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Evaluation of Soil-cement-fiber Composites Under Static Loads in Triaxial Tests

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ABSTRACT: In order to evaluate the effects of randomly distributed polymeric fibers elements on strength and deformability properties of a soil-cement matrix, drained triaxial compression tests were carried out. The data collected showed that the fibers presence increased the ductility improving cracking control and increasing ultimate strength when compared to samples without reinforcement. A fairly high aspect ratio fibers proved to be more effective in improving residual characteristics of the composite, while high aspect ratio fibers introduction showed to be more efficient increasing peak strength. The tenacity measured by strain energy, or area behind stress x strain curve, confirms the beneficial effects of fiber elements. The effect of the fiber inclusion was more evident for longer lengths. The composite stiffness is modified in different ways with the fiber addictions. The results achieved in this research clearly showed the importance and the potentiality of this kind of composite material in geotechnical engineering.

1 INTRODUCTION

Raising construction materials cost, reduction of natural materials availability and new demands/limitations in geotechnical construction, have been making engineers and researchers to look for new materials which associate good performance with low cost.

The addition of cements agents, like a Portland cement, is a technique of soils treatment that looks for improve its geotechnical properties. This procedure has been largely used for pavements, erosion control, slopes stabilization and reinforcement of superficial layers of soil. The compressive strength of both natural and artificially cemented soils has been studied in the past by several investigators, such Saxena et al. (1978), Clough et al. (1981), Leroueil and Vaughan (1990), Coop and Atkinson (1993) Schnaid et al. (2001) and Consoli et al. (2001).

The random inclusions of fibers in soil-cement has been proving the efficiency of this technique in the improvement of the mechanical features of the composite cemented material, essentially in the cracking control, increasing load capacity after peak, durability and ductility of the cemented material (Vidal, 1969; Crockford, 1993; Maher e Ho, 1993; Taylor, 1994; Hannant, 1994; Consoli et al., 1997; Specht, 2000). However, more work is necessary to comprehend the influence of different sort of fibers in characteristics of cemented soils.

Thus, this work has as general goal to study the mechanical behavior of an artificially cemented soil reinforced by random distributed polymeric fibers with distinct aspect ratio, under static loading conditions in triaxial tests. It will help to understand the behavior of reinforced cemented soils and try to establish a relationship among the individual features of the fibers and the mechanical behavior of the fibrous composite material.

2 BACKGROUND

The knowledge about the soil/fiber interaction is very important to understand the behavior of the mixture. This mechanism depends on several factors related with the matrix (soil, soil-cement or soil-lime) as grain size distribution, voids ratio and cementation degree, and with the reinforcement (fibers) as length, thickness, aspect ratio, roughness, stiffness, tenacity, etc.

Illston (1994) and Taylor (1994) presented the mathematical equation about the idealized strength balance when the fiber is loaded in the composite, as it demonstrates the Figure 1. In this hypothesis the fibers would be perpendicular to the cracking. It becomes evident the importance of the length of the fiber and its diameter. The relationship l/d or aspect ratio, as it is known, it is proportional to the quotient between the tensile strength (ft) of the fiber and the resistance of the adherence fiber/matrix (fs), in which "l" is length and "d" is the diameter of the fiber (Equation 1).

$$\frac{\pi d^2}{4} \times ft = \pi d \times \frac{l}{2} \times fs$$

$$\frac{l}{d} = \frac{ft}{2fs} \qquad (1)$$

The composite materials technology depends on this simple equation; if the fiber has a high tensile strength, as the steel fibers, then, it's necessary high adherence to prevent the pull out before the tensile strength is totally mobilized or fibers with high l/d relationship should be used.

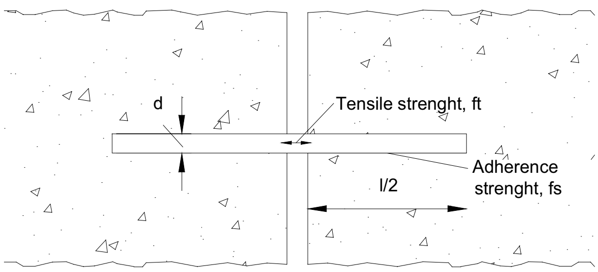

Figure 1 - Fiber/Cracking arrangement
Source: Taylor (1994)

3 EXPERIMENTAL PROGRAM

3.1 *Materials*

The soil samples used in the present study, derived from weathered sandstone, were obtained from the region of Porto Alegre, southern Brazil. The soil is classified as nonplastic silty sand (SM) according to Unified Soil Classification System. Specific Gravity of solids (G_s) is 2.7. The grain size distribution is 27.8% medium sand, 33.4% fine sand, 31.3% silt and 7.5% clay, with a Uniformity Coefficient (C_u) of 48. Atterberg limits of the fine portion of the material were: 22% Liquid Limit (ω_L) and 15% Plastic Limit (ω_P), which yields a Plasticity Index (PI) of 7%.

The fiber used was manufacturing in southern Brazil and used like concrete/mortar reinforced. The mechanical properties of polypropylene fibers used are given in Table 1 and the fibers pictures are given in Figure 2.

Table 1 - Mechanical properties of fibers

Feature	*Type I*	*Type II*
Thickness (µm)	23	278*
Aspect Ratio – l/d (adm.)	157	13
Specific Gravity	0.91	0.91
Young Modulus (GPa)	2.3	3.5 – 3.6
Tensile Strength (MPa)	120	320 - 400
Failure Strain (%)	80	25

Note:* - measured value in microscope pictures

a) b)

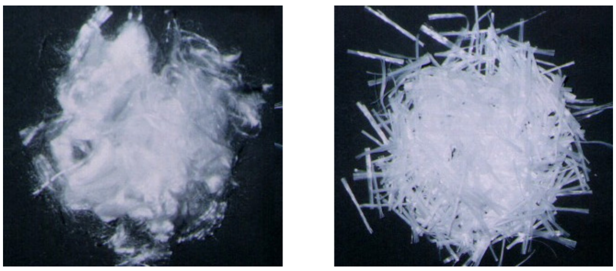

Figure 2 - Polypropylene fibers with 36 mm long: (a) fibers type I; (b) fibers type II

3.2 *Preparation and Testing of Specimens*

The samples were prepared by mixing soil, rapid-hardening Portland cement and fiber with addition of water. The optimum moisture content of 17.9kN/m^3 and maximum dry unit weight of 15.9% were reached for the cement content studied (7%), corresponding to the value obtained in standard Proctor compaction test carried out for soil-cement matrix. Finally, the samples were wrapped in moisture proof bags and stored in a humid room to cure for three days before testing.

The triaxial device used is a stain controlled one type that use an automatic data acquisition an internal measure of strain using Hall Effect Sensors (Soares et. al 1994; Clayton, 1996). The tests were carried out in according with the recommendations by Bishop e Henkel (1957) and Head (1986) and the strength parameters were calculated in according with Lambe and Whitmam (1979).

4 RESULTS AND DISCUSSION

The stress-strain curves obtained in static triaxial compression tests are given in Figures 3 (a) and 3 (b) (for confining pressure to 60kPa). Results are presented in Table 2. In Figures 3 (a) and (b), respectively, are plotted the behavior of soil-cement matrix in contrast to the matrix reinforced with 12 and 36mm long type I and II fibers. For fiber type I can be observed a small reduction at peak deviatoric stress, when compared to nonreinforced soil-cement results, 2% and 6% respectively for 12 and 36mm long fibers. The most impressive advantage of fiber inclusion when applied to cemented soils is the remarkable improvement of ductility of material. An absolute measure of such behavior is provided by the brittleness index (I_B) defined by the expression:

$$I_B = \frac{q_f}{q_u} - 1 \qquad (2)$$

in which q_f and q_u are, respectively, the failure and ultimate deviatoric stress. As the index decreases, approaching to zero, the failure behavior becomes increasingly ductile. The measured values, considering the average of all confining pressures, change from 3.6 for nonreinforced soil-cement mixture to 3.3 and 0.4 respectively for 12 and 36mm fiber lengths.

Figures 3 (a) reveal an uncommon secant modulus variation; it is necessary a small strain to the fiber start supporting loads and increase the elasticity modulus. The introduction of fiber type I in the soil-cement mixture causes a reduction in the volumetric strain dilatancy. Dilatancy reduces with increasing fiber length.

It can be observed in Figure 3 (b) that fiber type II lead to increase in peak deviatoric stress (29% for both lengths) and in the elasticity modulus. However, the brittleness index (I_B) tend to be larger then fiber I inclusion.

Tenacity means a fracture work or energy absorption ability and is defined by the expression:

$$E_{def} = \int_0^s q.ds \qquad (3)$$

on which E_{def} is the tenacity, q is deviatoric stress and s is strain. The tenacity value represents the area below the stress-strain curve. The values achieved for both fibers (measured at peak strain) are plotted in Figure 4 and denote, besides its increase, the proportionality between fiber length and E_{def}. The type I fiber reinforcement showed to be more effective.

When the soil-cement failure, there are crack opening and propagation and the fibers, presents in failure surface, tends to redistribute the stress in this region; fibers type I was more numerous and be more effective in after peak behavior. The ultimate deviatoric stress, q_s, presents in Table 2 confirm this.

A post-test evaluation showed that type I fibers stretches and fails for further deformation; however the type II fibers (with smaller aspect ratio) pulled out of the soil-cement matrix.

The shear strength of cemented soils, natural or artificial cemented, can be represented by a Mohr-Coulomb linear envelope, defined for the intercept cohesive (c') and of the friction angle (ϕ’). The Figure 5 presents the variation of these parameters versus the fiber length, for both studied fibers. For ϕ’ the same behavior can be observed for both fibers; the smaller ones increase more pronounced way the value of the internal friction angle of peak. It is probable that for the same reinforcement content, shorter fibers are more numerous inside the matrix and there are a larger possibility of them will be present shear surface. Maher and Ho (1993) and Consoli et al. (1998) agree that the inclusion of fibers increases the resistance frictional of the cemented soil.

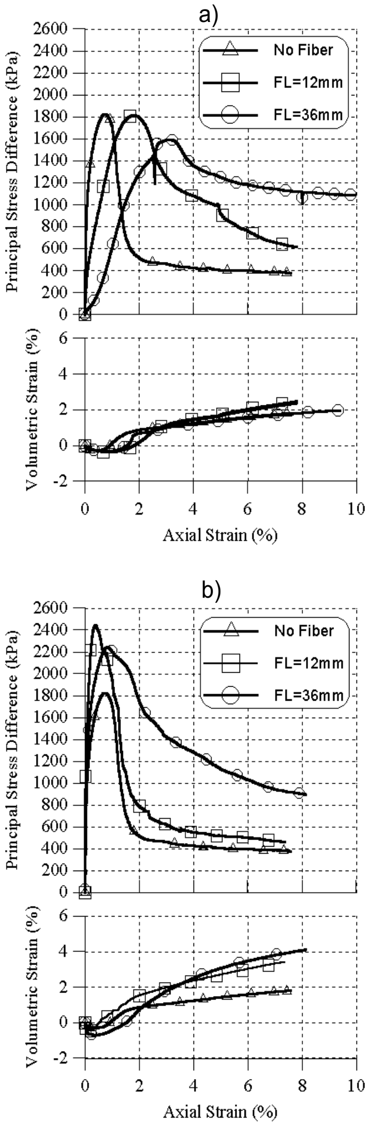

Figure 3: Stress-strain curves: (a) Fiber type I; (b) Fiber type II

For intercept cohesive, c', a different behavior can be observed, while the fiber II elevates a little the c' value the type I fiber reduces it slightly. The probable explanation for this behavior is that the fiber type II, which is more rigid, is requested in small deformations, contributing to an increment in the c' value; the increment is more evident for 36 mm length, which provides better adherence fiber/matrix. The shear strength increase for fiber type II of 12 mm is motivated by the increase of both resistance parameters, but notably for the pronounced increase of ϕ'. To 36 mm fibers the situation is inverse, the most pronounced increase is for the cohesion value.

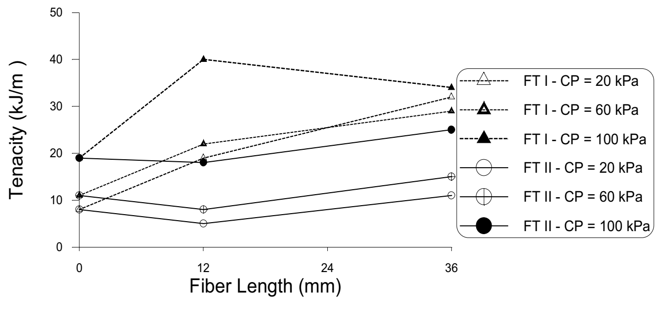

Figure 4: Relation between fiber length and tenacity measured at peak

Table 2 - Mechanical properties of cemented matrix and cemented matrix reinforced with polypropylene fibers

	Samples	q_f kPa	q_s kPa	$E_{s(0,01\%)}$ MPa	$E_{def(f)}$ kJ/m^3	ϕ' °	c' kPa
No Fiber	CC=7; FC=0; CP= 20	1614	287	2617	8	43	328
	CC=7; FC=0; CP= 60	1824	376	3430	11		
	CC=7; FC=0; CP= 100	1964	577	1329	19		
Reinforced matrix - FT I	CC=7; FC=0,5; FL=12; CP= 20;	1509	265	1029	19	44	319
	CC=7; FC=0,5; FL=12; CP= 60;	1813	500	950	22		
	CC=7; FC=0,5; FL=12;CP= 100;	1951	625	983	40		
	CC=7; FC=0,5; FL=36; CP= 20;	1622	1268	228	32	42	319
	CC=7; FC=0,5; FL=36; CP= 60;	1592	1085	235	29		
	CC=7; FC=0,5; FL=36;CP= 100;	1862	1328	194	34		
Reinforced matrix - FT II	CC=7; FC=0,5; FL=12; CP= 20;	2005	205	7990	5	50	343
	CC=7; FC=0,5; FL=12; CP= 60;	2442	410	7159	8		
	CC=7; FC=0,5; FL=12;CP= 100;	2543	640	3936	18		
	CC=7; FC=0,5; FL=36; CP= 20;	2223	418	3721	11	44	436
	CC=7; FC=0,5; FL=36; CP= 60;	2243	885	3372	15		
	CC=7; FC=0,5; FL=36;CP= 100;	2551	1242	1038	25		

Note: CC – Cement Content (%), FC – Fiber Content (%), FL – Fiber Length (mm), CP – Confining pressure (kPa), FT – Fiber Type (I or II).

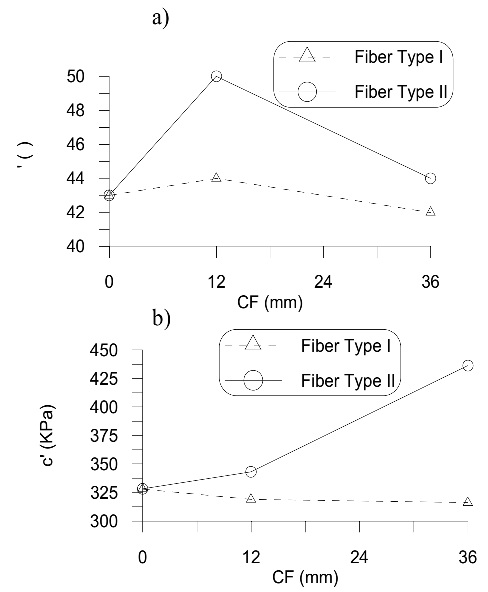

Figure 5: Relation between strength parameter and fiber length: a)friction angle; b) cohesion

The results achieved in this research allowed drawing some conclusion:

1. The composite material behavior composed by soil-cement matrix and reinforced with polypropylene fibers depends on the matrix and fiber features (fiber stiffness, shape, failure stress and strain); longer fibers can induce better mechanical behavior in contrast with shorter ones.

2. The fibers presence enhance the after peak features like ductility and tenacity.

3. The composite modulus was influenced essentially on the fiber characteristics (failure strain, modulus, diameter). The fiber content tends to reduce the modulus.

4. Based on triaxial tests it was possible to define the most important potential of each kind of fiber. Fibers with smaller aspect ratio (comparatively) are desirable when it is necessary to increase the peak resistance and to the modulus, however, high aspect ratio ones are more useful to increase the tenacity and to reduce the brittleness of the composite.

5. Exchanging some cement content by fiber can be profitable, it is possible to keep the same strength value and there is an improvement on tenacity and ductility of the composite material when compared with nonreinforced matrix. The fiber mix, with different diameters and mechanical features, can be considered an interesting possibility.

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