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Influence of Abaca Fiber Inclusion on the Unconfined Compressive Strength of Reconstituted Sandy Silts

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Abstract: The present investigation determines the influence of abaca (Musa textilis) fiber inclusion on the simple compressive strength of reconstituted sandy silt specimens. For this purpose, fibers of different lengths (5, 10 and 15 mm) and quantities (0.5, 1.0, 1.5 and 2.0% of soil dry weight) are added to produce the reconstituted specimens. Subsequently, the physical and mechanical behavior of soil–fiber mixtures were evaluated through compaction and unconfined compression tests. The experimental results showed that increases in fiber content or length, or both, led to a 1235.1% increase in maximum compression stress (compared to the fiber-free soil). Compression failure occurred at a greater axial strain when 10 and 15 mm fibers were added at 1% dosage or in percentages equal to or greater than 1.5% regardless of fiber length. A series of linear mixed models identified statistically significant effects of fiber length and percentage on the level of effort and on the unitary deformation.

Keywords: simple compression test; unconfined compression test; abaca fiber; soil improvement; fiber-reinforced soil

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1. Introduction

When soil improvement is required, various techniques are used to decrease settlement, and increase shearing resistance and bearing capacity [1]. Soil improvement is a solution to these problems and consists of modifying its properties to satisfy greater requirements and subsequent conversion into an appropriate material for a specific use [2]. Soil improvement minimizes resource use compared to other methods such as soil replacement. On one hand, transport is reduced since it is not necessary to carry competent soil over distances that are sometimes considerably long; while soil quantity is also reduced, since it allows reuse of material in the area, thus avoiding depletion of natural quarries. However, this requires space, methodologies, and infrastructure that can increase associated costs.

In recent years, various techniques have been used to improve soils such as jet grouting, deep soil mixing, bio-cementation (MICP), and the addition of waste materials, lime, cement, or fibers, among others. These techniques have been shown to improve the mechanical characteristics of soils, bringing enhancements in geomechanical parameters such as friction angle and cohesion, and thus providing increased liquefaction resistance and erosion resistance. Through biocementation settlements, reduction has been achieved [3,4]; greater resistance and improved compressibility behavior following the addition of waste rubber to the soil [5]. On the other hand, a higher unconfined compression resistance, higher CBR, and decreased linear contraction are obtained by adding lime and Prosopis fiber [6].

Of these techniques, it should be noted that the addition of fibers for the improvement of different materials has been practiced since small natural fibers were added for adobe production; however, since 1994 this technique has become considerably important in research [7]. Soil reinforcement can be achieved using both natural and synthetic fibers. In this way, coconut, palm, and processed cellulose in lengths ranging from 10 mm to 60 mm and percentages between 0.25% and 3% of the dry weight of soil had been used [7].

Soil reinforcement can be attained by adding fiber to the soil matrix in various ways. However, by adding them in a discrete and random manner, it is possible to denote isotropic resistance and potential planes of weakness absence, which can be formed in the direction of any other oriented reinforcement as metal strips, foils, fabrics, and grids [8,9]. When adding fibers, the mechanical behavior of improved soils will depend on their properties, added-fiber properties, content, orientation, the improved soil void ratio and the compaction method used [10–13].

The available bibliography affirms that the addition of fibers produce an improvement in the stress-deformation behavior, in peak and post-peak soil resistance [10,14–17]. This technique has been shown to produce positive effects in both granular and cohesive soils; in granular soils, increases in stiffness have been reported [16] and in its peak and post-peak shear resistance [8,10–12,18,19]. In silty and clayey soils, adding fibers were indicated to reduce potential cracking [20], greater simple compression resistance [20–26], improvement in resistance, deformation and shear failure [14,19,20], greater indirect tension resistance [20,22,24], increase in CBR values [25,26] and greater toughness [21,22,24].

The positive effects produced by adding fiber to the soil matrix are reported according to the literature due to the formation of a three-dimensional network of fiber confinement in the soil [22] and due to improved soil/fiber adhesion [22,27]. These effects have motivated the implementation of this technique both in stabilizing and repairing slopes, as well as in the construction and reinforcement of embankments [28]. Furthermore, it could be useful for reducing the liquefaction potential in loose sands [29] and to reduce expansive clay contraction and swelling pressures [30].

The incorporation of abaca fibers for the improvement of materials has been applied ranging from paper and concrete to different types of composites [31–37]. The intrinsic desirable mechanical properties of abaca fibers are comparable to those of synthetic materials. Studies suggest that fiber and matrix interactions are inevitable to produce mechanically sound composite materials [31–33]. In the case of paper, it is indicated that the high ratio between the length and width of the fiber partially explains the remarkable properties of "abaca" with long and thin cells, and an approximate composition of 77–80% cellulose, 6–8% hemicellulose and 5–10% lignin, even presenting microbial properties [35]. In the case of concrete, the results obtained by the abaca fiber concrete mixture for the composition (0.15%) and the ideal fiber length (50 mm), provided an optimum value increase in the compression test of 12.61%, 72.64% in the tensile test, and 98.98% in the flexural test of the normal concrete mixture [32]. The modulus of elasticity of abaca fiber concrete with a fiber length of 50 mm and a fiber volume of 0.15% presents the optimal parameters, providing 14.96% greater results in comparison to normal concrete [31]. For composites, the results of physical-mechanical properties reveal that % porosity, % water absorption, and % compressibility increase as the percentage of abaca fiber and Kevlar fiber in the polymer composite increase, while ash, hardness, and density decrease with an increased percentage of abaca and Kevlar fiber in the composite matrix [36].

In this context and in accordance with the great availability of abaca (Musa textilis) fiber in Ecuador, this research work seeks to examine the effect of abaca fiber (in different lengths and amounts) as an improved material through unconfined compression resistance.

The article consists of the following five sections: the details of the laboratory tests performed on the soil and the abaca fiber, the properties of the materials, the testing program, and the statistical analysis methodology will be presented in Section 2. In Section 3, the results obtained from the compaction curves for each length and percentage of fiber used, the unconfined compressive strength of each mixture, and the statistical analysis are presented. These results are discussed in Chapter 4, where a comparison with recent research related to the reinforcement of soil with other fiber types is presented. Finally, the conclusions are detailed in Section 5.

2. Materials and Methods

2.1. Soil

The soil used in the present investigation was obtained from Pomasqui, Quito, Ecuador. The material tested has a light brown color and is non-plastic. To characterize the physical properties of soil, it was sieved through sieve No. 4 to work with particles smaller than gravel. The procurement of soil samples and their processing in the laboratory are shown in Figure 1. Soil properties are presented in Table 1.

Figure 1. Soil sampling.

Table 1. Soil Properties.

Soil Properties	Values
Specific Gravity	2.66
Water Content	8.54%
Atterberg limits	
Liquid Limit	Nonplastic
Plastic Limit	Nonplastic
Plastic Index	Nonplastic
USCS Classification	ML
AASHTO Classification	A-4(0)
Grain Size Analysis	
Gravel	0.0%
Sand	42.7%
Silt	55.8%
Clay	1.5%
Optimum Water Content	15.4%
Maximum Dry Density	1.734 g/cm^3

The particle size distribution by sieving is obtained using the procedure of the ASTM D6913/6913M-17 standard: Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis [38]. To obtain fine particles from the soil, corresponding to clays and silts, the procedure of the ASTM D7928-21 standard was used: Standard Test Method for Particle-Size Distribution (Gradation) of Fine-Grained Soils Using the Sedimentation (Hydrometer) Analysis [39]. The results of both tests can be seen in Figure 2. Applying the ASTM D2487-17 standard [40], the soil corresponds to low plasticity silt, ML.

The modified compaction test allows finding the percentage of compaction and humidity for engineering purposes, which consists of improving the characteristics of the soil. These purposes consist of improving the mechanical characteristics of soil such as shear strength, compressibility, or permeability [41]. The modified compaction test follows the procedure of ASTM D1157-12: Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lb/ft3 (2700 kN-m/m^3)) [41]. The compaction curve obtained with this method can be seen in Figure 3, with an Optimum Water Content of 15.4% and a Maximum Dry Density of 1734 g/cm^3.

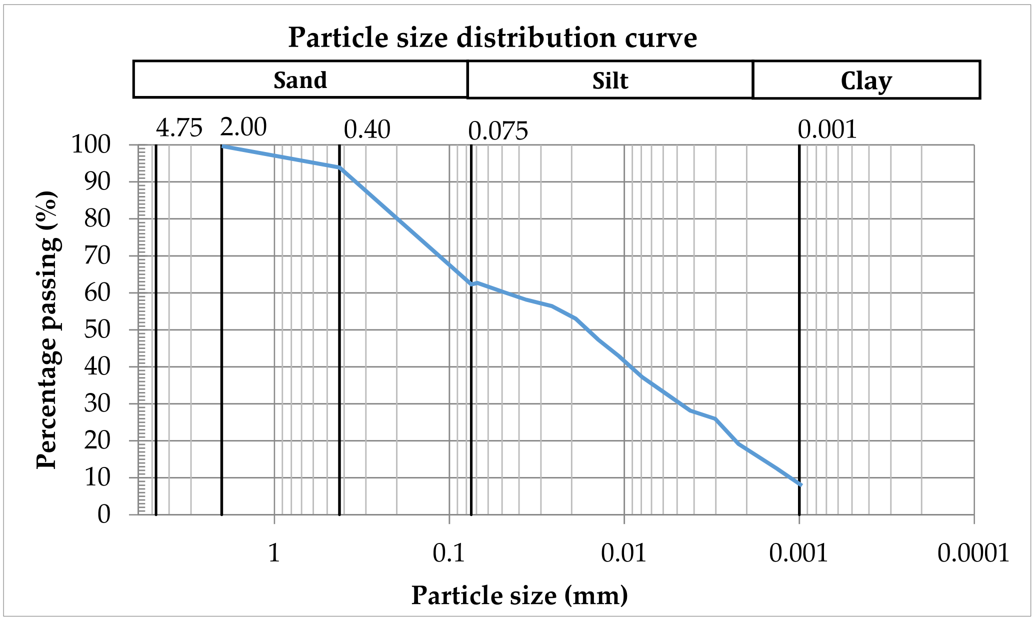

Figure 2. Particle Size Distribution Curve.

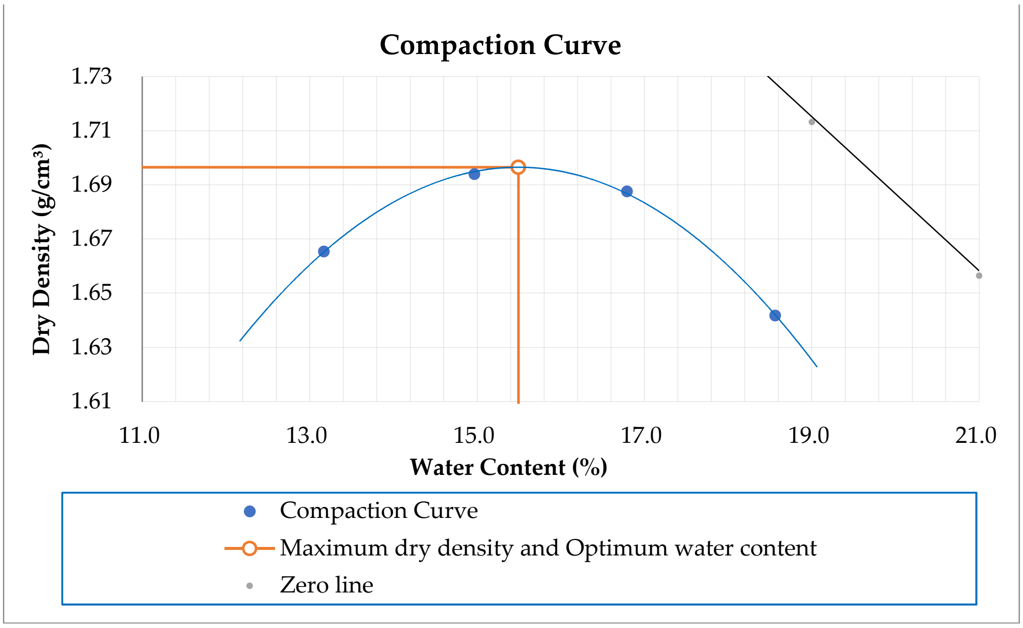

Figure 3. Soil Compaction Curve.

2.2. Abacá Fiber

Abaca fibers were obtained from Monterrey, Santo Domingo de los Tsáchilas, Ecuador. The fibers were cut into three lengths: 5, 10 and 15 mm, approximately. Before preparation, tests were conducted to characterize the fibers. The physical and mechanical properties, such as chemical composition, are shown in Tables 2 and 3, respectively. An image of the cut fibers before being added to the soil can be seen in Figure 4.

Table 2. Physical and mechanical properties of the fiber.

Fiber Properties	Values
Linear Density	40.9 Tex *
Water Content	6.11%
Tenacity	52.5 Cn/Tex
Breaking Load	21.4 N
Strain at Break	1.74%

* Tex: Mass in grams in 1000 m of fiber. Source: Tests conducted in CTP-Escuela Politécnica Nacional.

Table 3. Fiber Chemical composition.

Chemical Properties	Values
Cellulose	63.35%
Hemicellulose	18.30%
Lignin	6.30%
Ash Content	0.76%
Fats	1.24%

Source: Tests conducted in CESAQ-Pontificia Universidad Católica del Ecuador.

Figure 4. Abaca Fibers.

2.3. Specimen Preparation

The percentages and lengths of fiber were selected based on different studies [22,42]. A total of four fiber concentrations were selected: 0.5%, 1.0%, 1.5%, and 2.0% in relation to the dry weight of the soil as indicated by Equation (1); and three different lengths were cut: 5 mm, 10 mm, and 15 mm. With the selected percentages and fiber lengths, 13 different combinations were prepared as shown in Table 4.

Table 4. Soil–fiber mixtures.

Mixture No.	Fiber Content (%)	Fiber Length (mm)	Minimum No. of Specimens
1	0	0	2
2	0.5	5	2
3	1.0	5	2
4	1.5	5	2
5	2.0	5	2
6	0.5	10	2
7	1.0	10	2
8	1.5	10	2
9	2.0	10	2
10	0.5	15	2

Table 4. *Cont.*

Mixture No.	Fiber Content (%)	Fiber Length (mm)	Minimum No. of Specimens
11	1.0	15	2
12	1.5	15	2
13	2.0	15	2

The fiber content is given by Equation (1),

$$pf = \frac{wf}{w} \tag{1}$$

where *pf* is the fiber content, *wf* is the weight of the fiber and *w* is the dry weight of the soil.

The specimens were manually mixed, beginning with the addition of fiber to the soil (in the determined concentrations and lengths). Next, water was added according to the optimal water content (OWC) determined for each mixture. The soil–fiber mixtures were then left standing for 24 h. Subsequently, the specimens were compacted using the Harvard Miniature Compaction Apparatus in 8 layers in a mold 33.4 mm in diameter and 72.6 mm in height. The determination of the number of layers and blows necessary was adjusted so that the mixtures reach 95 ± 5% of the maximum dry density. This was achieved through trial-and-error tests until reaching the conclusion that 8 layers of soil with 45 blows each were necessary. The soil–abaca fibers mixture, the Harvard Miniature Compaction Apparatus, and the sample compaction process can be observed in Figure 5. Finally, the specimens were subjected to the simple unconfined compression test.

(**a**) (**b**) (**c**)

Figure 5. (**a**) Soil–Abaca fibers mixture, (**b**) Harvard Miniature Compaction Apparatus, (**c**) Sample compaction process.

2.4. Testing Program

For the determination of the OWC and maximum dry density (ρ_d), compaction tests were conducted according to ASTM D1557-12 [41]. The test mold has a height of 116 mm and a width of 102 mm. The hammer weighs 4.54 kg and has a fall height of 457.2 mm [41]. As detailed previously, the specimens were compacted using the Harvard Miniature Compaction Apparatus; in 8 layers in a mold 33.4 mm in diameter and 72.6 mm in height with the OWC obtained in the compaction tests.

The simple unconfined compression test was performed in accordance with ASTM D 2166-16 "Standard Test Method for Unconfined Compressive Strength of Cohesive Soil" [43]. A load was applied to produce an axial strain rate of 1% to the specimen for every minute. The maximum unconfined compression stress occurs when the specimen indicates a brittle failure or when its unit strain reaches 15% (whichever occurs first) [43]. The ELE Compression Frame, capable of performing simple and triaxial compression tests, model 25-3518/02, was used for compression of the samples. The compression equipment, as well as an example of a sample during and after the test, can be seen in Figure 6. All obtained data were tabulated, and an average was obtained from each combination of percentage and length, which is indicated in Figures 7 and 8. From these average values, a discussion and comparison with other fiber-improvement research works were performed in Section 4.

(**a**) (**b**) (**c**)

Figure 6. (**a**) ELE Compression Frame, (**b**) Sample during test, (**c**) Sample after the test.

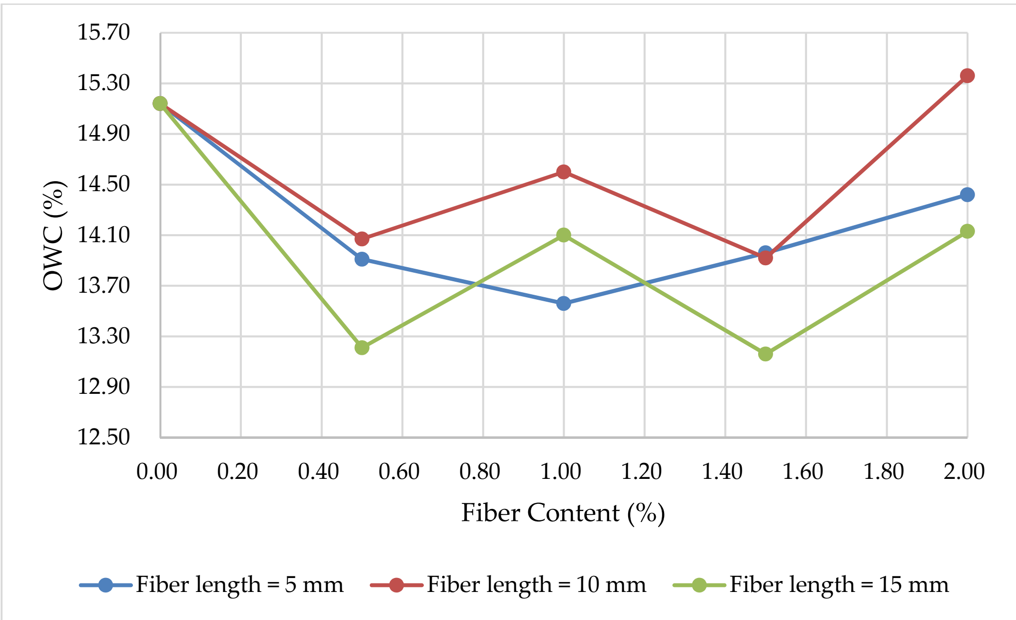

Figure 7. Levels of optimum water contents relative to percentage of fiber content.

2.5. Statistical Analyses

Because multiple readings of deformation and effort were gathered from the various experimental conditions, the study design violated the fundamental assumption of residual independence (i.e., pseudoreplication occurs). For a better understanding of the implications and consequences of not controlling for pseudoreplication effects, consider two experimental categories A and B. Under this hypothetical scenario, researchers collected data at various time points for each category: A1, A2, A3, B1, B2, and B3. It follows that the value of the criterion variable should be more similar within each group (A1, A2, and A3) relative to between groups (A1 and B1). Under these quantitative conditions, the use of statistical procedures not controlling for the repeated measures increases the probability of detecting incorrectly a significant effect (Type I error) as well as inflating the magnitude of the associated effect sizes. Consequently, the nature of the current study required the implementation of statistical models that control for underlying pseudoreplication.

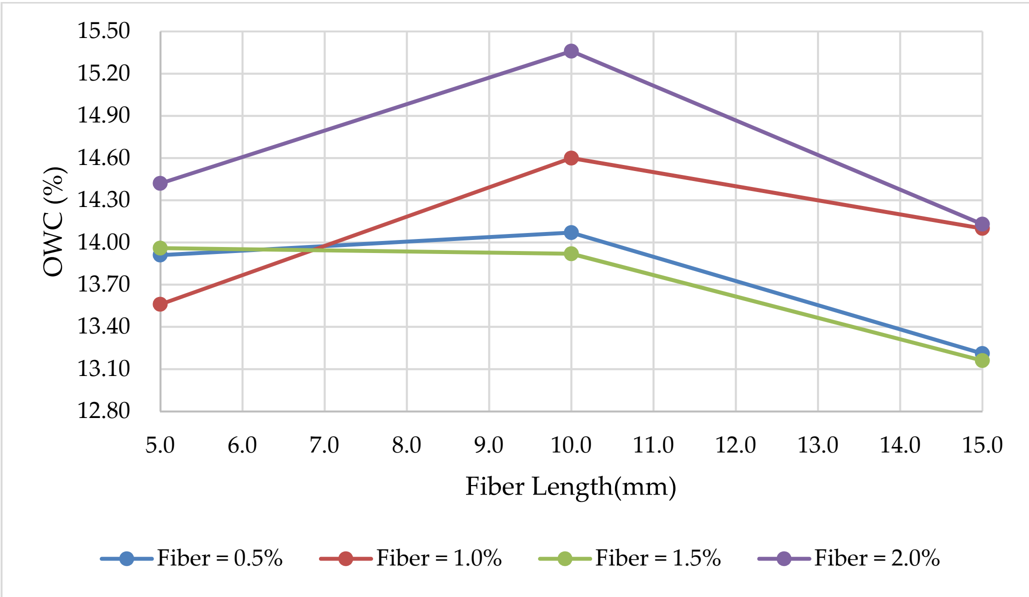

Figure 8. Levels of optimum water contents relative to percentage of fiber length.

Two linear mixed models with log10 transformation were computed to establish the degree to which the various treatments (considering the length and percentage of fiber) differed on the level of effort and unitary deformation, relative to the control condition. The models' estimations employed restricted maximum likelihood and used the trial ID as random effects. Rather than computing several post hoc comparisons, this study used the control condition as a reference category. It is worth noting that due to singularity issues, instead of using length and percentages as independent categories, these predictions were collapsed into a single factor comprised of 10 levels. The presence of outliers was assessed by standardizing the variables and winsorizing all values outside of a range of −3.0 to +3.0 standard deviations away from the mean. All statistical analyses were computed in R v.3.5.3 with the statistical packages lme4 [44], lmertest [45], and car [46].

3. Results

3.1. Compaction Behavior

The Optimum Water Content (OWC) and Dry density (ρ_d) were obtained from the compaction test.

The influence of the fiber on the OWC shown in Figures 3 and 4 does not follow a marked trend following variations in fiber content, length, or both. This behavior could be a consequence of interactions between the water and vegetable fibers, showing its absorption effect, which would not be significant for the percentages of fiber used in this research.

It is observed that the ρ_d of the soil–fiber mixtures tends to decrease when the fiber is increased in percentages that vary from 1.0% to 2% of the loose dry weight of the soil as observed in Figure 5. This decrease can be mainly justified by a greater occupation of spaces by the fiber (which is lighter than the soil), translating into a decrease in unit weight. This effect is also justified by the formation of lumps or fiber accumulations (especially in 1.5% and 2% fiber mixtures), which formed areas of low density [47]. The reduction in ρ_d also occurs because the fiber in the soil matrix produces some resistance to compaction, producing lower unit weights as the fiber content increases [12]. The effect of the fiber length on the ρ_d of mixtures is observed in Figure 6.

Fiber length is an important factor in ρ_d behavior; it is evident that, for each percentage of fiber, as its length increases, a decrease in ρ_d occurs in most cases, except for the 0.5% fiber mixture, where the maximum dry density rises. This can be attributed to a better packing configuration since the fibers and smaller soil particles fill the voids generated in the mixture, which has been observed in other investigations with fibers used in soil [48].

In this way, exchange rates of ρ_d vary from 0% to −1.94% (the latter with fibers of 15 mm at 2%), that is, the decrease rate is greater with larger fiber lengths. The decrease is justified because with regard to the fiber, the longer its length, the easier it will form lumps, which produces areas of low density and therefore a decrease in ρ_d. This tendency to form lumps was evidenced in the present research when using fibers of 15 mm or greater.

3.2. Unconfined Compression Strength

In Figure 8, the stress–strain curves for the lengths of 5, 10 and 15 mm are observed. It is shown that the maximum effort increased by the inclusion of fibers, regardless of the amount and length. Through the curves, the greater the inclusion of fibers, the increased maximum effort is evidenced; this happens for all the proposed lengths. In the curves a maximum effort of 206.68 kPa is observed for the soil without fibers.

For fibers with a length of 5 mm, there is an increase in the maximum stress of 272.57 kPa, 389.30 kPa, 470.29 kPa and 561.89 kPa for mixtures of 0.5%, 1.0%, 1.5% and 2.0%, respectively. Similarly, for 10 mm lengths, the peak stress increases to 304.81 kPa, 540.74 kPa, 648.20 kPa, and 877.19 kPa for fiber inclusions of 0.5%, 1.0%, 1.5%, and 2.0%, respectively. For lengths of 15 mm, the maximum stress of simple compression increases by 503.27 kPa, 677.25 kPa, 992.86 kPa and 2552.69 kPa for fiber percentages of 0.5%, 1.0%, 1.5% and 2.0% respectively.

3.3. Linear Mixed Models with REML and Log10 Transformation

The linear mixed model determined that relative to the control conditions, (except for 0.5 cm length and 0.5% fiber, and 1 cm length and 0.5% fiber) most of the experimental treatments had a statistically significant positive effect in the level of effort (Figure 9). The model also identified that ID had negligible variance (see Table 5).

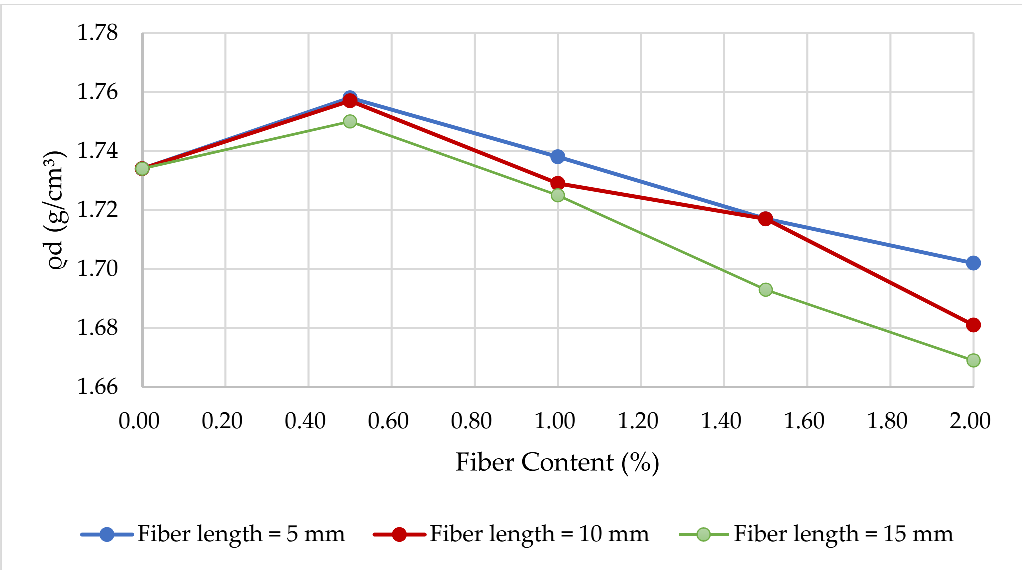

Figure 9. Max. Dry density vs. Fiber Content.

Alternatively, the linear mixed model exploring the difference between the experimental treatments and the control condition identified a positive and significant effect of 1 cm and 2%, 1.5 cm and 1.5%, and 1.5 cm and 2%, on the degree of unitary deformation (see Figures 10 and 11). The random effects analyses estimated that ID's variance remained low (Table 6).

Table 5. Linear mixed model examining the effect of condition on the log10 transformed effort. The model used ID as a random effect with control as a reference category. The estimation procedure was computed using REML.

Random Effects					
Groups	*Variance*	*Std.Dev.*			
ID	0.005	0.071			
Residual	0.326	0.571			
Fixed Effects					
Indicator	*Estimate*	*Std. Error*	*Df*	*t value*	*Pr(>∣t∣)*
(Intercept)	1.78	0.08	136.39	22.83	<0.0001
0.5 cm and 0.5%	0.10	0.11	125.37	0.87	0.39
0.5 cm and 1%	0.34	0.11	141.60	3.08	0.00
0.5 cm and 1.5%	0.42	0.11	124.62	3.86	0.00
0.5 cm and 2%	0.49	0.11	107.21	4.42	0.00
1 cm and 0.5%	0.20	0.10	127.99	1.98	0.05
1 cm and 1%	0.47	0.10	99.55	4.67	0.00
1 cm and 1.5%	0.64	0.10	99.22	6.32	0.00
1 cm and 2%	0.80	0.10	73.86	7.88	0.00
1.5 cm and 0.5%	0.44	0.11	117.43	4.17	0.00
1.5 cm and 1%	0.64	0.10	98.46	6.32	0.00
1.5 cm and 1.5%	0.90	0.09	81.89	9.72	0.00
1.5 cm and 2%	1.13	0.09	74.97	12.61	<0.0001

Note. Indicator: Predictors in the Mixed Model; Estimate: Statistical parameter concerning the unit-change in the effort as a function of percentage and length; Std. Error: Standard Error associated with the estimates; Df: Degrees of freedom; t-value: Test statistic; Pr(>∣t∣): Significance test based on the value of the critical t relative to the estimated t-value.

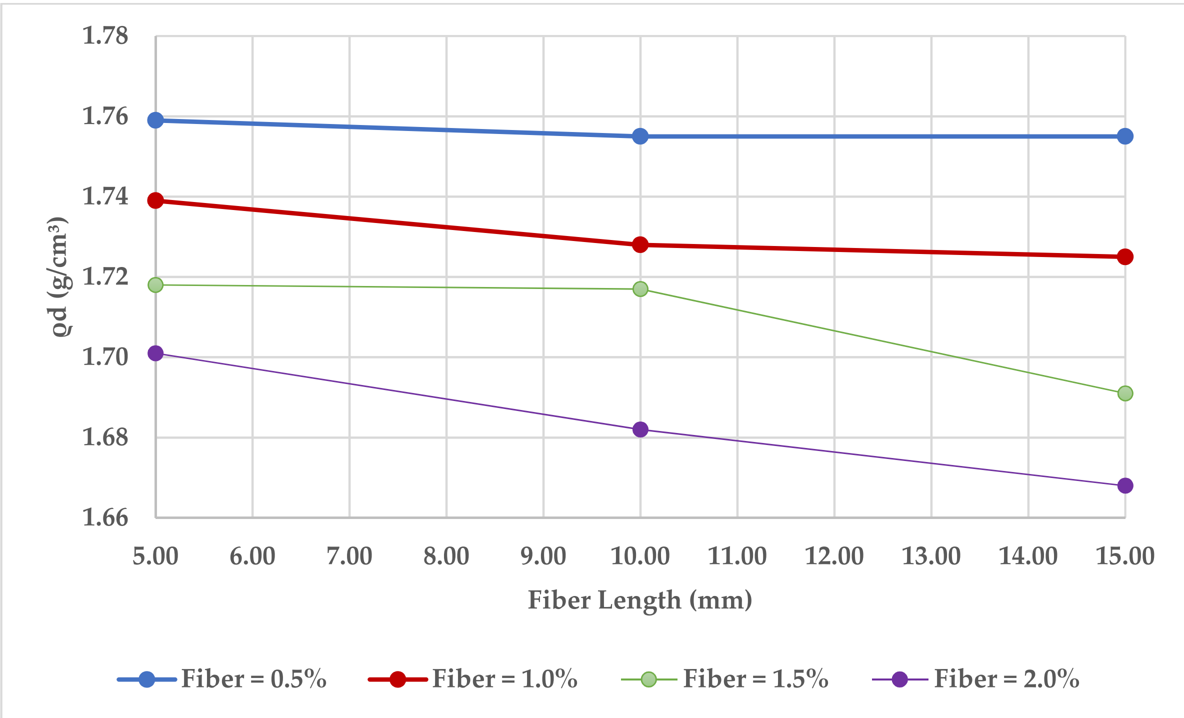

Figure 10. ρ_d vs. Fiber Length.

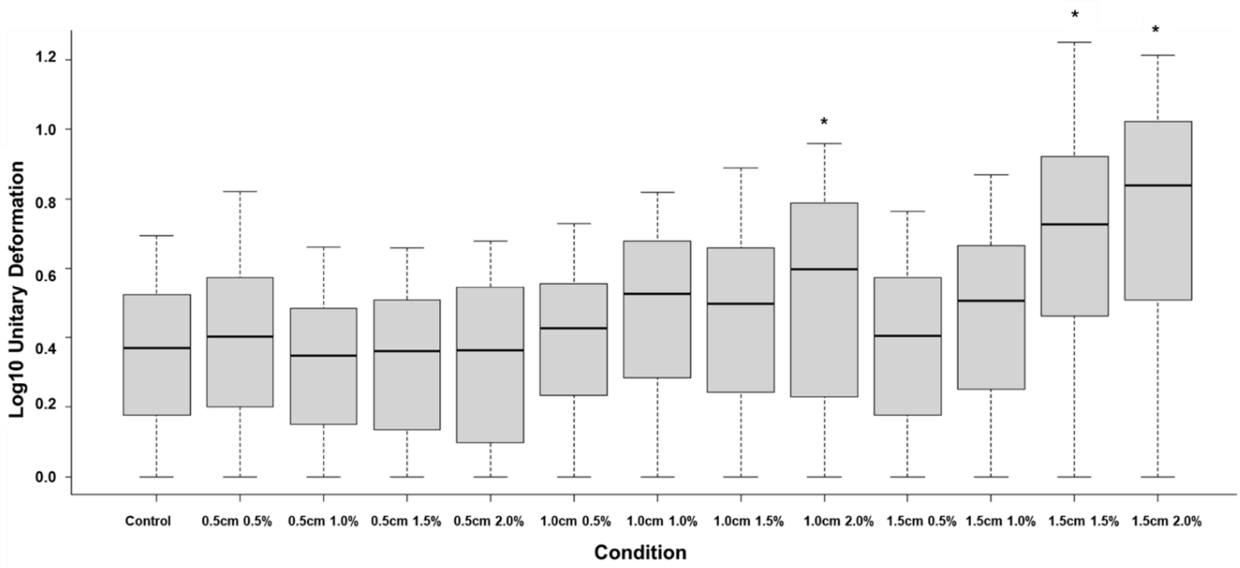

Figure 11. Boxplots evidencing the variation in log10 unitary deformation due to various experimental conditions. Note: * statistically significant difference between experimental and control conditions.

Table 6. Linear mixed model examining the effect of condition on the log10 transformed unitary deformation. The model used ID as a random effect, with control as a reference category. The estimation procedure was computed using REML.

		Random Effects			
Groups	*Variance*	*Std.Dev.*			
ID	0.007	0.082			
Residual	0.076	0.276			
		Fixed Effects			
Indicator	*Estimate*	*Std. Error*	*df*	*t value*	*Pr(>|t|)*
(Intercept)	0.34	0.05	62.76	6.46	0.00
0.5 cm and 0.5%	0.02	0.08	62.92	0.26	0.80
0.5 cm and 1%	−0.02	0.08	63.86	−0.31	0.76
0.5 cm and 1.5%	−0.02	0.07	59.90	−0.22	0.83
0.5 cm and 2%	−0.01	0.08	55.20	−0.09	0.93
1 cm and 0.5%	0.04	0.07	60.67	0.58	0.56
1 cm and 1%	0.13	0.07	53.31	1.77	0.08
1 cm and 1.5%	0.10	0.07	53.59	1.44	0.16
1 cm and 2%	0.18	0.08	46.54	2.35	0.02
1.5 cm and 0.5%	0.02	0.07	58.46	0.30	0.77
1.5 cm and 1%	0.11	0.07	53.29	1.56	0.12
1.5 cm and 1.5%	0.29	0.07	49.55	4.34	0.00
1.5 cm and 2%	0.39	0.07	47.00	5.89	0.00

Note. Indicator: Predictors in the Mixed Model; Estimate: Statistical parameter concerning the unit-change in the effort as a function of percentage and length; Std. Error: Standard Error associated with the estimates; Df: Degrees of freedom; t-value: Test statistic; Pr(>|t|): Significance test based on the value of the critical t relative to the estimated t-value.

4. Discussion

Stress–strain curves from unconfined compression tests show an increase in ultimate stress and in the tangential elastic modulus of specimens reinforced with abaca fiber (when compared to fiber-free specimens). These increases are produced by an interconnection force generated by the three-dimensional confinement network that forms the fiber in the soil matrix [22,27]. The increase in tangential elastic modulus implies a greater rigidity of the specimens and therefore greater resistance to compression. As indicated in Table 7, the tangential elastic modulus shows a marked trend with increasing fiber length with respect to its content. However, regarding this tendency of the tangential modulus of elasticity to increase, certain exceptions are observed, where the modulus of elasticity decreases despite increasing the percentage of fiber, for example, in the 5 mm fiber, the elastic modulus of 1% fiber content is 29,853 kPa, and decreases by 1.5% fiber content at 26,852 kPa. This effect is also observed in the 10 mm fiber, from 1.5% to 2.0% fiber content, and in the 15 mm fiber, from 0.5% to 1.0% fiber content. Considering that the tests were controlled and conducted under existing standards and procedures, these variations could probably be explained by two reasons. The first is that, when looking at the statistical data, a clear trend can be seen in the increase in length or percentage of fiber with the effort resisted by the samples. However, it is not so clear with the deformation, which would cause slight variations in the interpretation of the modulus of tangential elasticity. The second is the possible influence of the mixing and compaction process, despite the care taken in the process of executing the samples, which might generate a non-homogeneous distribution of the fibers throughout the specimen. This evidences a need to continue investigating the mixing and compaction procedures for fiber–soil mixtures, which should be investigated in greater depth in future research.

Table 7. Tangential elastic modulus.

Fiber Length (mm)	Fiber Content (%)	Elastic Modulus (kPa)
0	0	12,445
5	0.5	26,140
	1	29,853
	1.5	26,852
	2	31,150
10	0.5	26,578
	1	30,844
	1.5	45,657
	2	33,630
15	0.5	40,932
	1	38,288
	1.5	48,316
	2	52,347

The inclusion of natural abaca fiber in the percentages and lengths studied leads to improved resistance to simple compression of the soil. The maximum compression stress (qu) increases with an increased percentage of added fiber, length, or both. Among all the specimens, a maximum qu of 2552.69 kPa was recorded with a strain of 10.52%, in comparison to the maximum effort of 206.68 kPa observed for soil without fibers at 1.98% strain, representing a 1235.1% increase in maximum compression stress. The available bibliography affirms that the addition of fiber produces an improvement in the stress-deformation behavior, in peak and post-peak soil resistance [10,14–17]. However, regarding maximum compressive stress in fiber-reinforced soils, the increases in percentage range from 20% for silt-clay soils with sisal fiber [14], 38% with corn fiber [22], up to 85.6% with coconut fiber [42], thus highlighting the sheer magnitude of a 1235.1% increase. Considering the same strain at the peak stress of the unreinforced soil, of 1.98%, the soil reinforced with 2% fiber of 1.5 cm length, reaches 1071 kPa, which represents a 498% increase in its resistance. In a recent study, an analysis was performed on the effect of randomly distributed natural fibers on certain geotechnical characteristics of a lateritic soil containing 90 mm lengths of coconut fiber. The authors reported a 320% increase in the unconfined compression test, with maximum dry densities of the soil decreasing as fiber content was increased, whereas the optimum moisture content increased with increasing fiber content as observed in the present study [49]. Regarding future research employing these fibers, we recommend measuring the deformations with local LVDTs under more controlled conditions, such as in Triaxial CD tests, and evaluating the changes in shear resistance angle when reaching the critical condition with the fibers for further bio-inspired geotechnical applications.

5. Conclusions

A series of experimental tests were conducted to study the effect of randomly distributed abaca fibers on the simple compression resistance of soil. The following conclusions are derived from experimentation:

The dry density ρ_d of the soil–fiber mixtures tends to decrease when the fiber percentage is increased varying from 1.0% to 2%. The decrease can be mainly justified by a greater occupation of spaces by the fibers (which are lighter than the soil), which translates to a decrease in unit weight. This effect is also justified by the formation of lumps or fiber accumulations (especially in mixtures with 1.5% and 2% fiber), which form areas of low density [47]. The reduction in ρ_d also occurs because the fiber in the soil matrix produces some resistance to compaction, producing lower unit weights as the fiber content increases [12]. Regarding the 0.5% fiber mixture, the maximum dry density rises. This can be attributed to a better packing configuration since the low content of fibers and smaller soil particles fill the voids generated in the mixture, which was observed in other investigations with fiber used in the soil [48], as observed in Figure 5.

Stress–strain curves from unconfined compression tests show an increase in ultimate stress and in the tangential elastic modulus of specimens reinforced with abaca fiber (when compared to specimens without fiber). These increases are produced by an interconnection force generated by the three-dimensional confinement network that forms the fiber in the soil matrix [22,27]. The increase in tangential elastic modulus implies a greater rigidity of the specimens and therefore greater resistance to compression. As indicated in Table 7, the tangential elastic modulus shows a marked trend with increasing fiber length with respect to its content. However, in this tendency of the tangential modulus of elasticity to increase, certain exceptions are observed, where the modulus of elasticity decreases despite increasing the percentage of fiber, for example, in the fiber of 5 mm length, the elastic modulus of 1% fiber content is 29,853 kPa, and it decreases at 1.5% fiber content to 26,852 kPa. This effect is also observed in the 10 mm fiber, from 1.5% to 2.0% fiber content, and in the fiber of 15 mm, from 0.5% to 1.0% fiber content. Two possible reasons for this effect are discussed in the article, based on the statistical results of the deformation of the samples -related to its effect on the interpretation of the elastic modulus- and the molding of the samples -related to the internal distribution of the fibers in the soil-, which should be studied in greater depth in future research.

Including natural abaca fiber in the proposed percentages and lengths improves resistance to simple soil compression. The maximum compression stress (qu) increases with an increased percentage of added fiber, length, or both, as seen in Figure 12. Among all the specimens, a maximum qu of 2552.69 kPa with a strain of 10.52% was recorded with 15 mm length fiber used in a percentage of 2% of the dry weight of the soil in comparison to the maximum effort of 206.68 kPa observed for the soil without fibers at a 1.98% strain, which represents an increase of 1235.1% in the maximum compression stress (qu) with respect to the unreinforced soil, as seen in Figure 12c. Statistically, the linear mixed model determined that relative to the control conditions, (except for 0.5 cm. length and 0.5% fiber, and 1 cm. length and 0.5% fiber) most of the experimental treatments had a statistically significant positive effect in the level of effort, as seen in Figure 13 and Table 5.

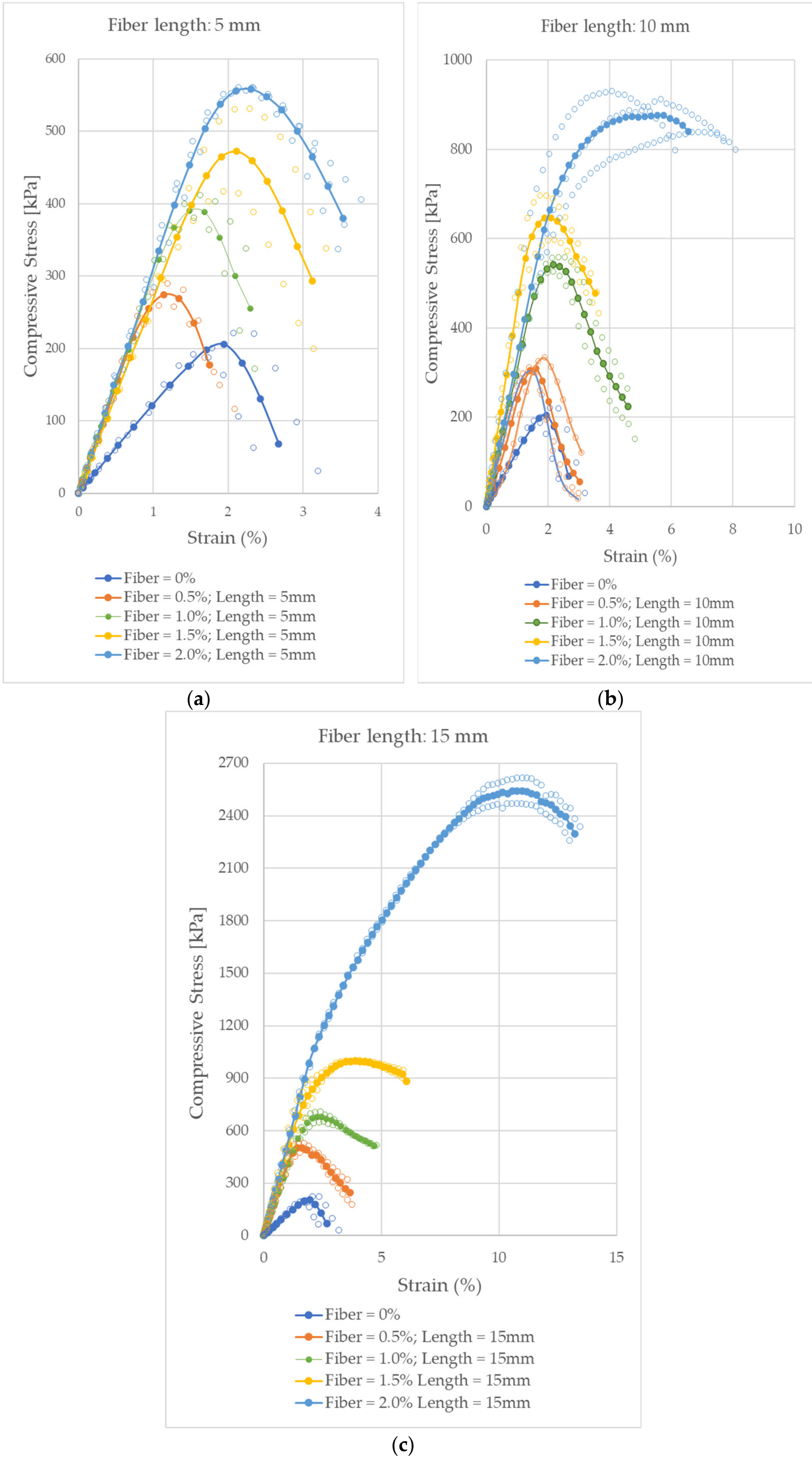

Figure 12. Stress–strain curve with variations of fiber content and fiber length (**a**) 5 mm; (**b**) 10 mm; (**c**) 15 mm.

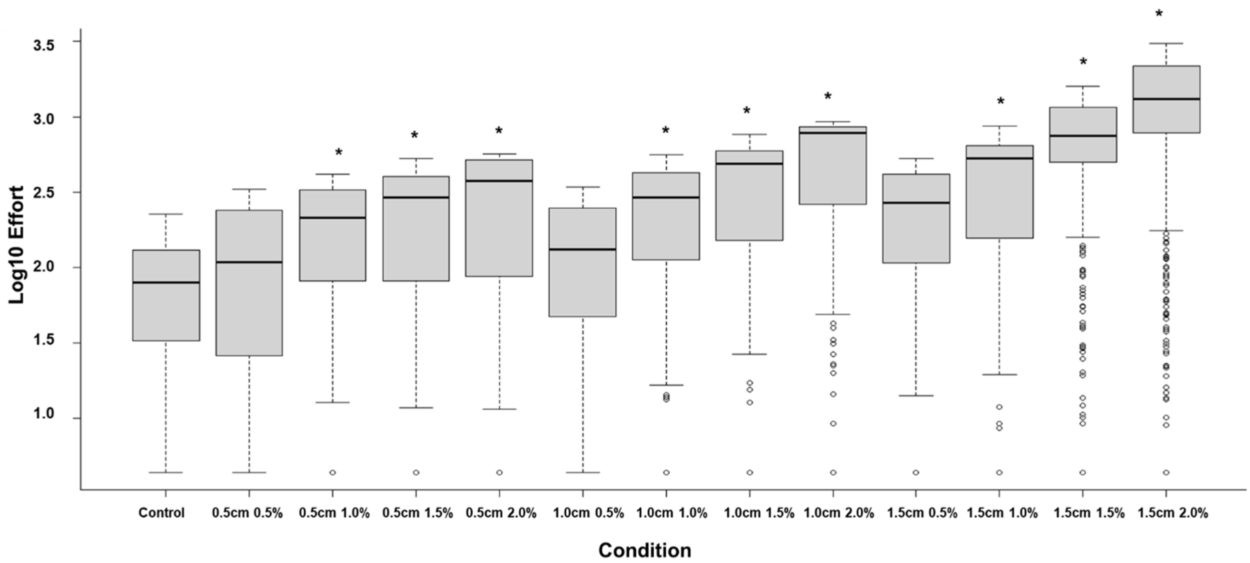

Figure 13. Boxplots evidencing the variation in log10 effort due to various experimental conditions. Note: * statistically significant difference between experimental and control conditions. Extreme values fell within a range of −3 to 3 standard deviations.

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