure patterns due to axial loading, including fracturing and structural collapse. (B) Specimens reinforced with eucalyptus leaves, display increased cohesion and an altered failure mechanism due to fiber reinforcement.

The strength enhancement at optimal EL content can be explained by the fiber–matrix interaction mechanism. Leaf fibers act as discrete reinforcement within the soil matrix, creating mechanical interlocking and increasing resistance against pull-out. The high lignin–cellulose composition of *E. globulus* leaves complements this, providing tensile strength that effectively bridges soil particles under load. Experimental studies confirm that such natural fibers perform as reinforcement akin to composite behavior, increasing tensile resistance as shear stress mobilizes fiber strength within the soil matrix [25]. Furthermore, longer fibers enhance interlocking and the strength gain in shear tests, while a threshold exists beyond which excess fibers may cluster and reduce performance [26].

3.3. Effect of *Eucalyptus globulus* Leaves on California Bearing Ratio (CBR)

CBR tests revealed a significant enhancement in soil load-bearing capacity with moderate inclusion of *Eucalyptus globulus* leaves (EL). In Saños Chaupi (Sch, C-1), the CBR value for unreinforced soil was 7.3% (e), indicating a relatively low resistance to penetration under applied loads. With 2% EL reinforcement, the CBR value increased significantly to 19.2% (k), representing the highest recorded value in this site and differing statistically ($p < 0.05$) from all other treatments. When the reinforcement was increased to 3% EL, the CBR value reached 15.4% (i), indicating a reduction compared to the 2% reinforcement level ($p < 0.05$) but still superior to the unreinforced soil. However, at 5% EL, the CBR value dropped to 4.1% (b), being significantly lower than all other reinforcement levels, including the natural soil ($p < 0.05$). Table 5 presents the CBR and associated Dry Density results obtained for the different percentages of *Eucalyptus globulus* reinforcement and compaction efforts.

Table 5. CBR and Dry Density Results for Different *Eucalyptus globulus* Reinforcement Percentages

Reinforcement (%)	Number of Blows	10	25	56
Without reinforcement	CBR (%)	5.7^{c}	6.7^{d}	7.3^{e}
	Dry Density (g/cm^3)	1.82^{e}	1.83^{e}	1.87^{f}
2% EL	CBR (%)	13.1^{g}	17.5^{j}	19.2^{k}
	Dry Density (g/cm^3)	1.77^{d}	1.88^{f}	1.92^{g}
3% EL	CBR (%)	11.81^{f}	13.9^{h}	15.4^{i}
	Dry Density (g/cm^3)	1.57^{a}	1.78^{d}	1.87^{f}
5% EL	CBR (%)	3.6^{a}	3.91^{ab}	4.1^{b}
	Dry Density (g/cm^3)	1.61^{b}	1.65^{c}	1.76^{d}

Similar statistical patterns were observed across the different compaction energies (10, 25, and 56 blows), confirming the consistency of the 2% EL treatment as the optimal reinforcement level. The dry density of the soil also improved with reinforcement, reaching 1.92 g/cm^3(g) for 2% EL at 56 blows of compaction force, which was significantly higher ($p < 0.05$) than most other treatments.

This performance aligns with studies on sisal fibers, which increased CBR to 8.12% [20], and sugarcane bagasse ash, which improved CBR from 1.78% to 10.62% [14]. Additionally, rice husk fiber (RHF) at 4% reinforcement increased CBR to 31% in soaked conditions for subgrade improvement in road construction applications [11].

Figure 4 presents the variation in CBR values for soil samples under natural conditions and with eucalyptus fiber reinforcement (EL) at 2%, 3%, and 5%, tested at compaction efforts of 10g, 25g, and 56g in Saños Chaupi, C-1. The results indicate that 2% reinforcement yields the highest CBR values across all compaction levels, demonstrating an optimal balance between soil cohesion and reinforcement interaction. At higher reinforcement levels (5%), a decrease in CBR is observed, likely due to reduced soil compactibility and structural integrity. The polynomial trendlines for each compaction effort exhibit a high correlation ($R^2 > 0.97$), confirming the reliability of the fitted models.

Figure 5 illustrates the relationship between CBR (%) and dry density (g/cm^3) for soil samples with different eucalyptus fiber reinforcement levels (2%, 3%, and 5%) compared to non-reinforced soil. The results show a positive correlation, where an increase in CBR generally leads to a higher dry density, except for the 5% reinforcement, which exhibits lower compaction efficiency. The linear regression models for each reinforcement level demonstrate high R^2 values (>0.78), confirming the strong relationship between these variables. Figure 6 shows two sets of soil samples tested using the California Bearing Ratio (CBR) procedure. In the upper section (A), soil samples in their natural condition, without any reinforcement, can be observed. In the lower section (B), the soil samples have been stabilized with 2% dried and crushed *Eucalyptus globulus* leaves.

The visual analysis reveals significant differences in the structural integrity and cohesion of the soil after the reinforcement application. In the unreinforced samples (A), evident fractures and disintegration around the load application point are noticeable, suggesting a lower bearing capacity and greater susceptibility to deformation under applied loads. In contrast, the samples reinforced with 2% *Eucalyptus globulus* leaves (B) exhibit a more cohesive structure, reduced disintegration, and better load distribution, indicating an improvement in soil strength and an increase in its bearing capacity.

Although *Eucalyptus globulus* leaves proved effective in improving UCS and CBR in the short term, their biodegradable nature may influence long-term durability under field conditions. Natural fibers can degrade due to microbial activity, moisture fluctuations, and environmental exposure, potentially reducing reinforcement effectiveness over time. Reviews indicate that fiber–matrix composites, including lignocellulosic fibers, must balance mechanical strength with controlled degradability, as degradation can impact structural performance and lifecycle sustainability [27,28]. Further, mechanisms of strength loss under cyclic environmental stress, such as freeze–thaw, exhibit exponential decline in shear strength tied to interfacial degradation [29]. However, eucalyptus leaves contain natural biocidal oils that may slow microbial decomposition compared to other fibers [30]. Considering these findings, we recommend long-term aging studies, including biodegradation assays and cyclic environmental testing, to determine the field persistence of EL reinforcement and appropriate maintenance intervals.

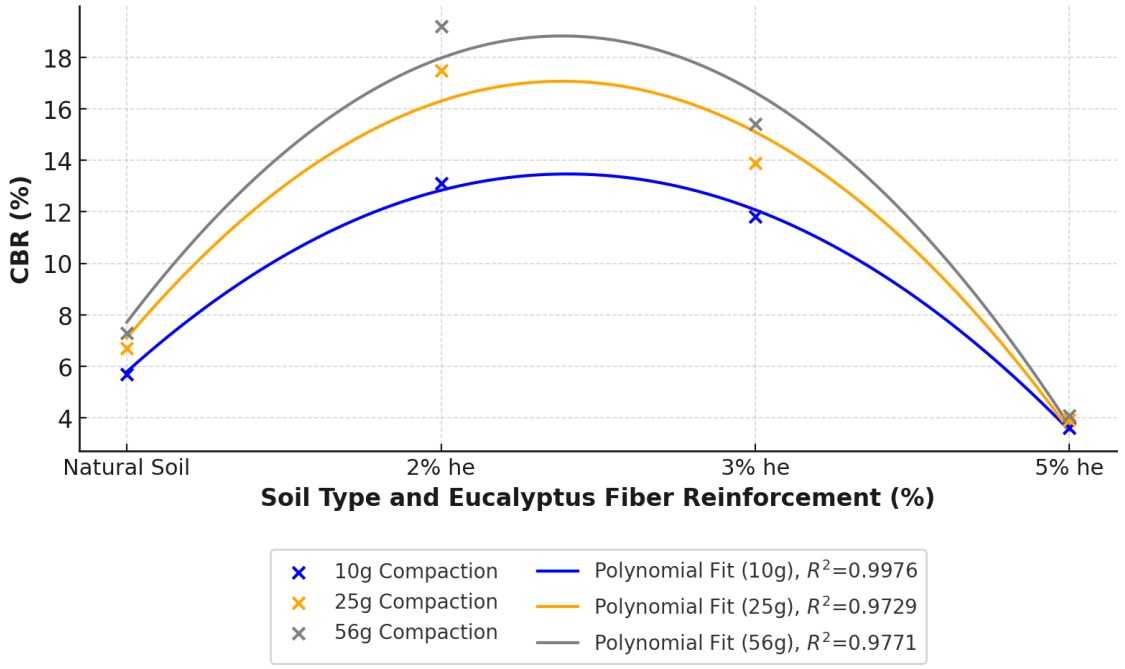

Figure 4. CBR Variation in Natural and Reinforced Soil with Eucalyptus Fibers (2%, 3%, 5%) at Different Compaction Efforts (10g, 25g, 56g) – Sa ños Chaupi, C-1

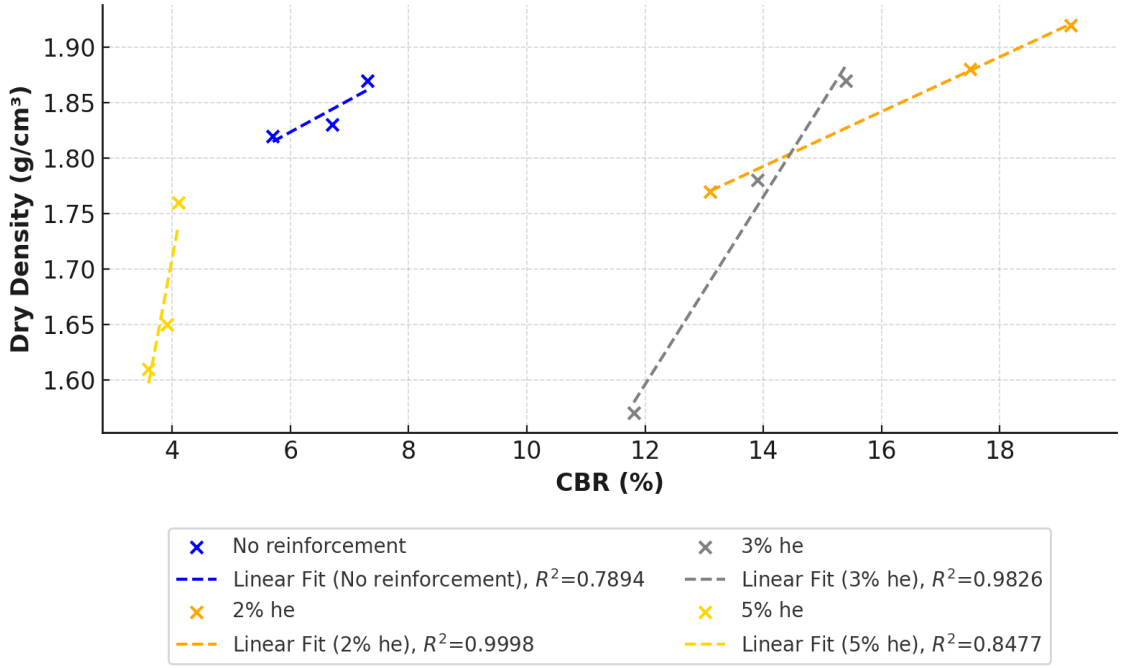

Figure 5. Correlation Between CBR and Dry Density for Different Reinforcement Levels, Sch

Figure 6. Comparison of Soil Samples Before and After Reinforcement with 2% *Eucalyptus globulus* Leaves in CBR Tests

4. Conclusions

The results indicate that the plasticity index in both soil groups, Saños Chaupi (Sch) and Parco (P), does not show a significant reduction with the addition of 2% *Eucalyptus globulus* (EL). However, with a 5% increment, the decrease is minimal, which may be attributed to the reinforcement material passing through sieve No. 40, limiting its effect on soil plasticity. Regarding unconfined compressive strength (UCS), both soil groups exhibit a progressive increase in strength with the inclusion of EL, achieving values higher than those of the natural soil. However, the best mechanical response is obtained with the addition of 2% EL, establishing this percentage as the optimal reinforcement level.

In terms of load-bearing capacity measured through the California Bearing Ratio (CBR) in soaked conditions, a significant improvement is observed in Saños Chaupi with the inclusion of 2% and 3% EL, with the latter providing the highest resistance compared to unreinforced soil. However, when the EL content is increased to 5%, resistance decreases, suggesting a saturation point in the stabilizer's effectiveness. In the Parco (P) group, 2% EL reinforcement also demonstrates an improvement in the soil's load-bearing capacity.

Both UCS and CBR values were obtained using natural reinforcements under dry conditions with material passing through sieve No. 4. In both cases, the reinforced soils exhibited improved performance, confirming the viability and potential of *Eucalyptus globulus* leaves as an effective natural stabilizer. The use of natural fibers not only enhances soil strength but also represents an eco-friendly alternative to conventional stabilization methods. As a renewable and biodegradable material, *Eucalyptus globulus* reduces environmental impact without compromising soil functionality for construction purposes. The need for sustainable and environmentally friendly stabilizers is essential for developing more resilient and eco-conscious infrastructure.

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