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Assessment of Predictability of Fiber-Reinforced Cemented Soils Unconfined Compressive and Tensile Strength

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Abstract. Soil improvement techniques as part of the design of transmission towers' foundations are being studied by the market. Considering the admixture of these materials can be performed by surface mixing, the cement and fibers show potential application in construction sites with difficult access, in which the use of large equipment is unfeasible. In order to make this alternative applicable, it is necessary to understand the complexity of calibrating a dosage method, due to the numerous mixtures' variables. With the objective of predicting the strength of improved soils with polypropylene fibers and type III cement, previous researchers have developed an equation which ties the amounts of these materials to the unconfined compressive and tensile strength of the mixtures. This equation is adjusted by an external coefficient named α . The assessment of some of the key factors that influence the value of α was done by the following research. Results suggests the tensile strength of the polypropylene fibers and the curing time of the specimens do not have an influence on the coefficient value. When compared to unimproved soils, the addition of 0.5% polypropylene fibers alone did not result in significant gains in tensile strength (11%) but provided an increase in soil ductility. The combined addition of polypropylene fibers and cement resulted in significant gains in both unconfined compressive (up to 700%) and tensile strength (up to 480%).

Keywords. Soil improvement, polypropylene fibers, cement, foundations of transmission towers.

1. Introduction

Many soil improvement technologies often require the use of large equipment or transporting large quantities of materials to the site. Therefore, construction sites with difficult access are not feasible to receive some improved soil solutions as an alternative for the design of foundation with reduced sizes – which could be a convenient approach for transmission line construction companies, given the typical standardization of projects within a certain area. Indeed, these companies are searching for solutions to this problem by finding alternatives to the foundations of transmission towers through soil improvement technologies that are easily applied to hard-to-reach areas [1].

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In this context, soil improvement with polypropylene fibers and cement is an attractive technology: the superficial mixing of these materials does not require large equipment; the loaded weight in cement is not heavy, given the small percentage by mass that is normally mixed to the soil [2]; the mass of the polypropylene fibers is negligible. In addition, because the main types of transmission towers' foundations require backfilling [3], the surface mixing technique seems to be coherent. Being able to be carried out in a soil that is already removed as part of the foundations' construction process itself, the mixture is efficient, as it does not require a totally separate intervention.

2. Background

Historically, soils have been improved with fibers for a long time. Some indications of the use of this technique go back to the construction of the Great Wall of China - with the use of vegetable fibers - and the construction of Inca roads - with the use of llama wool. [4]. However, great advances in this area only occurred during World War II, due to military needs, in the construction of routes above soils with small bearing capacity [5]. Polypropylene fibers have been considered the most promising due to their high tensile strength, water inertia and application flexibility [6]. The addition of fibers to the soil increases the strength of the mixture, besides increasing the ductility [7]. These characteristics can be explained by the fact that fibers maintain the interfaces of the fractures together, being beneficial to the properties of composite materials, especially after their rupture [8].

Therefore, the combined addition of fibers and cement seems interesting. The addition of cement to the soil alone generates little increase in tensile strength, besides increasing the fragile rupture behavior of the mixtures [9]. To counteract the brittle behavior of cemented soils, the insertion of fibers can be performed [10]. Moreover, to counteract the poor tensile and flexural strength gains of improved soils with cement alone, the addition of fibers is advantageous - for mixtures with up to 10% cement [11]. In fact, the addition of fibers even increases the unconfined compressive strength of cemented soils [2]. Regarding the strength predictability of fiber-reinforced cemented soils, the amount of cement and the porosity of the mixture are key parameters for the evaluation of unconfined compressive and tensile strength, given by Eqs. (1), (2) and (3) [12 and 13].

$$\eta = 100 - 100 \left\{ \left[\frac{\gamma_d}{1+C/100+F/100} \right] * \left[\frac{1}{\gamma_{s_s}} + \frac{C/100}{\gamma_{s_c}} + \frac{F/100}{\gamma_{s_f}} \right] \right\} \quad (1)$$

$$C_{iv} = 100 * \frac{C * \gamma_d}{(1+C) * \gamma_{s_c}} \quad (2)$$

$$q_u \text{ or } q_t = A \left[\frac{\eta}{C_{iv}^{0.28}} \right]^{-\alpha} \quad (3)$$

For clayey sand, the original proposed x-axis (C_{iv}/η) was corrected by an internal coefficient equal to 0.28, as given by Eq. (4). It was observed that this value is a function of the soil and cement characteristics, because, regardless of the percentage of fibers used, it implied the best fit [14]. For several other soils tested, the value of the internal coefficient 0.28 was verified, and the external coefficient (α) suggested was 2.45 [15].

This statement is valid for the following restrictions: 1) Soils with at least 10% fines; 2) Polypropylene fibers, 0.023 in diameter and 6 mm to 24 mm in length, ranging from 0.25% to 0.75%; 3) Type III cement, ranging from 0.5% to 7%, 7 days of curing; 4) Δ between 15 and 80.

$$\Delta = \frac{\eta}{C_{iv}^{0.28}} \quad (4)$$

$$\frac{q_u}{q_u[\text{for a particular } \Delta]} \text{ or } \frac{q_t}{q_t[\text{for a particular } \Delta]} = \Delta^\alpha \left[\frac{\eta}{C_{iv}^{0.28}} \right]^{-\alpha} \quad (5)$$

3. Experimental materials and methods

This research used a soil and cement whose characteristics respect the restrictions listed previously but uses polypropylene fibers with very different tensile strength to those used for the calibration of $\alpha = 2.45$. Another variation was the curing time: in addition to 7 days, tests with curing times of 14 and 28 days were carried out. Thus, this research aimed to understand the influence of fiber tensile strength and curing time on the α value.

3.1. Materials

The available sand, representative of the soil found on the coast of the state of Paraná (Brazil), was collected from a sand deposit in the municipality of Pontal do Sul. The sand was then mixed with bentonite, ratio of 20%, in order to obtain a particularly unique soil, but still respecting a minimum of 10% fines. The resulting soil granulometry is observed in Figure 1. The specific gravity is 2.68. The dry unit weight (γ_d) is 1.74 g/cm³, while the optimum moisture content is 16.5%.

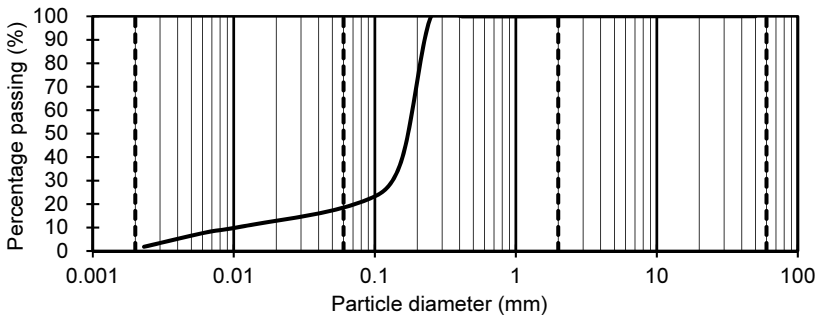


Figure 1. Particle-size distribution.

The fibers used are made of polypropylene, 24 mm long. These fibers receive the FibroMac24® nomenclature with the following characteristics: 1) Tensile strength equal to 300 MPa; 2) Elastic modulus equal to 3 GPa; 3) Length equal to 24 mm; 3) Thickness equal to 0.018mm. The cementitious material used is a high early strength Portland cement - Type III (ASTM C150-09) - with a specific gravity of 3.09.

3.2. Methods

Cylindrical specimens measuring 5 cm in diameter by 10 cm in height were molded according to Table 1. The cement contents are a function of the dry mass of the soil. The fiber content is a function of the dry mass of the soil plus the mass of the cement. The materials were mixed by hand, with 3 replicas, until complete homogenization. All the specimens were molded by manual compaction with the optimum moisture content of the soil. The humidity and mass of each specimens were recorded. During the curing time, the specimens were involved in plastic wrap and stored under controlled temperature (23°C). The true specific gravity achieved was calculated for every specimen. Unconfined compressive tests (based on ASTM C39-10), and splitting tensile test (based on ASTM C496-11) were performed.

Table 1. Mixture matrix.

Mixture	Cement content (%)	Fiber (%)	Target γ_d (g/cm ³)	Moisture (%)	Strength tests	Curing time (days)
S	0	0				-
F	0	0.5	1.74	16.5	Compressive & Tensile	-
CF	1, 2, 3, 5	0.5				7, 14, 28

4. Results and analysis

Under compressive loading, specimens improved with fibers alone have a higher maximum strength than unimproved specimens, and do not present a peak strength. Thus, it was defined that the rupture of the fiber-enhanced specimens occurred in the deformation of 15%. Comparatively, the fiber-free specimens had more abrupt ruptures. These characteristics corroborate that fiber-reinforced soils have great applicability in works that are susceptible to large deformations, such as reinforcement of road pavements [16]. This recommendation is due to the fact that- as it is also observed in Figure 2 -, improved soils with fibers have a more ductile behavior, with a residual strength higher than residual strength of unimproved soils. In summary, the addition of fibers resulted in a 62% increase in unconfined compressive strength (Table 2). The addition of cement to the mixture results in a less ductile behavior, resembling the unimproved specimens. On the other hand, the difference between the peak strength and the residual strength is not as large as in unimproved specimens. In summary, the addition of cement and fibers resulted in an increase of up to 700% in the unconfined compressive strength (for 5% cement, curing time of 24 days).

When subjected to splitting tensile tests, the most significant difference in behavior between unimproved specimens and fiber-reinforced specimens is that those have a peak when the vertical deformation is about 1 mm, as shown in Figure 3. Regarding the gains in strength, the addition of fibers increased the tensile strength by just 11%. This small gain is justified because the mobilization of the fibers does not occur in low deformations [17], which is verified during splitting tensile tests. Regarding the fiber-reinforced cemented specimens, the maximum tensile strength was taken to be the first peak, about 0.8-1.5 mm of vertical displacement, depending on the mixture, which was coincident with the appearance of the first cracks. In summary, the addition of cement and fibers resulted in an increase of up to 480% in the tensile strength (for 5% cement, curing time of 24 days).

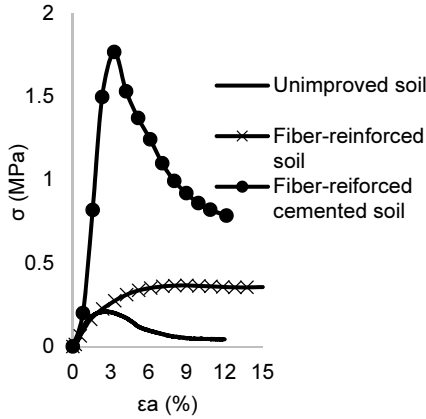


Figure 2. Unconfined compressive test typical behavior.

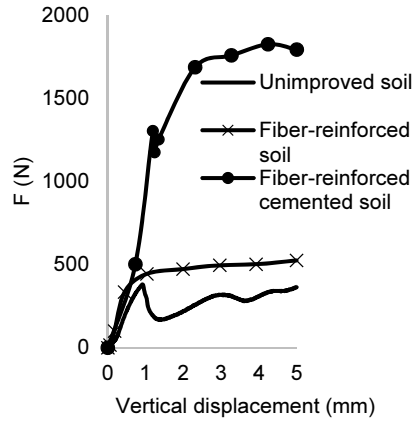


Figure 3. Tensile test typical behavior.

Table 2. Maximum strengths recorded.

Mixture C (%)	S					F					CF				
	-	-	1	2	3	5	1	2	3	5	1	2	3	5	
Curing time (days)	-	-			7				14				28		
qu (kPa)	216	349	407	487	542	576	597	638	969	1048	1158	1426	1598	1736	
qt (kPa)	47	52	81	92	89	108	126	134	152	193	184	235	255	273	

After plotting the strength data using Eq. (4) as the x-axis, the α values that generates the best fit of Eq. (5) are given in Table 3. These values were obtained throughout the applications of Eq. (5), normalized by $\Delta \approx 30$, although any Δ could be used for the normalization [18]. Even though the best fits are not when α equals 2.45, if this value is used, the value of R^2 is not considerably affected. This analysis is consistent since the α values found for each mixture varies, with 2.45 being the mean value that best fit all of them [15].

Table 3. Assessment of α value considering different curing times.

	α compressive	α tensile	R^2			
			α compressive	α tensile	$\alpha=2.45$ compressive	$\alpha=2.45$ tensile
7 days	3.31	2.99	0.961	0.943	0.903	0.915
14 days	3.36	2.81	0.893	0.924	0.839	0.914
28 days	2.87	2.68	0.942	0.761	0.922	0.756

Moreover, Figure 4 shows the compressive and tensile data of this research are well integrated into the normalized equation, referring to curing times of 7 days, from previous studies. It is important to note the α value that best fits this entire range of specimens is, indeed, still 2.45. For these reasons, it can be acknowledged the value of α does not seem to be influenced by the type of fiber. This assertion is supported by the fact that, even using fibers with different characteristics, the rupture behavior of the

specimens is expected to be similar: regarding the macrostructure, there is an increase in ductility; as for the microstructure, the tensioning of the fibers and sliding are expected, as can be observed in Figure 5. In fact, the microstructural behavior of an improved soil with fibers, of the most varied characteristics, is that part of them slip, while another part is pulled enough to be elongated [19]. In this study, however, the final fiber length (after the rupture of the specimens) was not measured to verify the latter information.

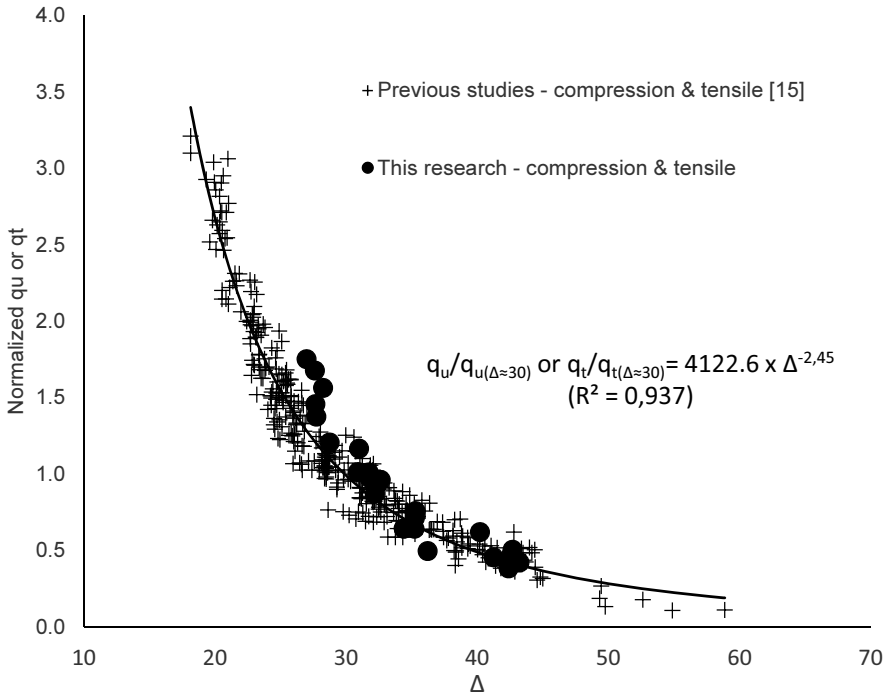


Figure 4. Normalized data under curing time of 7 days.

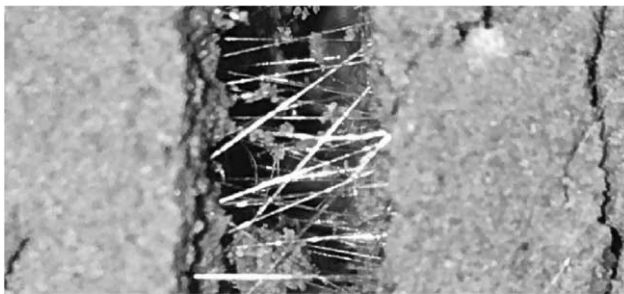


Figure 5. Tensioning of fibers during rupture.

Figure 6 suggests that the curing time moves the curves from Eq. (3) vertically, without normalization. This is due to the change in the value of A. This indicates an easy method to predict the strength of specimens for various times of curing. Thus, given the target strength, and the curing time to obtain it, it is possible to carry out the proper dosage by choosing the percentage of cement and compaction required.

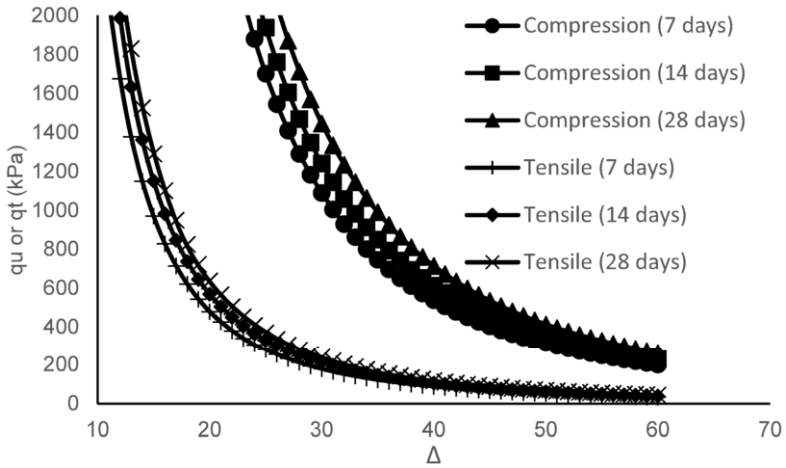


Figure 6. Best-fit curves for curing times of 7, 14 and 28 days.

5. Conclusions

- The addition of polypropylene fibers to the soil increases the ductility of the mixture. The addition of 0.5% of polypropylene fibers alone did not result in an expressive gain in the tensile strength of the soil (11%);
- Considering the design of transmission towers' foundation aims at small deformations, the main characteristic the polypropylene fibers-only addition implies to the soil (ductility) may not be relevant. However, it would be valuable to evaluate the behavior in cyclic loading;
- The combined addition of cement and fibers proved to be very interesting for this application, since it significantly increased the compressive (up to 700%) and tensile strength (up to 480%) of the soil;
- The external coefficient (α) seems to be independent of the tensile strength of the fibers - although a larger range of fibers should be tested. The curing time and the test performed (compressive or tensile) do not seem to influence it either.

Notation

C	cement content (dimensionless)
Civ	volumetric cement content (dimensionless)
F	fiber content (dimensionless)
qt	tensile strength (Pa)
qu	unconfined compressive strength (Pa)
R ²	coefficient of determination (dimensionless)
γ_d	dry unit weight (N/m ³)
γ_sC	specific gravity of cement (dimensionless)
γ_sF	specific gravity of fibers (dimensionless)
γ_sS	specific gravity of soil (dimensionless)
η	porosity (dimensionless)

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