

Article

Influence of Abacá Fiber Treated with Sodium Hydroxide on Undrained Shear Strength in Organic Silt

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Abstract

Highly decomposed organic soils exhibit low strength and stability, which pose challenges for geotechnical engineering. This study evaluates the effectiveness of abacá natural fibers treated with 5% NaOH to prevent biodegradation and reinforce organic silt. An experimental program was conducted to investigate the effects of fiber content (1, 1.5, and 2%) and length (5, 10, and 15 mm) on the undrained shear strength (S_u), elastic modulus (E_{50}), maximum dry density (MDD), and optimum water content (OWC). The results revealed a slight reduction in MDD and OWC, while S_u increased significantly, reaching 104.13% for 1.5% fiber content and 15 mm fiber length. E_{50} decreased by up to 52.61%, indicating a transition toward more ductile behavior and variability due to the inherent heterogeneity of the soil. ANOVA and post hoc Tukey analyses confirmed the statistical significance of fiber content and length on S_u , with optimal performance observed at 1.5% content and 15 mm length. These findings demonstrate that chemically treated abacá fibers provide effective and sustainable soil reinforcement and that chemical treatment is essential to maintain short-term durability in biologically active organic soils.

Keywords: abacá fibers; organic silt; soil reinforcement; undrained shear strength; elastic modulus; chemical treatment



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1. Introduction

Organic soils exhibit low compressive strength, which often results in excessive deformation, differential settlement, and ground instability, posing significant challenges for infrastructure development in the affected areas. Therefore, it is necessary to explore alternative methods to enhance their mechanical properties. Conventional solutions include the incorporation of nanomaterials; lime; cement; or synthetic fibers such as glass, polyvinyl alcohol, and polypropylene [1,2]. Complementary non-conventional techniques aimed at reducing the carbon footprint have also been proposed, including biocementation, use of biopolymers, microbial-induced calcium carbonate precipitation [3,4], utilization of agricultural waste such as rice husks [5], and the addition of natural fibers. The latter has demonstrated effectiveness in improving the mechanical performance of various materials, including structural concrete, paving blocks, synthetic polymers, and soft soils [6–8].

With respect to soil reinforcement using natural fibers, notable materials include bamboo, jute, coir, palm, sugarcane bagasse, rice husk, and sisal [9]. Experimental evidence

indicates that these fibers enhance the compressive strength of both the peak and residual in confined unconfined conditions and improve the California Bearing Ratio (CBR), cohesion, and friction angle under both drained and undrained conditions. Additionally, they contribute to reducing hydraulic conductivity and shrinkage, decreasing the maximum dry density (MDD) and optimum moisture content (OMC), and controlling the expansion and consolidation processes [10–12].

Albuja-Sánchez et al. [13] evaluated the Unconfined Compressive Strength (UCS), elastic modulus, MDD, and OMC of a sandy silt reinforced with abacá fibers treated with NaOH. The fibers were randomly distributed within the soil matrix at contents of 0.5, 1, 1.5, and 2% and lengths of 5, 10, and 15 mm. The authors observed an increase in MDD at 0.5% fiber content for all lengths, followed by a decrease at higher fiber contents. In contrast, the OMC increased as the fiber content decreased. The maximum increase in the UCS (1235.10%) was recorded for the 2% fiber content at a length of 15 mm, corresponding to a strain of 10.52% compared to 1.98% in natural soil. This behavior reflects a remarkable enhancement in the material deformability, which was also observed for other combinations of fiber content and length. The authors attributed this improvement to the formation of a three-dimensional confinement network created by the fibers within the soil matrix.

R. Islam et al. [14] investigated the effects of reinforcement of clay soil on UCS and CBR using randomly distributed sugarcane fibers at contents of 0.4, 0.6, 0.8, and 1%, with lengths ranging from 20 to 30 mm. The fibers were oven-dried prior to mixing to eliminate microbial activity. The results showed that a 0.6% fiber content led to a 62.50% increase in the UCS, accompanied by a general decrease in the elastic modulus compared to the natural soil, except at a 0.6% dosage. Furthermore, the CBR values increased by 67.35% under unsaturated conditions and 76.98% under saturated conditions, corresponding to fiber contents of 0.6% and 0.8%, respectively. The authors attributed these improvements to the anchoring effect of the fibers, which enhanced particle interlocking. However, fiber contents above 0.6% acted as wedges, separating the soil particles and reducing the interlocking effect.

Moslemi et al. [15] investigated the effects of fiber content (0.5, 1, and 2%); fiber length (0.5, 1, and 1.5 mm); and curing time (1 and 7 days) on the strength of sandy soil reinforced with three types of randomly distributed oven-dried lignocellulosic fibers: softwood bleached kraft pulp (S.B.), old corrugated containers, and high-yield wheat straw soda pulp (W.S.). Optimum performance was obtained with 1% S.B. fibers at a length of 1.5 mm, which led to a 67.25% increase in strength and a 51.76% reduction in pore pressure. However, fiber contents exceeding 1% negatively affected the integrity of the mixture, while dosages greater than 0.5% resulted in a reduction in the elastic modulus relative to that value, although still higher than that of the natural soil. After seven days of curing, an increase in the effective cohesion and a slight decrease in the friction angle were observed. No variations in soil pH, fiber degradation, or the formation of cementitious compounds were detected. Combined with SEM observations, these findings confirmed that the improvement mechanism was exclusively physical and was associated with enhanced interparticle contact between the soil particles and fibers during curing.

Bawadi et al. [16] performed standard compaction tests on clayey soil reinforced with natural fibers from banana, kenaf, and coconut at dosages of 0.3, 0.5, and 1.0% by dry weight of the soil. The fibers were oven-dried before use. The results indicated that, at fiber contents of 1% or higher, regardless of the fiber type, the OWC of the mixture increased because of the higher water absorption capacity of the untreated fibers. At the same time, the MDD decreased, reflecting the lower relative density of the fibers compared to the soil mineral particles.

In summary, the existing literature demonstrates that natural fiber reinforcement is a promising technique for improving the mechanical performance of different soil types, providing comparable benefits to synthetic materials in terms of strength and sustainability. Nonetheless, challenges persist regarding the durability of fibers in aggressive environments, where they are prone to biodegradation, as well as the limited understanding of their influence on organic soils, which are typically characterized by high compressibility and low bearing capacity.

1.1. Organic Soil

Organic soils are composed of plant residues at various stages of decomposition, typically under conditions of excessive moisture for most of the year [17]. These soils commonly originate from the flooding of alluvial plains, where layers of organic residue accumulate. Combined with low temperatures and high precipitation, these conditions create anaerobic environments that slow the decomposition of plant material, ultimately leading to peat formation [18]. Organic soils are characterized by their dark color, putrid odor, spongy consistency, high permeability, high water content, high void ratio, and low density, among other properties [19,20]. Soils are classified as organic when their organic matter content exceeds 20%, and materials with more than 75% organic matter are referred to as peat [21].

Soil organic matter comprises living organisms (bacteria and fungi), partially decomposed material, and fully decomposed material. The fibrous fraction, mainly composed of lignin, cellulose, and hemicellulose, is responsible for water absorption, whereas lignin is more resistant to microbial degradation. Its low specific surface area accounts for its lower density than mineral soils with low or negligible organic contents [22]. Fully decomposed material, known as humus, can be classified as hemic or sapric, depending on its degree of decomposition. Humus formation results from the anaerobic respiration of microorganisms, which obtain energy by breaking down undecomposed or partially decomposed organic matter [23]. Humus primarily consists of humic acids, fulvic acids, and residual lignin [24,25]. These amorphous and colloidal substances exhibit high cation exchange capacities and substantial water retention capabilities. This is because the hydroxyl groups (phenolic and alcoholic) in humic acids and the carboxyl groups (-COOH) are predominant in fulvic acids, with the latter being the main contributor to soil acidity [23].

The organic matter content significantly influences the geotechnical properties of the soils. Huat et al. [26] conducted tests on fibrous and hemic peats from Malaysia and concluded that a higher organic content reduces density, specific gravity, and strength while increasing compressibility, plasticity, and water retention capacity. They also observed that fibrous peats exhibited superior mechanical behavior compared to hemic or sapric peats.

This study focuses on the behavior of organic soil collected from El Garrochal, Quito, Ecuador. Calderón-Carrasco et al. [27] reported that a prehistoric lagoon might have existed in the El Garrochal sector, which gradually drained into the Machángara River, leaving organic sediments that now form part of the soil layers. Mayanquer et al. [28] conducted four boreholes up to 10 m in depth at the site, determining that the soil consists of silty layers with organic matter contents ranging from 6.91% to 40.04%.

Sánchez et al. [29] analyzed soil from Caupicho, a nearby area, using samples and SDMT tests. They identified organic soil layers and, through XRD, found that the soil was mainly composed of plagioclase (78%), muscovite (17%), quartz (3%), and cordierite (2%). Organic matter content ranged from 5% to 25%, and SEM revealed microscopic diatom fossils and unicellular algae with silica walls associated with allophanic volcanic ash from Andean lacustrine environments.

Solórzano-Blacio et al. [30] improved the silty soil from El Garrochal, with a 43.84% predominantly sapric organic content, by adding nanosilica. The XRD analysis showed that the soil primarily contained plagioclase (85%), anhydrite (6%), cordierite (4%), maghemite (3%), and sodalite (2%). The incorporation of 1% nanosilica resulted in a 211.28% increase in the undrained shear strength, slight decrease in the MDD, increase in the OWC, and enhanced liquid and plastic limits.

1.2. Abacá Fiber

Fibers incorporated into soils can vary in shape, diameter, texture, stiffness, and tensile strength, depending on the plant species from which they are extracted. However, for geotechnical applications, the fiber length, dosage, orientation, and their combinations play critical roles in enhancing the soil properties [31,32]. When reinforced soil is subjected to compressive stresses, deformation occurs, generating contact between soil particles and fibers. This contact induces friction, which deforms the fibers and generates tensile stresses within them, as illustrated in Figure 1. Together, these mechanisms form a structural mesh that binds to the soil and increases its strength [33].

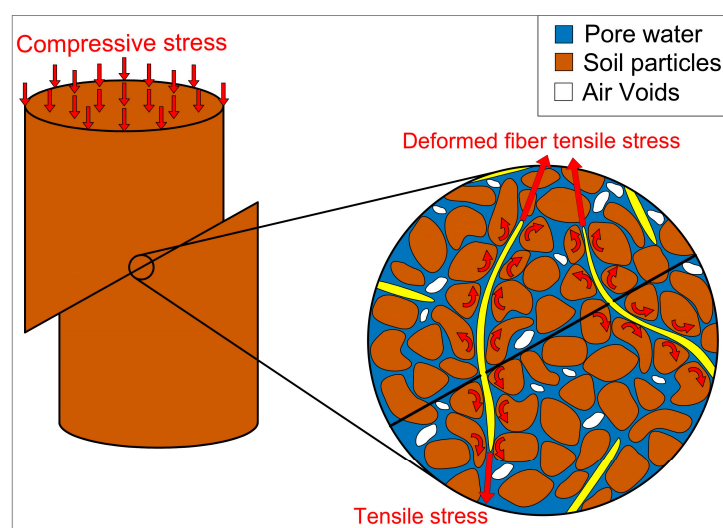


Figure 1. Interaction mechanism between fibers and soil particles.

Fibers may be randomly distributed, as typically occurs when lime, cement, or nano-materials are added, producing isotropy and minimizing unreinforced zones [34]. Alternatively, fibers can be oriented in a controlled manner, as in the case of geotextiles.

Wang et al. [35] investigated the effects of jute fibers in expansive soil using direct shear and CU triaxial tests. Fiber contents of 0.3, 0.6, and 0.9%; lengths of 6, 12, and 18 mm; and orientations of 0°, 30°, 60°, and 90° relative to the horizontal, in addition to a random distribution, were considered. Optimal results were achieved with a 0.6% fiber content, 12 mm length, and random distribution, yielding a 48% increase in cohesion, 50% increase in shear strength, and reduction in residual strength loss. They also observed that the soil stiffness decreased with the fiber addition, regardless of the length, dosage, or orientation. Fiber contents above 0.6% led to the formation of weak planes, reducing strength and generating adverse effects, particularly at 0.9% fiber content. Controlled orientations generally exhibit poorer performance than random distribution, because oriented fibers are compressed before being tensioned, which does not contribute to strength and can reduce specimen compactness due to bending and bulging.

Because natural fibers are composed of cellulose, hemicellulose, and lignin, they are susceptible to microbial decomposition. Moisture absorption and biodegradation are

closely related and significantly affect fiber strength [36]. Thermal, biological, and moisture-induced degradation, as well as water absorption, are primarily caused by hemicelluloses in natural fibers [37]. Hollow natural fibers, such as abacá, composed of approximately 56–66% cellulose, 20–25% hemicellulose, and 7–13% lignin, exhibit lower bulk densities and higher water retention capacities [38]. Consequently, a higher moisture absorption increases the risk of microbial attack.

In this context, the present study evaluated the performance of an organic soil improved with abacá fibers subjected to alkaline treatment with NaOH. The influence of fiber content and length was analyzed with respect to key properties, such as Unconfined Compressive Strength, elastic modulus, and compaction characteristics, with the aim of providing new experimental evidence to advance the understanding and practical application of this sustainable ground improvement technique.

2. Materials and Methods

2.1. Sampling Site

A soil sample was collected at a depth of 1.30 m in the “El Garrochal” area, located in the southern part of Quito, Ecuador (Figure 2). The test pit was situated at $0^{\circ}20'23.83''$ S latitude and $78^{\circ}31'57.05''$ W longitude, at an elevation of approximately 2993 m.a.s.l.



Figure 2. Location of El Garrochal.

The study site lies near the Atacazo and Pichincha Volcanoes within the Quito-San Antonio-Guayllabamba basin, through which the Machángara River flows [39], specifically in the Sanguanchi River subbasin, in the Turubamba sector [40]. The inter-Andean basin comprises tectonically controlled subbasins generally formed by fluvial sedimentary deposits, including pumice, sand, silt, clay, and volcanic ash [41].

2.2. Fiber Treatment

Abacá fiber obtained from Monterrey, Santo Domingo de los Tsáchilas, Ecuador, was used in this study (Figure 3). Fiber dosages of 1, 1.5, and 2% and lengths of 5, 10, and 15 mm were considered with random distribution.



Figure 3. Abacá fibers with lengths of 5 mm, 10 mm, and 15 mm were used.

Organic soils, such as those from El Garrochal, naturally harbor abundant microbial communities that actively decompose organic matter, primarily fungi and bacteria. To demonstrate the microbial activity in the soil used in this study, a trap consisting of cooked rice wrapped in sterilized porous mesh was placed in contact with a soil sample, as shown in Figure 4a. The trap was maintained for seven days under hermetic conditions in a controlled room for ambient humidity and temperature, shielded from direct sunlight. After this period, the porous mesh and cooked rice (Figure 4b,c) exhibited extensive microbial colonization, indicating a high capacity for biological degradation.

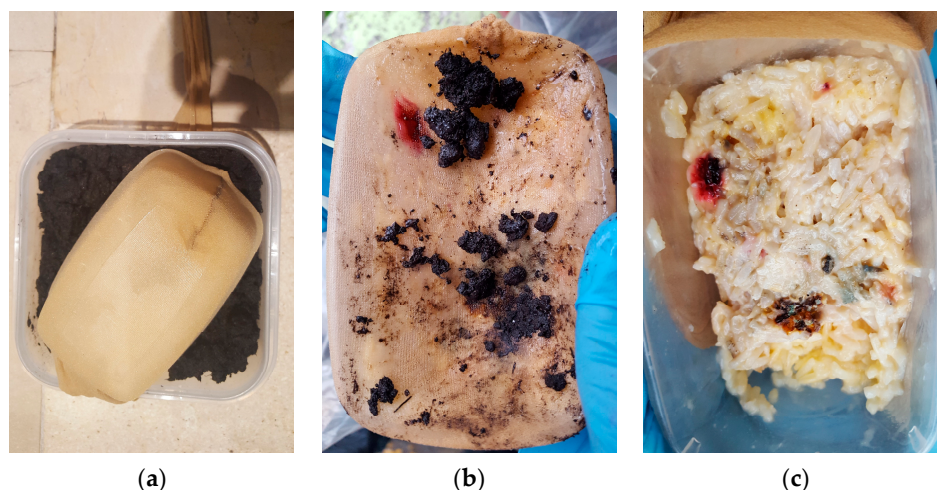
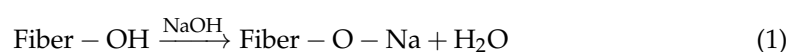


Figure 4. (a) Installation of the rice trap; (b) rice trap mesh bag before 7 days of microbial colonization; (c) colonized rice before 7 days of microbial colonization.

Similarly, plant fibers incorporated into the soil are highly susceptible to accelerated deterioration of their mechanical properties owing to microbial activity. Therefore, chemical treatment of the fibers prior to soil incorporation is necessary to reduce their vulnerability to biodegradation [42].

The fibers were treated using an alkaline method: they were immersed in a 5% NaOH solution for 2 h, rinsed with water to remove residues, and oven-dried at 80 °C for 2 h. Cai et al. [43] demonstrated that this treatment removes hemicelluloses and other noncellulosic constituents without causing structural damage to the fiber bundles.

According to Gowthaman et al. [33], this treatment replaces the hydrogen bonds in the hydroxyl groups of cellulose and hemicellulose that bind water molecules, as shown in Equation (1), thereby reducing the water absorption and increasing the fiber surface roughness.



2.3. Homogenization Process of Organic Content and Abacá Fiber Dosage

Studies on the specific gravity of organic soils indicate that a drying temperature between 60 °C and 70 °C is optimal, as higher temperatures can cause carbonization, oxidation, or volatilization of organic components. Conversely, temperatures below 50 °C leave significant amounts of residual water in soil pores [44,45]. Accordingly, all moisture and specific gravity tests in this study were conducted at 60 °C.

Analysis of the collected soil revealed considerable variability in the organic content. To minimize the influence of this variability on the experimental results, the extracted sample was mechanically homogenized with a shovel and then divided into subsamples. These subsamples underwent a second homogenization process using a hand mixer for 15 min. The moisture and organic content were subsequently verified.

The dosage of the treated fibers was determined based on the dry weight obtained from the control moisture tests. Fibers were then incorporated into the homogenized moist soil at the specified lengths and percentages and mechanically mixed until a uniform random distribution was achieved. This procedure is illustrated in Figure 5.

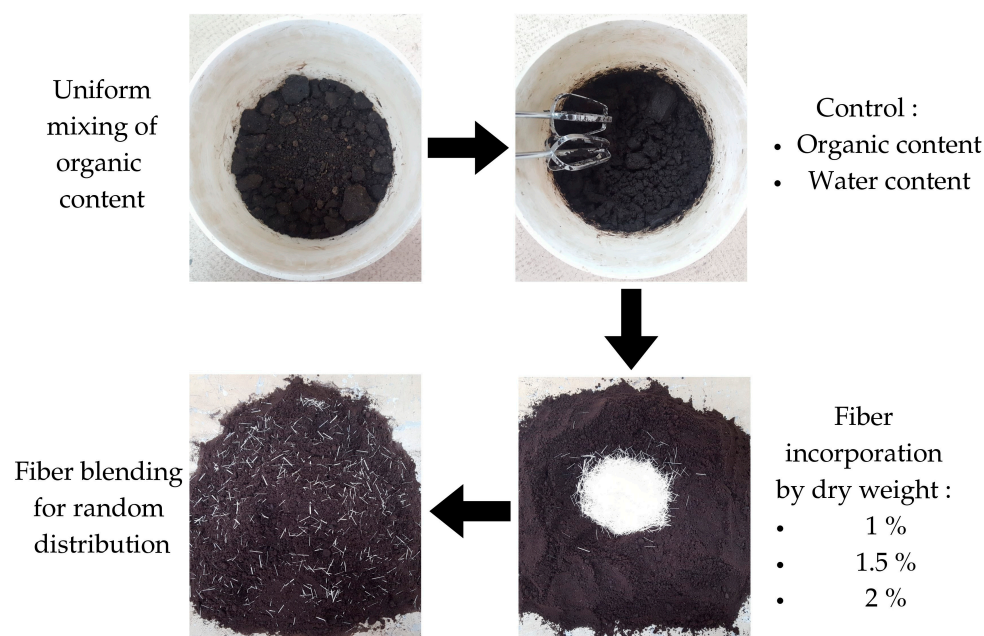


Figure 5. Homogenization of the organic content and fiber dosage.

2.4. Testing Program

Once the samples were homogenized and the moisture and organic content of the subsamples were determined, some were allocated for physical and chemical characterization, while others were reserved for mechanical testing. Physical and chemical characterization tests, together with the mechanical behavior tests listed in Table 1, were conducted using the wet method in accordance with standard specifications to preserve the integrity of the soil's organic content.

The subsamples intended for mechanical testing were allowed to air dry slowly at ambient temperature, avoiding direct sunlight, to reach the target moisture content required for the proposed tests. Once the desired moisture content was achieved, the fibers were incorporated following the procedure described in Section 2.3.

Compaction tests, from which the MDD and OWC were obtained, were performed on natural soil within a moisture range of 40–110%, while, for fiber-reinforced soil, the test was conducted immediately after fiber addition once the moisture content reached 60–90%.

Subsequently, the results for each fiber combination were compared to those of natural soil to determine the effect of the fiber content and length on the compaction behavior.

Table 1. Summary of tests performed, applicable standards, and number of repetitions.

Laboratory Test	Parameter	Standard	Test Realized Number
Particle-Size Distribution	Gravel, sand, lime and clay fraction [%]	ASTM D 7928 [46] ASTM D 1140 [47]	3 for each standard
Atterberg Limits	LL, LP, IP [%]	ASTM D 4318 [48]	3 for homogenized sample
USCS Classification	Soil Classification	ASTM D 2487 [49]	3 for homogenized sample
Organic Content	Organic fraction [%]	ASTM D 2974 [50]	9 triplicate tests on homogenized sample, for a total of 27
Specific Gravity	G _s	ASTM D 854 [51]	2 for homogenized sample
Laboratory Compaction	MDD and OWC	ASTM D 1557 [52]	1 for each combination of dosage and fiber content at least
Unconfined Compression Test	Su, E ₅₀	ASTM D 2166 [53]	3 for each combination of dosage and fiber content
pH determination	pH	ASTM D 5298 [54]	3 for homogenized sample
Von Post Classification	H1 to H10	ASTM D 5715 [55]	3 for homogenized sample

The effect of fiber content and length on undrained shear strength was evaluated through unconfined compression tests for each fiber–length combination, conducted in triplicate. Remolded cylindrical specimens were prepared at 95% of the MDD and OWC and tested after a seven-day curing period. Stress–strain curves were obtained from these tests, from which the peak stress corresponding to the maximum compressive strength was determined. The undrained shear strength (Su) was taken as 50% of the peak stress. Similarly, the secant modulus corresponding to 50% of the maximum strength was determined from these curves.

Finally, the effects of fiber content and length on the undrained shear strength and elastic modulus were analyzed using two-way analysis of variance (ANOVA), followed by a post hoc Tukey test.

2.5. Physical and Chemical Characterization of the Organic Soil

Sieving and sedimentation analyses were performed to determine the particle size distribution. The results presented in Figure 6 indicate that the soil was predominantly composed of silt (59.94%), sand (34.05%), and clay (6.01%). According to Sánchez et al. [29] and Solórzano-Blacio et al. [30], the predominant mineral at the study site is plagioclase, which is an aluminosilicate belonging to the tectosilicate group. These minerals, consisting of tetrahedral silica-aluminum structures, exhibit high internal stability and, combined with the predominance of silt and clay particle sizes, exhibit limited adsorption or chemical reactivity [26].

For organic matter characterization, manual/visual classification according to the Von Post scale was performed, along with pH measurement of the homogenized sample. When compressed, the soil exhibited a pasty consistency and flowed easily, releasing minimal turbid water. Partially decomposed organic matter was barely recognizable within this matrix. Consequently, the soil was classified as H7, which corresponds to highly decomposed peat with a pH of 5. These results align with those reported by Solórzano-Blacio et al. [30], who observed very low fiber content and acidic conditions characteristic of predominantly sapric or humic soils.

The organic content averages and standard deviations indicated low variability among the measurements. Reporting this variability is important, because it represents an additional factor that may help explain the differences in the mechanical behavior of the soil.

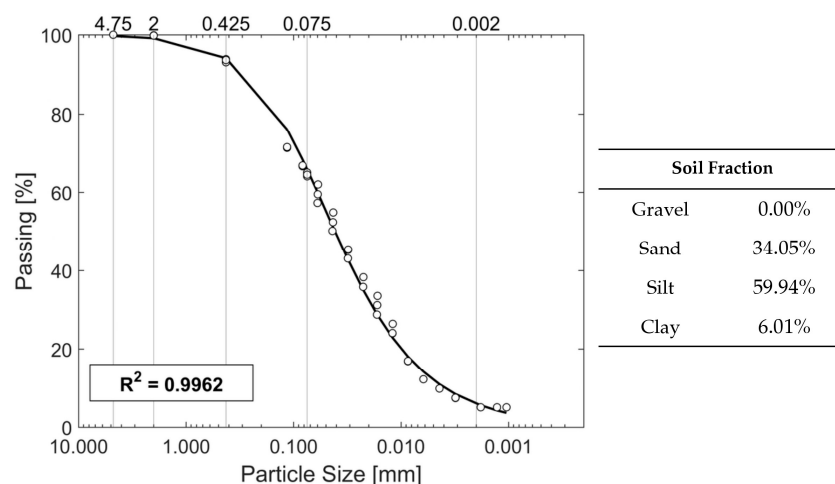


Figure 6. Particle size distribution of the soil.

The complete soil characterization results are summarized in Table 2.

Table 2. Summary of the organic soil properties.

Property	Value	Property	Value
Sand fraction	34.05%	Specific gravity	1.98
Silt fraction	59.94%	MDD	0.6618 gr/cm ³
Clay fraction	6.01%	OWC	75.53%
Liquid limit, LL	349.85%	Von Post Classification	H7
Plastic limit, PL	194.95%	pH	5
Plasticity index, PI	154.90%	Average Organic Content [%]	33.88%
USCS classification	Organic silt with sand (OH)	Organic Content Standard Deviation	2.17

3. Results

3.1. Compaction Behavior

Compaction tests were conducted for each combination of fiber length and dosage, and the natural soil was tested in triplicate. ASTM Method A was employed based on particle size distribution. The compaction curves for each combination, as well as for natural soil, were fitted using quadratic functions. The results are summarized in Table 3, which shows a general trend of reduced MDD and OWC, with high coefficients of determination (R^2) for the fitted curves.

Table 3. Summary of the effects of fibers on MDD and OWC.

Fiber Content [%]	Fiber Length [mm]	MDD [g/cm ³]	OWC [%]	R^2	MDD Reduction [%]	OWC Reduction [%]
0	0	0.6618	75.53	0.8421	-----	-----
1	5	0.6235	69.51	0.9289	5.79%	7.97%
1.5	5	0.6226	69.02	0.9456	5.92%	8.62%
2	5	0.6256	70.86	0.9907	5.47%	6.18%
1	10	0.6185	69.49	0.9863	6.54%	8.00%
1.5	10	0.6225	70.13	0.9382	5.94%	7.15%
2	10	0.6333	68.94	0.9819	4.31%	8.73%
1	15	0.6192	69.86	0.9447	6.44%	7.51%
1.5	15	0.6225	70.17	0.9922	5.94%	7.10%
2	15	0.6294	72.47	0.9576	4.90%	4.05%

Figure 7a illustrates the relationship between MDD and fiber content for different lengths. An initial reduction in the MDD was observed, followed by stabilization, independent from both the fiber content and length.

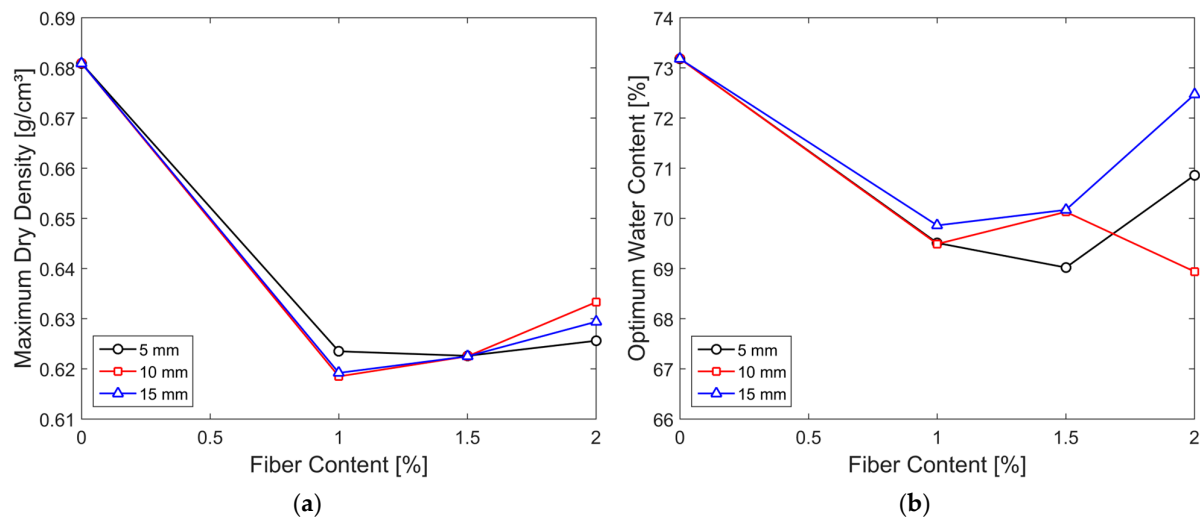


Figure 7. Effect of fiber content at different fiber lengths on (a) MDD; (b) OWC.

Figure 7b shows the relationship between the OWC and fiber content for each length. A slight initial reduction was followed by a small increase, never exceeding the initial value and showing no clear trend.

3.2. Unconfined Compression Strength

Unconfined compressive tests were conducted in triplicate on remolded specimens prepared at OWC and 95% MDD. Table 4 presents the average void ratios and degrees of saturation of the specimens. Notably, despite the high compaction, the void ratio remained relatively high.

Table 4. Summary of the average physical properties of remolded specimens.

Fiber Content [%]	Fiber Length [mm]	Average Water Content [%]	Average Dry Density [g/cm³]	Average Degree of Saturation [%]	Average Void Ratio
0	0	72.89	0.62	65.87	2.20
1	5	72.40	0.60	62.14	2.31
1.5	5	72.77	0.59	61.26	2.35
2	5	72.47	0.60	62.22	2.31
1	10	72.58	0.60	63.03	2.28
1.5	10	72.28	0.60	61.74	2.32
2	10	72.40	0.60	62.34	2.30
1	15	72.66	0.61	63.68	2.26
1.5	15	72.48	0.60	62.33	2.30
2	15	72.62	0.60	61.87	2.32

The S_u results are presented in Figure 8, which shows the S_u for each fiber combination compared with the natural soil, including error bars. The maximum increase of 104.13% (46.17 kPa) was achieved with 15 mm fibers at a 1.5% content, significantly exceeding that of the natural soil, which exhibited 22.62 kPa.

It can be observed that the peak stress increases with fiber inclusion compared to the unreinforced samples, regardless of the fiber content or length. Moreover, a higher fiber content corresponds to a higher peak stress, which is consistent across all the tested fiber lengths. Finally, the short error bars indicate high reliability of the results obtained for this parameter.

E_{50} exhibited nonlinear behavior and greater variability across fiber combinations compared to S_u , as shown in Figure 9. In general, fiber incorporation tended to reduce E_{50} by up to 52.61% relative to natural soil, indicating a more ductile response. Although a maximum E_{50} of 1.67 MPa was observed for 1.5% fibers at 15 mm, similar to the combinations yielding the highest S_u , other high-strength combinations, such as 2% fibers at 10 mm, resulted in a lower E_{50} of 0.86 MPa.

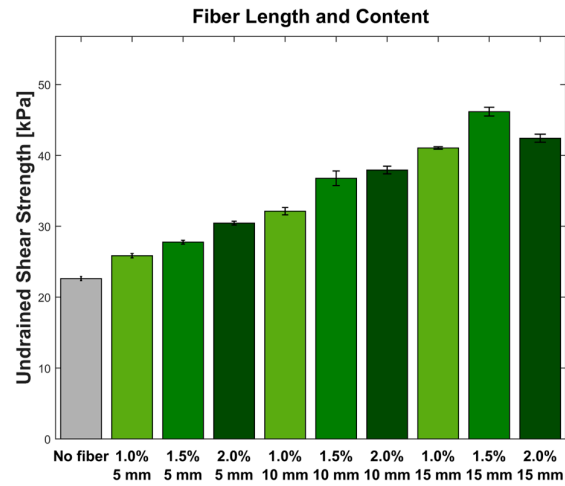


Figure 8. Comparison of the undrained shear strength between the fiber combinations and control specimens with error bars.

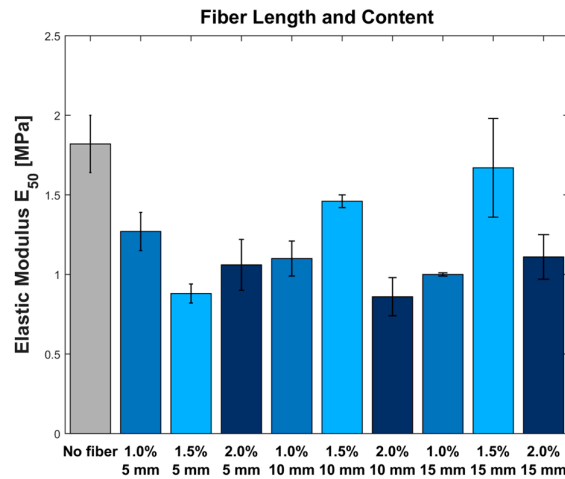


Figure 9. Comparison of elastic modulus between fiber combinations and control specimen with error bars.

Figure 10 shows the tested specimens after 7 days of curing. No evidence of degradation of the treated fibers or odors, indicating deterioration, was observed. Furthermore, the pH measurements of the specimens revealed no changes relative to the initial values.



Figure 10. Soil specimen tested after 7 days of curing.

4. Discussion

4.1. Effect of Abacá Fibers on MDD and OWC

This reduction in MDD aligns with the findings of Bawadi et al. [16] and Albuja-Sánchez et al. [13], who reported that the dry density decreased at fiber contents equal to or greater than 1%. This reduction can be explained by the replacement of soil mineral particles with fibers. Because organic matter is lighter than minerals, its density decreases. However, in this study, the soil had a high organic content with a density similar to that of natural fibers. Consequently, soil organic matter partially replaced the mineral particles, resulting in a low natural MDD. Upon adding abacá fiber, both soil organic matter and mineral particles are partially replaced, and as the densities of organic matter and fibers are similar, the change becomes negligible and density stabilizes, regardless of the fiber length or dosage. This is evident in Figure 7a, where no significant differences are observed among the trends for different fiber lengths.

Regarding OWC, the organic matter replaced by abacá fibers, which are predominantly sapric, has a high water absorption capacity. In contrast, NaOH-treated fibers, which do not decompose like natural organic matter, exhibit a lower water absorption capacity, explaining the overall reduction in OWC. However, no significant variation in the OWC was observed as a function of fiber content or length, as shown in Figure 7b. Table 3 shows that the OWC values ranged from 68.94% to 72.47%, representing a relatively small variability of 3.53%.

4.2. Effect of Abacá Fibers on Undrained Shear Strength

Summary of the ANOVA presented in Table 5 confirmed that fiber content, fiber length, and their interaction had a statistically significant effect on S_u ($p < 0.05$), with a very high coefficient of determination ($R^2 = 0.9956$). This indicates that nearly all of the variability in S_u can be explained by the experimental factors evaluated.

Table 5. ANOVA of the undrained shear strength.

Experimental Factor	Sum of Squares	Degrees of Freedom	Mean Square	F Value	p-Value	F Critical Value	Significance (ANOVA)
Fiber Content	91.53	2	45.77	158.65	3.70×10^{-12}	3.55	Yes
Fiber Length	1039.22	2	519.61	1801.18	1.86×10^{-21}	3.55	Yes
Interaction	39.22	4	9.81	33.99	3.65×10^{-8}	2.93	Yes
Error	5.19	18	0.29	—	—	—	—
Total	1175.17	26	—	—	—	—	—
Coefficient of Determination (R^2)						0.9956	

The post hoc Tukey test, summarized in Table 6, showed that all pairwise comparisons between fiber lengths (5, 10, and 15 mm) were significant, demonstrating a clear trend of increasing S_u with the fiber length. Regarding fiber content, significant differences were observed between 1.0–1.5% and 1.0–2.0%, whereas the 1.5–2.0% comparison showed no significant difference. This suggests that the effects of fibers at 1.5% and 2.0% are statistically indistinguishable, indicating that the optimal fiber content for this study was 1.5%. Higher fiber contents may have limited benefits owing to the formation of agglomerates and local weak planes, which reduces the homogeneity of the internal reinforcement distribution.

The observed increase in S_u is particularly relevant, given the highly organic nature of the soil. The alkaline NaOH treatment likely enhanced the surface roughness of the fibers, contributing to greater friction and mechanical anchoring between the organic and mineral components of the soil and fibers. Additionally, this treatment prevented fiber decomposition during the curing period despite the high microbial activity, promoting more efficient interactions between components, as reported by Moslemi et al. [15].

Table 6. Post hoc Tukey analysis of the undrained shear strength.

Fiber Length Comparisons			Fiber Content Comparisons		
Mean difference critical value		1.12	Mean difference critical value		1.12
Pairwise Comparison	Mean Difference	Significant (Tukey Test)	Pairwise Comparison	Mean Difference	Significant (Tukey Test)
15 mm vs. 5 mm	15.20	Yes	1.5% vs. 2.0%	0.03	No
15 mm vs. 10 mm	7.60	Yes	1.5% vs. 1.0%	3.89	Yes
10 mm vs. 5 mm	7.59	Yes	1.0% vs. 2.0%	3.92	Yes

4.3. Effect of Abacá Fibers on Elastic Modulus

This result is consistent with the findings of R. Islam et al. [14] and Wang et al. [35], where fibers acted as tensile elements and delayed brittle failure but reduced the initial stiffness. This variability is reflected in the error bars in Figure 9.

The ANOVA presented in Table 7 indicates the significant effects of the experimental factors and their interaction on E_{50} ($p < 0.05$), although with lower explanatory power ($R^2 = 0.8236$). The post hoc Tukey test shown in Table 8 revealed that only the difference between 1.5% and 2.0% fiber content was significant. This suggests that, although fiber inclusion modifies the overall behavior of E_{50} , the pointwise differences between pairs of fiber lengths or contents are generally not statistically significant. This result indicates that the effect of fibers on stiffness is subtler and more heterogeneous than that on the undrained shear strength, which is consistent with the higher variability observed in the error bars in Figure 9.

Table 7. ANOVA of the elastic modulus.

Experimental Factor	Sum of Squares	Degrees of Freedom	Mean Square	F Value	p-Value	F Critical Value	Significance (ANOVA)
Fiber Content	0.50	2	0.25	12.28	4.33×10^{-4}	3.55	Yes
Fiber Length	0.17	2	0.08	4.10	3.42×10^{-2}	3.55	Yes
Interaction	1.05	4	0.26	12.83	4.12×10^{-5}	2.93	Yes
Error	0.37	18	0.02	—	—	—	—
Total	2.08	26	—	—	—	—	—
Coefficient of Determination (R^2)						0.8236	

Table 8. Post hoc Tukey analysis of the elastic modulus.

Fiber Length Comparisons			Fiber Content Comparisons		
Mean difference critical value		0.30	Mean difference critical value		0.30
Pairwise Comparison	Mean Difference	Significant (Tukey Test)	Pairwise Comparison	Mean Difference	Significant (Tukey Test)
15 mm vs. 5 mm	0.19	No	1.5% vs. 2.0%	0.33	Yes
15 mm vs. 10 mm	0.12	No	1.5% vs. 1.0%	0.11	No
10 mm vs. 5 mm	0.07	No	1.0% vs. 2.0%	0.11	No

The coefficient of determination indicates that 82.36% of the variations in E_{50} are explained by fiber content, fiber length, and their interaction, whereas the remaining 17.64% can be attributed mainly to the heterogeneity of organic soil, as noted by Huat et al. [26]. Despite homogenization, a standard deviation of 2.17% in organic content may have produced local structural variations, making it difficult for fiber reinforcement to generate consistent effects on stiffness. Consequently, the ANOVA detected global differences in the E_{50} reduction, but the Tukey test did not identify significant changes in most pairwise comparisons. In contrast, S_u was less affected by this heterogeneity, which explains why the differences between combinations were statistically significant in that case.

5. Conclusions

This study investigated the effect of incorporating abacá fibers treated with 5% NaOH on the geotechnical properties of highly decomposed organic silt (Von Post Classification H7). The main findings derived from the statistical analysis led to the following conclusions.

- **Influence on compaction properties:** The addition of treated abacá fibers caused a slight reduction in MDD and OWC. This behavior is attributed to the replacement of mineral and organic soil components with a lower-density fibrous material, which, due to chemical treatment, exhibits a lower water absorption capacity than the natural sapric organic matter of the soil.
- **Significant strength improvement:** Reinforcement with treated abacá fibers proved effective in increasing S_u of the organic silt. A maximum increase of 104.13% was observed for a fiber content of 1.5% and length of 15 mm. ANOVA confirmed that fiber content, fiber length, and their interaction had a statistically significant effect on S_u , explaining 99.56% of the observed variability. This improvement is attributed to the anchoring and friction mechanisms between the fibers and the soil matrix, as well as the NaOH treatment, which prevented biodegradation and increased the fiber surface roughness, thereby enhancing the reinforcement mechanism.
- **Optimization of reinforcement parameters:** Post hoc Tukey analysis indicated that fiber length significantly influences S_u , with the best results obtained using 15 mm fibers. Regarding fiber content, the optimal dosage was identified as 1.5%, as no statistically significant differences were observed compared to the 2.0% dosage. The lack of additional benefit at higher contents is likely due to agglomerate formation, which can reduce the effectiveness of fiber reinforcement.
- **Increase in ductility:** Fiber incorporation transformed the soil behavior from brittle to ductile, as evidenced by a general reduction in E_{50} of up to 52.61%. However, this parameter exhibited a high variability. Although the ANOVA confirmed a significant effect of the experimental factors, its predictive power was moderate ($R^2 = 0.8236$). This result, together with the post hoc Tukey analysis, which found no significant differences for most pairs of fiber lengths or contents, is attributed to the inherent heterogeneity of the organic soil. These findings indicate that E_{50} is more sensitive to soil variability than the undrained shear strength.

While this study provides valuable evidence regarding the effectiveness of treated abacá fibers in improving the properties of organic silt, certain limitations must be acknowledged.

- **Long-Term Durability and Environmental Considerations:** The seven-day curing period does not allow for an assessment of fiber durability in active organic soils. Although NaOH treatment and the absence of visible decomposition are promising, microbial degradation and the potential gradual release of Na^+ into soil cannot be ruled out. This release could affect the electrical conductivity, pH, and exchangeable cations of the sapric soils. Fibers were rinsed to minimize residual NaOH; however, future studies should monitor these parameters to ensure the long-term effectiveness and safety of fiber reinforcement.
- **Necessity of NaOH treatment:** Future research could quantitatively assess the need for fiber treatment by comparing untreated samples with fibers subjected to different curing durations. This approach allows the evaluation of the effect of fiber biodegradation on the undrained shear strength and elastic modulus.
- **Limited Parameter Range:** The study was limited to three fiber dosages (1, 1.5, and 2%) and three lengths (5, 10, and 15 mm). While this range allowed the identification of

an optimal trend, the maximum strength might be achieved with longer fibers, which could introduce handling and homogenization challenges.

- **Elastic Modulus Variability:** The high variability observed in E_{50} can be attributed to the fact that only three tests were performed per combination. Future studies could consider testing a larger number of specimens per combination to reduce this variability and better clarify the elastic modulus trend.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/fib13100139/s1>.

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Abbreviations

The following abbreviations are used in this manuscript:

MDD	Maximum dry density
OWC	Optimum water content
S_u	Undrained shear strength
E_{50}	Elastic modulus at 50% of maximum strength
UCS	Unconfined Compressive Strength
NaOH	Sodium hydroxide
SEM	Scanning electron microscopy
XRD	X-ray diffraction
CBR	California Bearing Ratio
CU	Consolidated undrained (triaxial test)
R^2	Coefficient of determination
ANOVA	Analysis of variance
H7	Von Post Classification: highly decomposed peat

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