Research Journal of Applied Sciences, Engineering and Technology 7(20): 4327-4342, 2014
DOI:10.19026/rjaset.7.805
ISSN: 2040-7459; e-ISSN: 2040-7467

Submitted: January 06, 2014 Accepted: January 17, 2014 Published: May 20, 2014

Research Article

Evaluation of the Shear Strength Behaviour of Polypropylene and Carbon Fibre Reinforced Cohesive Soils

[1]Costas A. Anagnostopoulos, [2]Dimitrios Tzetzis and [3]Kyriakos Berketis
[1]Department of Civil Engineering, Technological Educational Institute of Thessaloniki,
School of Technological Applications, 57400 Thessaloniki, Greece
[2]International Hellenic University, 57001 Thermi, Greece
[3]Spectrum Labs SA, Efplias 49, Piraeus, Greece

Abstract: The purpose of this study is to investigate the influence of various parameters involved, such as the strength properties of fibres, the relative size of fibres and grains and the rate of shear on the shear strength of polypropylene or carbon fibre reinforced cohesive soils with different percentage loading of fibres. The experimental results reveal that the inclusion of polypropylene fibres in soil increases considerably the shear strength. Contrarily, the inclusion of the carbon fibres did not produce a clear beneficial effect. In both cases, the shear strengths results are attributed to the different micro mechanisms involved in the fibre/soil interactions as studied through scanning electron micrographs. A significant outcome from the current work is that the strength of the reinforced soil composites is independent of the fibre mechanical indexes.

Keywords: Carbon fibres, polypropylene fibres, reinforced soil

INTRODUCTION

The use of fibre inclusion for the improvement of the mechanical properties of weak soils is a method that has lately seen widespread attention in the scientific field of civil engineering. Applications aiming to achieve increased soil strength by mixing the soil with fibres are stabilization of soil slopes (Gregory and Chill, 1998), embankment construction with low strength soil, minimization of expansion-contraction cracks in condensed clay layers (Ziegler *et al*., 1998), mechanical stabilization of flexible roads (Choubane *et al*., 1999) and landing strip pavements base courses (Webster and Santoni, 1997; Tingle *et al*., 1999), improvement of bearing capacity (Tang *et al*., 2007) and soil surface erosion protection. Moreover, short discrete fibres can provide isotropic increase in the mechanical behavior of the soil composite without introducing continuous planes of weakness. The construction of fibre reinforced soils is easily achieved by simply mixing soil with fibres as in the case of other stabilizing admixtures like cement, lime, calcium sulfate, fly ash and silica fume (Ahmad *et al*., 2010).

The behavior of fibre reinforced soils has been a common subject of research in the recent years. More specifically, many researchers have focused their research on the mechanical behavior of fibre reinforced sandy soils (Consoli *et al*., 2002; Shewbridge and Sitar, 1990; Murray *et al*., 2000; Maher and Gray, 1990; Gray and Ohashi, 1983; Bauer and Oancea, 1996). Experimental results showed that the addition of fibres in soil mass improves significantly the strength of sand composite especially when the relative size of fibres and grains satisfies some criteria (Zornberg, 2002; Michalowski and Cermak, 2003). Accordingly, the length of the fibres needs to be at least one order of magnitude larger than the size of the sand particles, otherwise there is no activation fibre-particle interaction. Likewise, if the diameter of the fibre is an order of magnitude smaller than the grain size, no load can be transferred to the fibres, since the fibres will slip in the process of matrix deformation accommodated entirely by the pore space (Michalowski, 1997).

The aforementioned experimentally established specific values of size effect indicate that the use of discrete fibres for reinforcing soils consisted of very small particles like cohesive soils can improve substantially their strength, hence providing suitable solutions for many cases of geotechnical constructions or soil stabilization. Previous studies on reinforced cohesive soils have shown the significant improvement of shear strength (Casagrande *et al*., 2006; Casagrande *et al*., 2007; Consoli *et al*., 2003; Falorca *et al*., 2006). However, there has not been a general consensus regarding the effect of fibres on the mechanical behaviour of fine soils.

Consoli *et al*. (2003) carried out Consolidated Drained (CD) triaxial tests on cohesive soil and showed that fibres substantially increased the cohesion (c) while

Corresponding Author: Costas A. Anagnostopoulos, Department of Civil Engineering, Technological Educational Institute of Thessaloniki, School of Technological Applications, 57400 Thessaloniki, Greece

friction angle (φ) was barely affected by polypropylene fibre inclusion. Similar results were achieved from CD direct shear tests by Zaimoglu and Yetimoglu (2012). In contradiction, research conducted by Tang *et al.* (2007), Ahmad *et al.* (2010) and Pradhan *et al.* (2012) demonstrated that the percentage of fibre plays an important role in the increase of both shear strength parameters φ and c. Hence, more work is necessary to highlight the influence of fibres on shear strength of soils and particularly on the efficacy of fibre addition in the different parameters (friction angle, cohesion, volumetric response) of shear behavior of cohesive soils.

The specific objectives of this comprehensive experimental study is to supplement the data available in the literature on the mechanical behavior of Fibre Reinforced fine Soils (FRSs) and to investigate the effect of some parameters on the mechanical behavior of FRSs such as the strength properties of fibre, the relative size of fibres and grains as well as the rate of shear. A series of direct shear tests were carried out on fine soil samples with different percentages of polypropylene and carbon fibres. Subsequently, the microstructure and the interface between soil grains and both types of fibres were investigated by Scanning Electron Microscopy tests (SEM) to highlight the interaction mechanism between the two constituents of the composites.

MATERIALS AND EXPERIMENTAL DETAILS

Two types of commercially available discrete polypropylene fibres and one type of carbon fibres were used as reinforcement. Some of their index and strength properties given by the manufacturer are presented in Table 1.

Sandy silt and silty clay soils used in the experiments were obtained from the wider area of Northern Greece. The grain size distribution and the index properties of the two soils are presented in Fig. 1 and Table 2.

Table 1: Index and mechanical properties of fibres used in the study

Notation	Diameter (μm)	Length (mm)	Density (t/m^3)	Tensile strength (MPa)	Elongation at break (%)	Elastic modulus (GPa)	Aspect ratio (length/diameter)
Polypropylene fibre f_1	30	12	0.91	500	20	7	400
Polypropylene fibre f_2	25	12	0.91	400	29	4	480
Carbon fibre	7	12	1.79	4,500	1.9	240	1,714

Table 2: Properties of soils used in the study

Soil	Mean grain size D_{50} (mm)	Liquid limit (%)	Plastic limit (%)	Plasticity index	Specific gravity	USCS classification
Sandy silt	0.055	20.2	14.1	6.1	2.64	SC-SM
Silty clay	0.004	32.6	19.4	13.2	2.71	CL

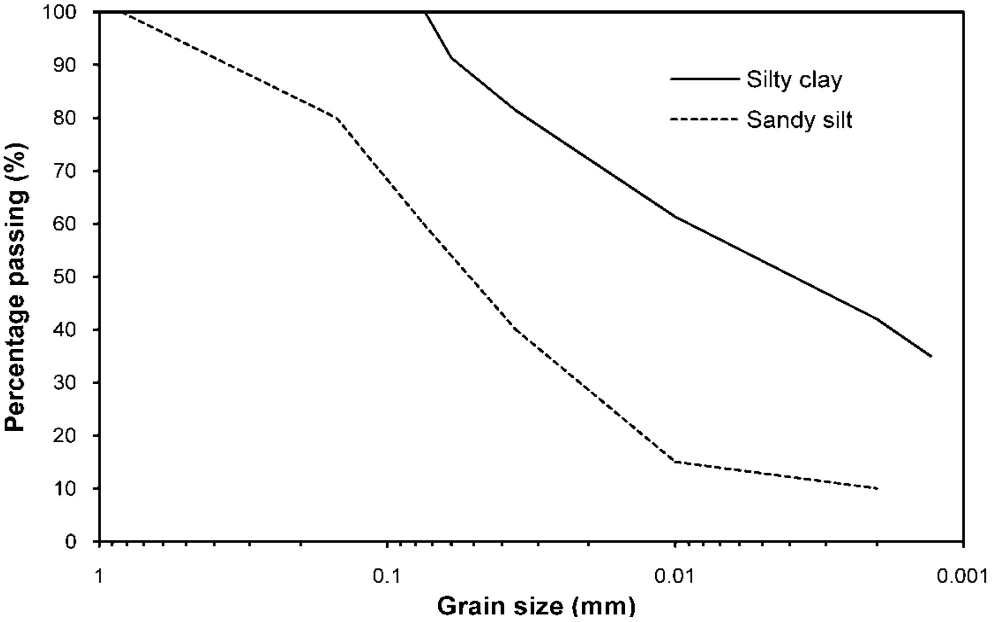
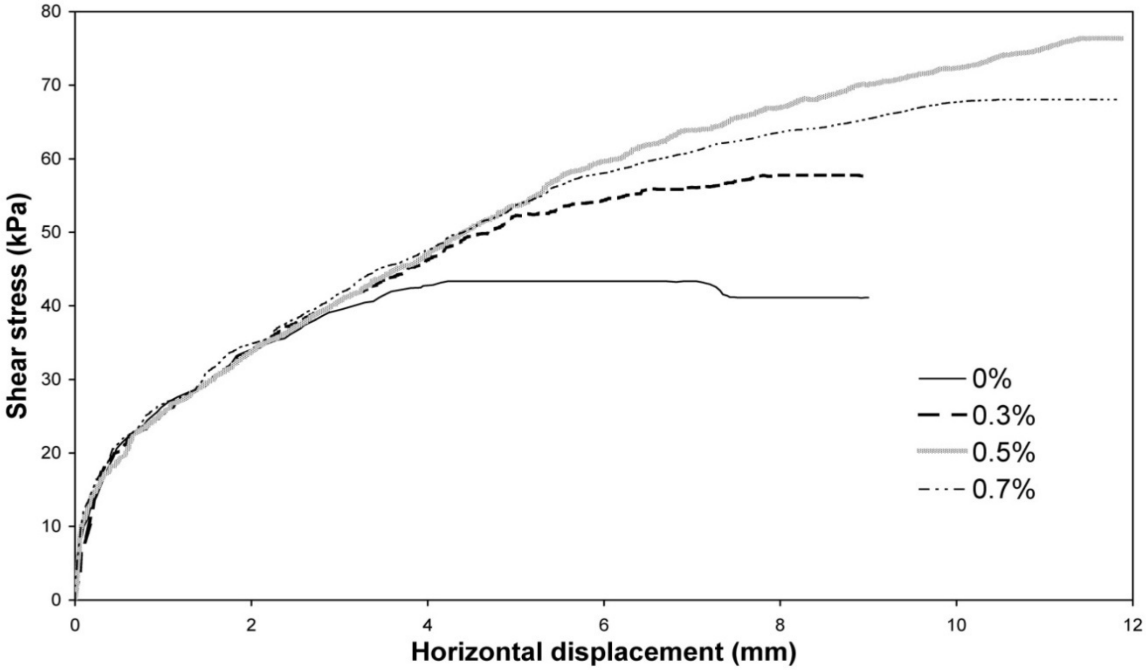


Fig. 1: Grain size distribution of sandy silt and silty clay

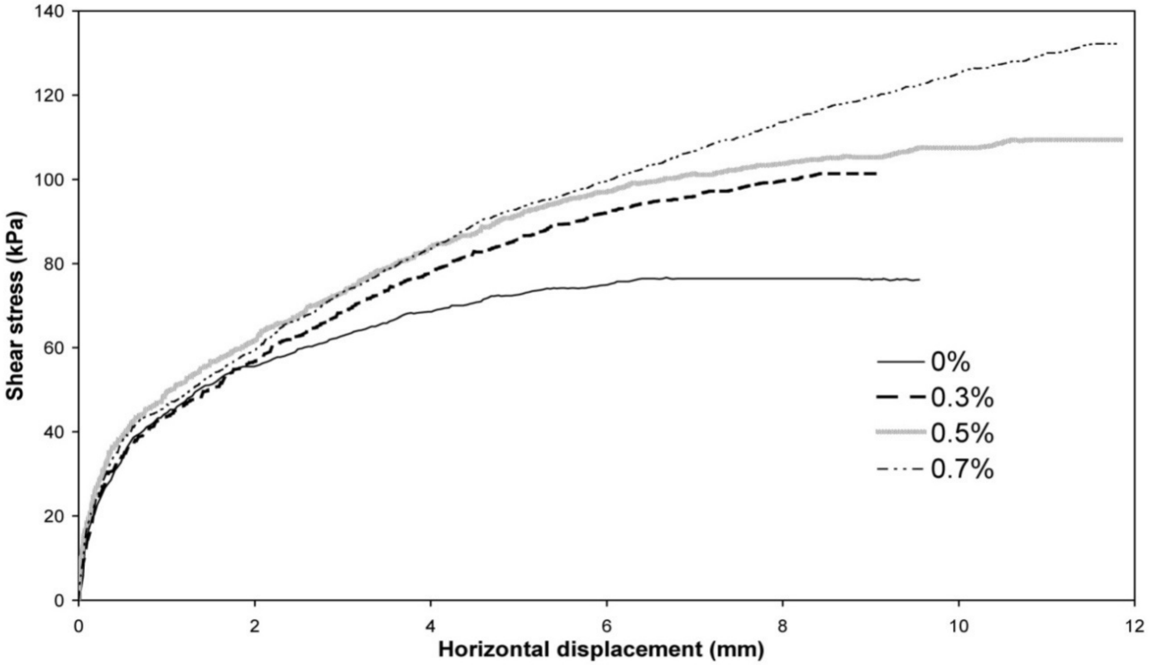
FRS specimens were fabricated that had a fibre content ranging from 0.3 to 1.1% by weight of dry soil. Beyond the value of 1.1% homogeneous mixtures of reinforced specimens could not be obtained because a large number of fibres adhered together resulting in the formation of pockets of low density. The fibre content is defined herein as: W_f/W_s where W_f is the dry weight of the fibres and W_s is the dry weight of soil. The quantities of the fibres and soil needed to prepare each specimen were weighed to a resolution of 0.1 g. FRS specimens were prepared by manually mixing soil, water and fibres. Water was added to prevent fibre segregation during the sample formation. Water content for all specimens ranged from 35-40% by weight of dry soil. This high quantity of water was necessary for the preparation of FRS specimens, because it facilitated the uniform mixing of soil and fibres, especially in the case of high fibre content where the fibres are sticking together. The mixing process between soil, water and fibres was done with the proper care to get a homogeneous mixture and was stopped when fibres were evenly distributed and randomly oriented throughout the soil mass. Afterwards, a quantity of the reinforced soil was poured inside the shear box and the desired normal stress was applied. A shear box of 60×60 mm in plan and 30 mm in depth was used in the tests. After the deformation caused by the consolidation had ceased, the specimen was sheared at a constant rate of displacement. In the case of CD tests, the rate of displacement ($L\varepsilon_f/t_f$) was determined from the consolidation data of the application of the vertical stress using time to failure t_f which was taken equal to 8.5 times of t_{100} (time for the completion of consolidation) as suggested by Ozkul and Baycal (2007). The maximum recorded value of t_{100} was 67 min and the consequent allowable rate was 0.003 mm/min. In order to ensure that no water pressure would be developed during testing the actual rate used in the experiments was lower (0.001 mm/min). In the case of Consolidated Un-drained tests (CU), the rate of displacement was 1.2 mm/min. This rate was chosen because it was the rate nearest or similar to the one proposed by other researchers who conducted direct shear tests on FRSs (Sadek *et al.*, 2010; Ibraim and Fourmont, 2006; Rao and Nasr, 2012).

An extensive Direct Shear Testing (DST) program was conducted in an effort to study the parameters which affect the shear strength of FRSs. DST was adopted because of its simplicity and suitability for testing a wide range of geo materials despite some inherent apparatus limitations such as the non uniform stress distribution and the non uniform shear zone thickness as well as other various parameters. Also, the consistency of some preliminary test results showed that these shortcomings could not influence considerably the experimental data and consequently the validation of any resulting conclusion.

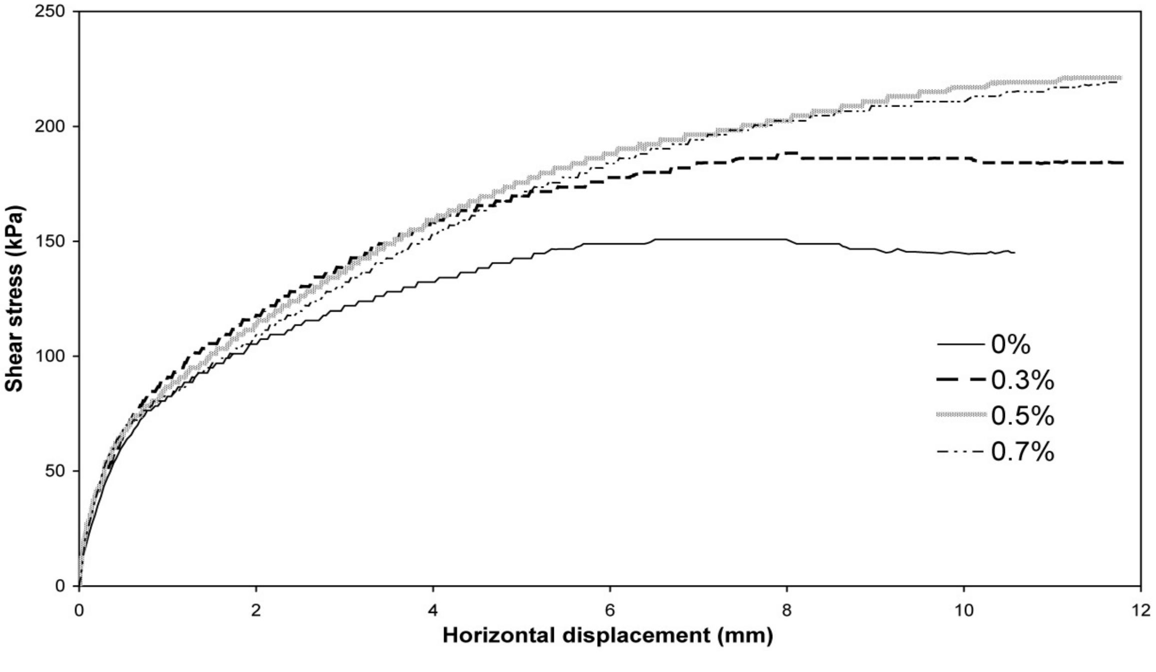
A total of 100 direct shear tests were performed using unreinforced and reinforced sandy silt and silty clay specimens in order to define the shear strength parameters φ and c. Particularly, CU tests were carried out on reinforced sandy silt. Both CU and CD tests were conducted on fibre reinforced silty clay to determine the shear strength characteristics of the



(a)



(b)



(c)

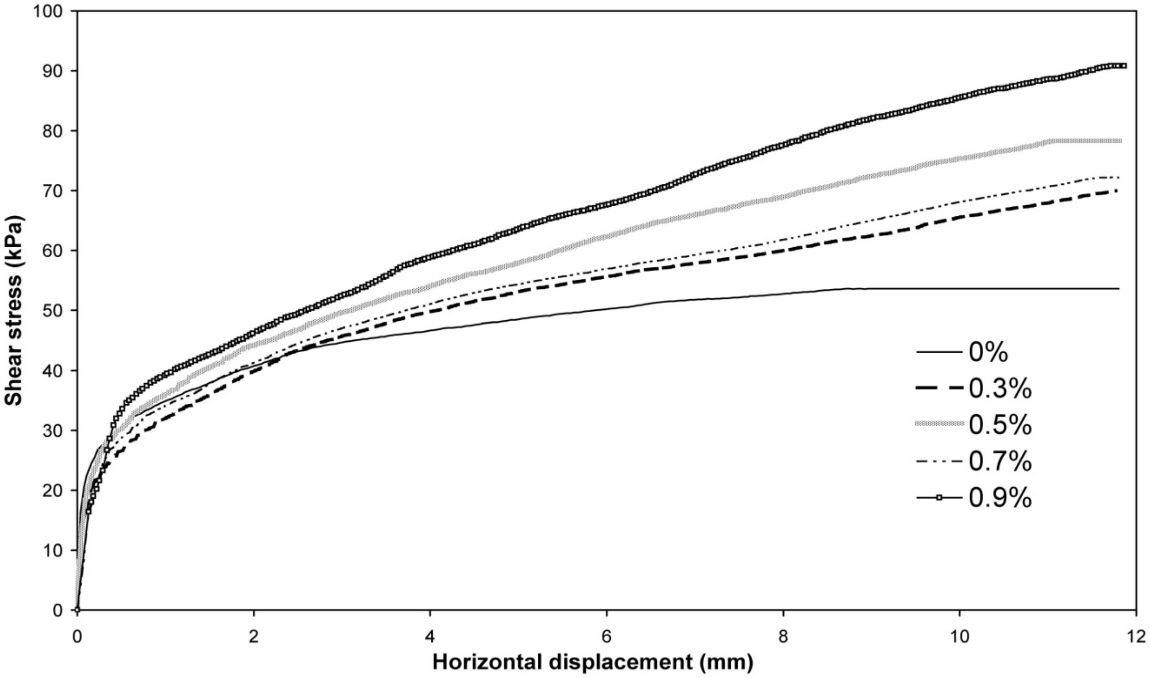
Fig. 2: Variation of shear stress with horizontal displacement for unreinforced and reinforced sandy silt obtained from CU tests at normal stress of (a) 50 kPa, (b) 100 kPa, (c) 200 kPa

reinforced soil under drained and un-drained loading conditions, since the Mohr-Coulomb failure envelope of the unreinforced soil obtained from CD tests differs considerably from the one obtained from CU tests and consequently the effect of fibre addition on the shear strength parameters under slow or quick loading conditions could be clearly examined. The shearing load and the vertical displacement were recorded as functions of the horizontal displacement using a load cell and LVDTs. Total horizontal displacements of 12 mm were reached. The tests were performed at normal stresses of σ_n = 50, 100 and 200 kPa.

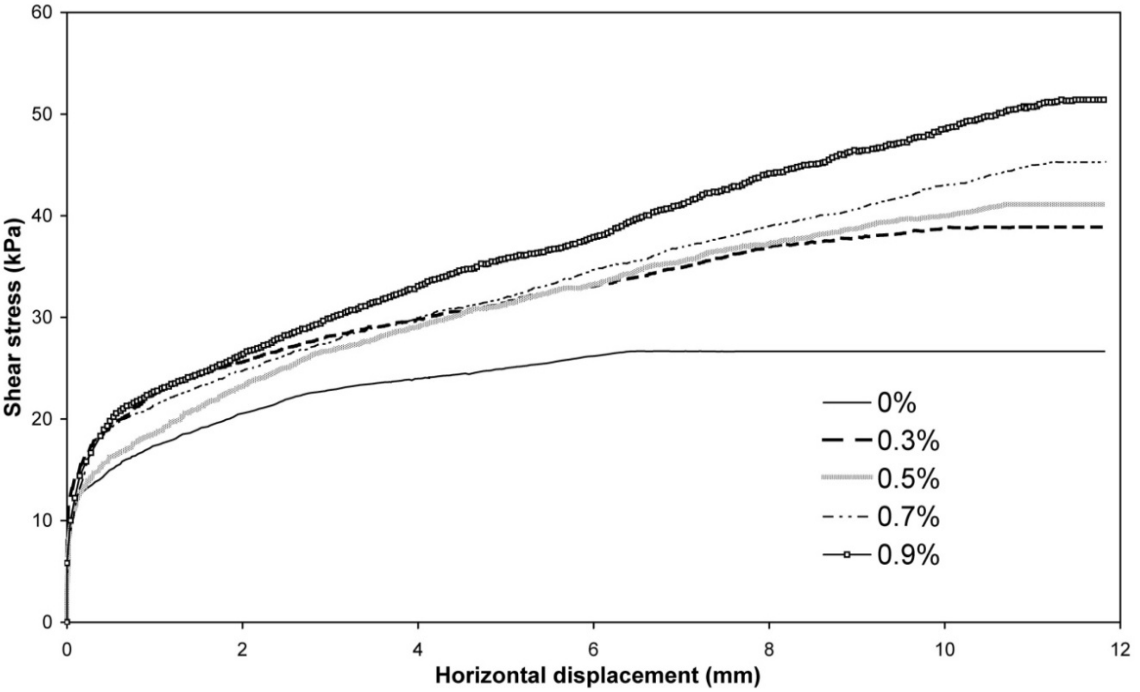
RESULTS AND DISCUSSION

The effect of the grain size on the shear strength: The shear stress-horizontal displacement curves obtained from CU tests for unreinforced and reinforced sandy silt with different contents of F_1 type of polypropylene fibres are given in Fig. 2 and for unreinforced and reinforced silty clay with the same type of fibres in Fig. 3.

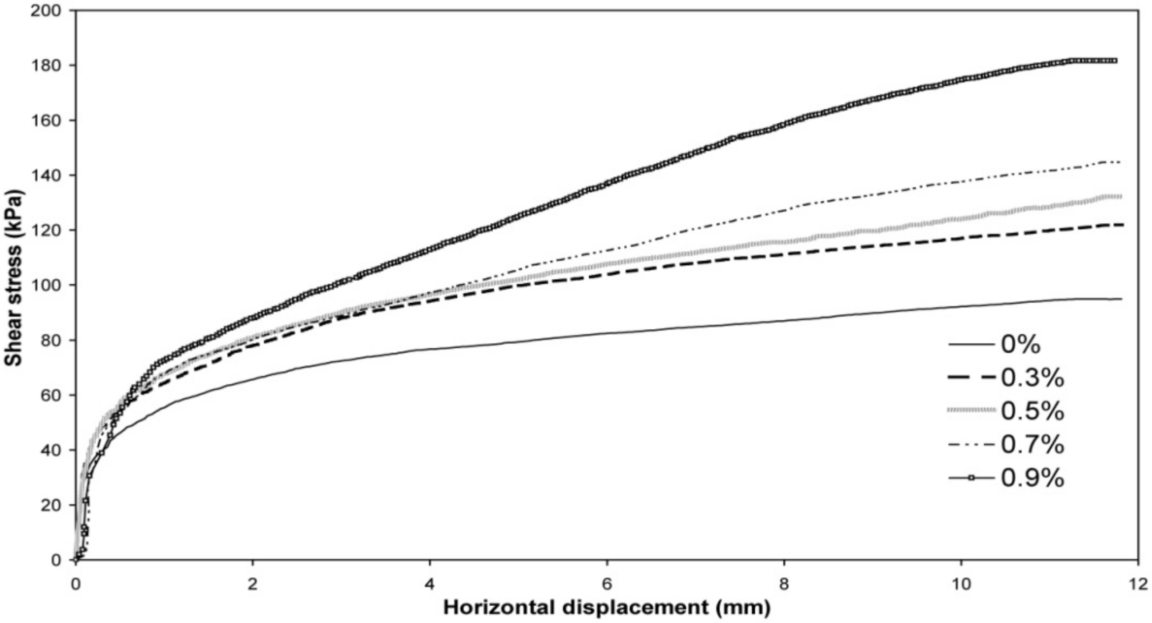
The shear strength parameters φ and c of unreinforced and reinforced (Fig. 4) soils in terms of total stresses and the extent of strength improvement



(a)



(b)



(c)

Fig. 3: Variation of shear stress with horizontal displacement for unreinforced and reinforced silty clay obtained from CU tests at normal stress of, (a) 50 kPa, (b) 100 kPa, (c) 200 kPa

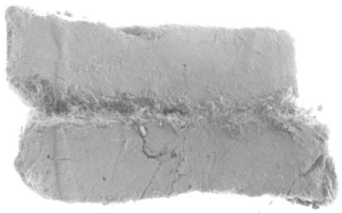


Fig. 4: A typical view of reinforced silty clay specimen (0.9% fibre content) after shearing

are summarized in Table 3 and 4. No bilinear or curved linear shear strength envelopes were observed. Shear strength of all soils is represented by linear envelopes found by linear regression analysis. The correlation coefficients R^2 are almost equal to unity in the analyses.

It can be seen that fibre inclusion enhanced the peak shear stress and the failure strain of both soils resulted in higher values of φ and c which were found to increase with increasing fibre content up to 0.5 and 0.9% for sandy silt and silty clay, respectively. Beyond the optimum dose, the observed shear parameters decreases or nearly remain the same. This is due to the fact that high fibre content resulted in poor mixing with less contact between soil particles reducing the availability of soil matrix for holding the fibre and developing a sufficient bond between fibres and soil. The experimental results indicate that the percentage of fibre plays an important role in the development of φ for both soils. Despite the reinforced soils exhibited an increase in c, the contribution of cohesion in the total strength of the composites is considered to be very limited. The most appreciable improvement of φ was observed for the silty clay at the optimum dose. Particularly, φ increased approximately 59% for silty clay and 24% for sandy silt. This effect may be due to the relative size of fibres and soil grains. According to this size effect, highlighted by previous research mentioned in the paragraphs above concerning fibre reinforced sands, the length of the fibres needs to be at least one order of magnitude larger than the size of the soil particles and the diameter of the fibre should not be one order of magnitude smaller than the diameter of the grains. In the first case the reinforcement will be efficient only if it is a continuous filament so that the tensile force in the filament can be induced due to its adequate "wrapping" around the grains. The latter case considers the reinforcement efficiency to be dependent on the number of fibre-grains contact points. The comparison of the ratios length of fibre to mean grain size (L_f/D_{50}) and mean grain size to diameter of fibre (D_{50}/D_f) between the sandy silt and silty clay corroborates that there is a size effect stemming from the length and diameter of the fibre. In the case of sandy silt the length of fibre is 218 times the D_{50} and the diameter of fibre is almost 2 times smaller from D_{50} whereas in the case of silty clay the length of fibre is 3000 times the D_{50} and its diameter is approximately 6 times higher than D_{50}. Even though the ratio L_f/D_{50} is considered to be appropriate for ensuring the adequate "wrapping" of fibre around the grains for both soils, there is a significant difference of size between the diameter of fibre and clay particles resulting in much

Table 3: Peak shear strength and shear strength parameters of F_1 fibre reinforced and unreinforced sandy silt samples based on CU tests

Fibre content (%)	Normal stress (kPa)	Peak shear strength (kPa)	Peak shear strength improvement (%)	φ (degrees)	c (kPa)
0	50	43.3		35.8	2.5
	100	76.4			
	200	150.8			
0.3	50	57.8	33.3	41.0	10.0
	100	101.4	32.8		
	200	188.3	24.9		
0.5	50	76.4	76.3	44.6	15.6
	100	109.4	43.3		
	200	221.1	46.6		
0.7	50	68.1	57.0	44.6	19.6
	100	132.2	73.0		
	200	219.2	45.3		

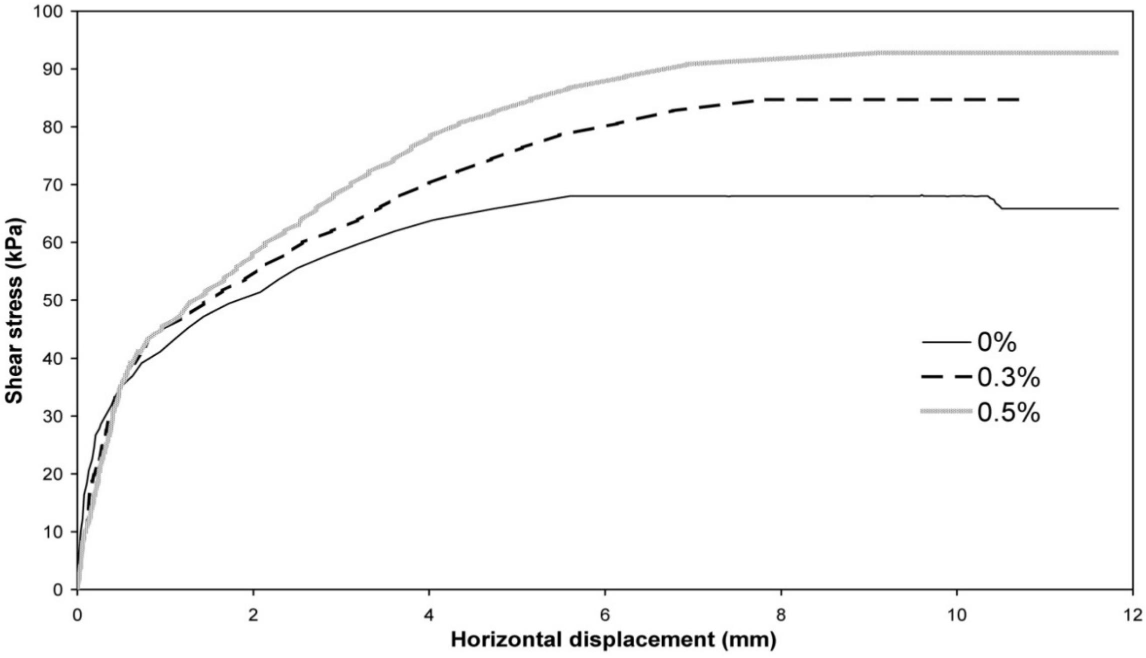
Table 4: Peak shear strength and shear strength parameters of F_1 fibre reinforced and unreinforced silty clay samples based on CU tests

Fibre content (%)	Normal stress (kPa)	Peak shear strength (kPa)	Peak shear strength improvement (%)	φ (degrees)	c (kPa)
0	50	26.7		24.1	4.7
	100	55.6			
	200	95.0			
0.3	50	38.9	45.8	28.8	10.2
	100	70.0	26.0		
	200	122.0	28.4		
0.5	50	41.1	54.1	30.9	11.2
	100	78.3	40.9		
	200	132.2	39.2		
0.7	50	45.3	69.7	33.9	5.7
	100	72.2	30.0		
	200	144.7	52.3		
0.9	50	51.4	92.7	38.3	8.0
	100	90.8	63.4		
	200	169.7	78.6		
1.1	50	48.0	80.0	33.0	13.9
	100	84.7	52.4		
	200	146.4	54.0		

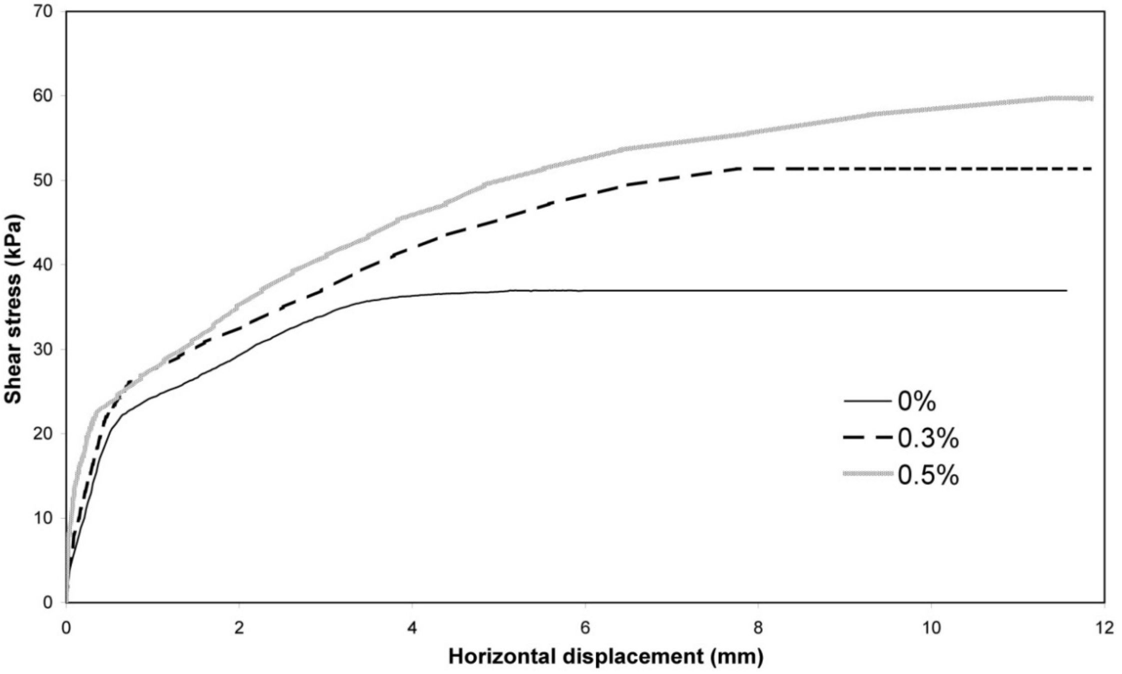
higher number of fibre-grains contact points. This could explain the fact that the addition of fibres is more efficient in the case of silty clay than in the case of sandy silt.

It is also revealed that initial stiffness (initial slope of the shear stress-horizontal displacement curve) of the composites is not practically affected by the fibre inclusion either for small or large concentration of fibres for both sandy silt and silty clay soils as shown in Fig. 2 and 3. This result is in line with previous studies which reported similar findings (Michalowski and Cermak, 2003; Zaimoglu and Yetimoglu, 2012; Ibraim and Fourmont, 2006). It should be noted that direct shear tests do not allow the production of any deformation modulus due to their inherent problems. However, many researchers used the initial stiffness based on the shear stress-horizontal displacement curve as parameter in the interpretation of their experimental results for FRSs. It is worth noting that although the shear stress-displacement relationships seem to be similar at low horizontal displacements, beyond a certain value of displacement and up to the end of the test they appear to differentiate significantly. It is a strong evidence supporting the hypothesis (Li, 2005) that the increase of strength of reinforced soils is directly related to the mechanism of interaction between fibres and soil matrix based on a relative initial rearrangement of soil particles at the failure plane causing a consequent stretching and mobilizing gradually a part of the fibre tensile strength as will be discussed more thoroughly in a next paragraph.

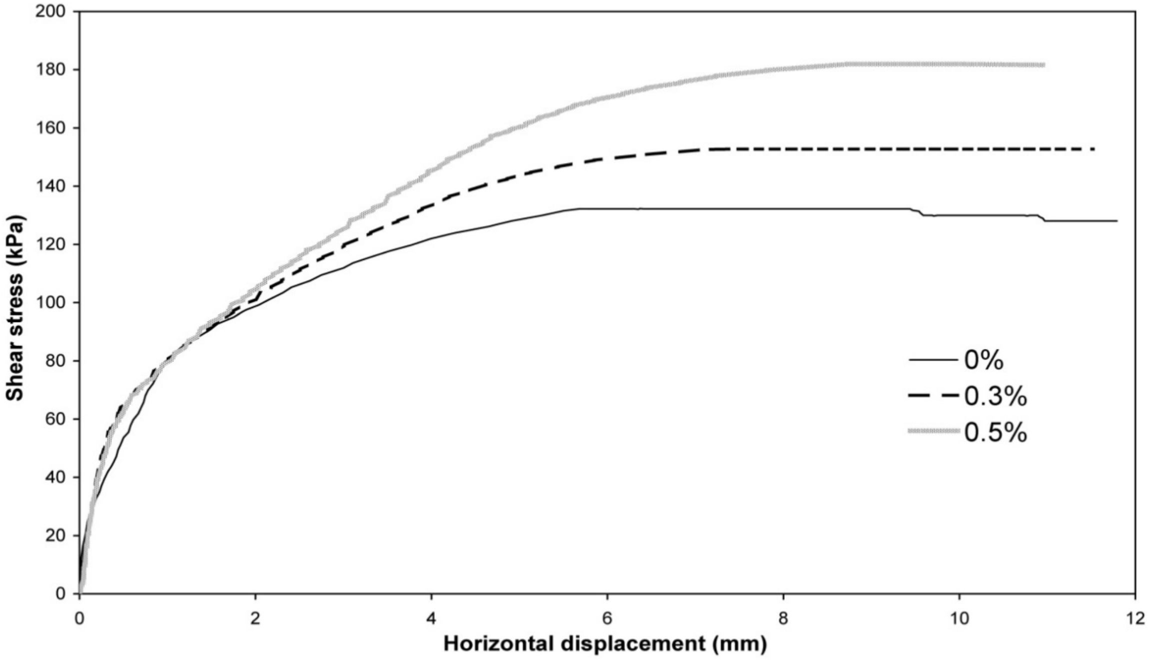
The effect of the loading condition on the shear strength: Figure 5 compares the shear stress-horizontal displacement behavior of both unreinforced and fibre reinforced silty clay with different F_1 fibre content under CD loading condition. As with CU tests, the curves show a consistent increase in the maximum shear stress and the failure strain as the fibre content increased, whereas initial shear stiffness appears to be unaffected by the increasing percentage of PP fibre inclusion. Shear strength parameters φ´ and c´ (in terms of effective stresses) increased with increasing fibre content up to 0.5%. Beyond the optimum dose, the shear parameters decrease or nearly remain the same. A summary of φ´ and c´ obtained from CD tests is presented in Table 5. Data in Table 5 indicate that optimum fibre dose enhanced φ´ from 32.5° to 39.5° whereas c´ increased but remain marginal. The reinforcing effect in effective friction angle (22% improvement) is not so pronounced as it is in total friction angle (59% improvement). This reveals the significant influence of loading condition on fibre-soil interaction mechanism. Similar results were attained by Freilich *et al*. (2010) from CD and CU triaxial tests on polypropylene fibre reinforced clay soils, providing evidence of an influence of either shearing time or drainage, or both, on the mechanical behavior of FRS. Additionally, the influence of loading rate was demonstrated from pull-out tests on High Density Polyethylene (HDPE) textured geomembrane-cohesive soil interfaces performed by Fishman and Pal (1994) which showed that the pullout resistance under CU is higher than that under CD loading condition for the same initial effective normal stress. On the contrary, according to the findings of many researchers (Farrag and Griffin, 1993; Al Wahab and Al-Qurna, 1995), the development of pore pressure during quick shear (CU) may reduce the effective stress between particles



(a)



(b)



(c)

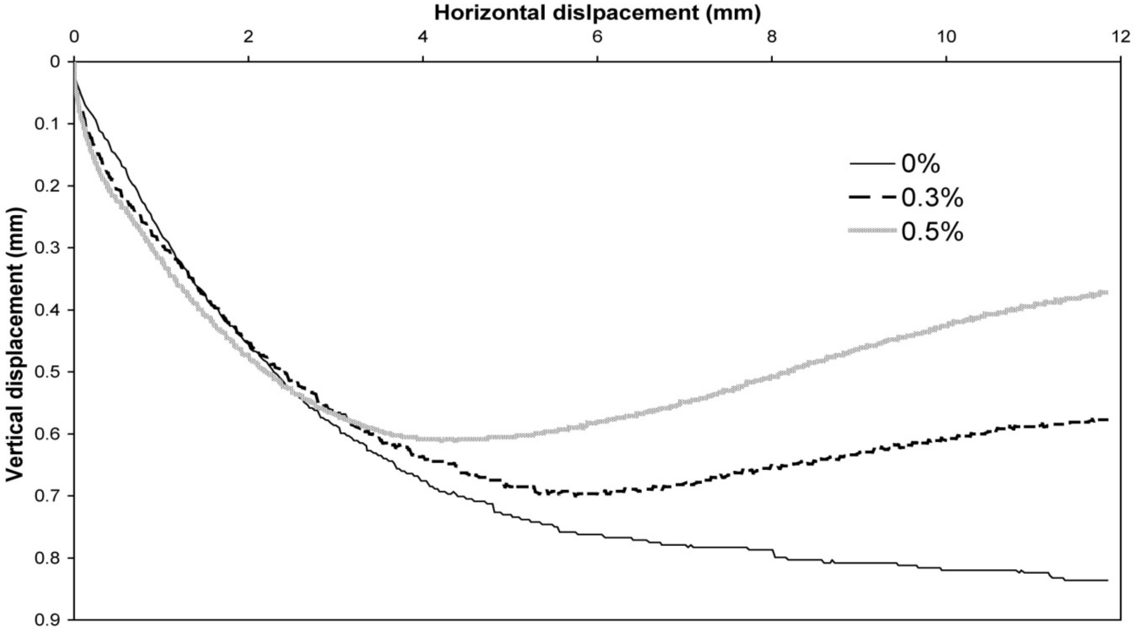
Fig. 5: Variation of shear stress with horizontal displacement for unreinforced and reinforced silty clay obtained from CD tests at normal stress of, (a) 50 kPa, (b) 100 kPa, (c) 200 kPa

Table 5: Peak shear strength and shear strength parameters of F_1 fibre reinforced and unreinforced silty clay samples based on CD tests

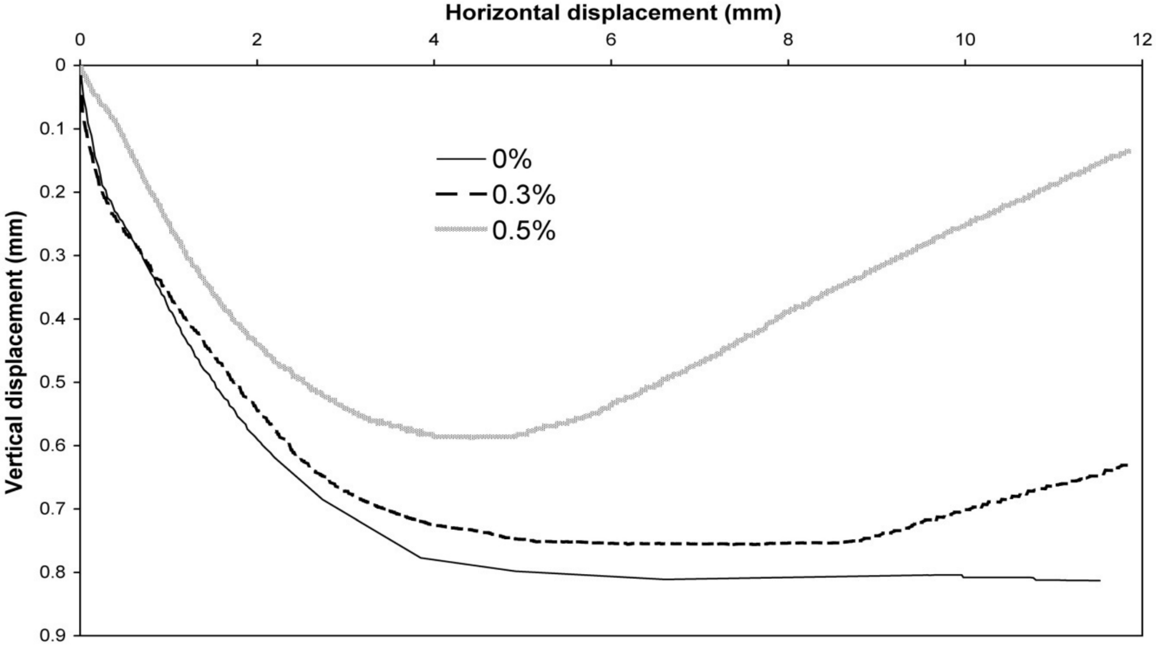
Fibre content (%)	Normal stress (kPa)	Peak shear strength (kPa)	Peak shear strength improvement (%)	φ′ (degrees)	c′ (kPa)
0	50	36.9		32.5	1.7
	100	68.1			
	200	132.2			
0.3	50	51.4	39.1	34.1	11.0
	100	84.7	24.5		
	200	152.8	15.5		
0.5	50	59.7	61.7	39.5	11.0
	100	92.8	36.3		
	200	181.9	37.6		
0.7	50	57.5	55.6	38.7	13.2
	100	97.2	42.8		
	200	177.8	34.4		
0.9	50	57.8	56.4	39.1	13.2
	100	98.3	44.4		
	200	179.3	35.6		
1.1	50	49.2	33.3	35.1	11.0
	100	85.8	26.0		
	200	155.1	17.3		

resulting in their easy disturbance and rearrangement on interface, hence weakening of interfacial resistance (Fredlund and Rahardjo, 1993). Consequently, it would be expected that the improvement of shear strength to be more obvious under CD loading condition than under CU. Fishman and Pal (1994) attributed the differences in CD and CU shear strength to a local tendency for dilation at the fibre-soil particles interface during un-drained shearing which may induce negative interfacial pore water pressure, increasing the effective confining pressure and resulting in an increased bonding of the soil paricles near the interface. Another possible influential factor is the development of creep strains along the interface (Freilich *et al*., 2010) such as time-dependent slip or soil particle rearrangement during drained shearing conditions. Also, drainage during CD testing may be another key factor. The fibres within a fine grained soil act as a flow network, increasing the hydraulic conductivity of the mixture (Al Wahab and El-Kedrah, 1995). By allowing drainage, water flows towards to the fibres and increases the water content along the interface, decreasing the interfacial strength and reducing the influence of the fibres.

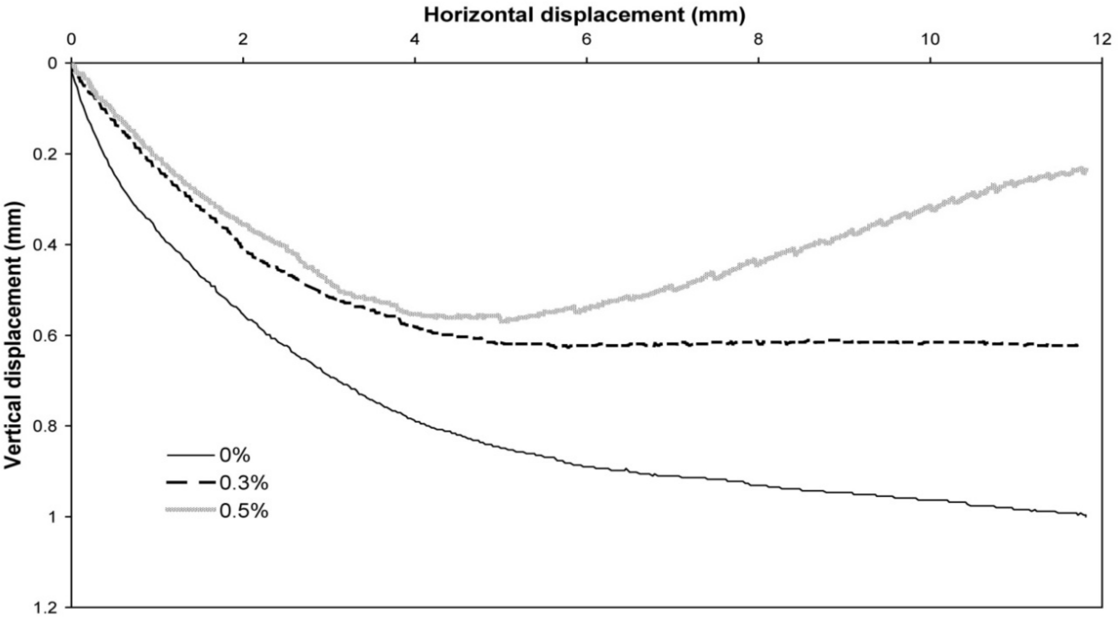
Experimental results showed that there is a relation between the shear strength increment of FRS and normal stress, which was found to be much higher for normal stress of 50 kPa than the one obtained for normal stress of 100 and 200 kPa. It is an observation confirmed also by previous researchers (Falorca *et al*., 2006; Lopes and Ladeira, 1996; Moraci and Gioffre, 2006) evidencing the interaction mechanism between fibre and soil particles based on dilation. Inside the soil mass, the randomly distributed fibres act as a spatial network, interlocking with soil particles to form a unitary matrix. Soil matrix resists most of the applied load at relatively low strain levels. As the strain level increases, rearrangement or rotation of particles, gradually mobilizes the tensile strength in the interlocked fibres, which will then contribute to resist the applied shear force (Li, 2005). Under high normal stress, the restriction of particle rearrangement



(a)



(b)



(c)

Fig. 6: Variation of vertical displacement with horizontal displacement for unreinforced and reinforced silty clay obtained from CD tests at normal stress of, (a) 50 kPa, (b) 100 kPa, (c) 200 kPa

lead to slippage between particles and fibres and consequently to a reduction of stretching in the reinforcement.

Figure 6 depicts the variation in vertical displacement with horizontal displacement during the test. The volume condensation of fibre reinforced specimens was found to be smaller than that of unreinforced ones and directly related with fibre content. After an initial reduction in volume, less significant than the one of unreinforced soil, there was volumetric dilation approaching the characteristic response of a dense soil. The volumetric change curves indicate clearly that the presence of fibres considerably limited the tendency for contraction at all different normal stresses whereas for high fibre contents specimens appeared to dilate. This behavior is interesting since it is in opposition with the results reported by Michalowski and Zao (1996), Michalowski and Cermak (2003), Ahmad *et al*. (2010) and Gray and Ohashi (1983) supporting that fibres generally inhibit dilatancy whereas it is in agreement with the results published by other researchers (Sadek *et al*., 2010; Ibraim and Fourmont, 2006; Kaniraj and Havanagi, 2001; Ibraim *et al*., 2010). These results suggest that the volumetric response from contractive for the unreinforced soil to dilative for the reinforced one could be a consequence of an apparent densification of the composite matrix resulting from the interaction mechanism between fibre net and soil particles. Li (2005) attributed this volumetric response on the fibres distributing stresses within the soil mass which increase the soil mass undergoing shear and therefore more soil mass deforms.

Fibre type effect on the shear strength: CD and CU shear tests have, also, been performed for unreinforced and reinforced silty clay with different contents of F_2 type of polypropylene fibre and the one type of carbon fibre. The results and their dependence on the consolidation pressure are listed in Table 6 to 9. The optimum doses for reinforced specimens with F_2 fibre were found to be 0.9% at CU tests and 0.5% at CD tests, as in the case of F_1 fibre. Despite the mechanical strength of F_2 fibre is significantly lower than the one of F_1 fibre, the shear strength parameters of F_2 fibre reinforced silty clay are very close to those obtained when F_1 fibre used as reinforcement. Generally, the values of φ and φ' were slightly lower compared to the ones observed for specimens with F_1 fibre inclusion. On the other hand, the shear strength of carbon fibre reinforced specimens did not change significantly. CU test results indicated that the peak strengths of composite specimens are comparable to, or are marginally higher than, those of silty clay alone for all normal stresses. In addition, the presence of carbon fibres reduced slightly the strengths of the composite under CD loading. Thus, it can be said that the mechanical indexes of the inclusions has no discernible effect on the increment of soil strength, a fact which additionally suggests that the improvement of soil strength depends on the interaction mechanism between fibre and grains and not just on the peak strength or yielding of fibres. Obviously, increment of strength is directly related with the distributed fibres which act as a spatial network, interlocking soil particles to form a unitary matrix. This coherent structure resists the

Table 6: Peak shear strength and shear strength parameters of F_2 fibre reinforced and unreinforced silty clay samples based on CU tests

Fibre content (%)	Normal stress (kPa)	Peak shear strength (kPa)	Peak shear strength improvement (%)	φ (degrees)	c (kPa)
0	50	26.7		24.1	4.7
	100	55.6			
	200	95.0			
0.3	50	39.2	47.2	29.5	7.4
	100	66.1	19.0		
	200	123.9	30.4		
0.5	50	41.3	54.8	30.9	10.0
	100	75.5	35.9		
	200	132.0	38.9		
0.7	50	44.0	65.0	33.4	5.2
	100	70.6	27.0		
	200	141.6	49.0		
0.9	50	44.9	68.0	37.9	6.0
	100	83.8	50.7		
	200	161.7	70.0		

Table 7: Peak shear strength and shear strength parameters of F_2 fibre reinforced and unreinforced silty clay samples based on CD tests

Fibre content (%)	Normal stress (kPa)	Peak shear strength (kPa)	Peak shear strength improvement (%)	φ´ (degrees)	c´ (kPa)
0	50	36.9		32.5	1.7
	100	68.1			
	200	132.2			
0.3	50	49.4	33.8	33.9	10.5
	100	78.3	15.0		
	200	149.4	13.0		
0.5	50	57.7	56.2	38.4	9.7
	100	86.4	27.0		
	200	174.5	32.0		
0.7	50	55.0	48.9	37.4	12.4
	100	91.2	34.0		
	200	169.2	28.0		

Table 8: Peak shear strength and shear strength parameters of carbon fibre reinforced and unreinforced silty clay samples based on CU tests

Fibre content (%)	Normal stress (kPa)	Peak shear strength (kPa)	Peak shear strength improvement (%)	φ (degrees)	c (kPa)
0	50	26.7		24.1	4.7
	100	55.6			
	200	95.0			
0.3	50	22.5	-15.6	27.3	0.0
	100	53.3	-4.0		
	200	101.1	6.4		
0.5	50	30.5	14.2	27.1	6.3
	100	59.7	7.3		
	200	108.0	13.6		
0.7	50	28.4	6.4	26.5	4.9
	100	57.0	2.5		
	200	104.0	9.5		

Table 9: Peak shear strength and shear strength parameters of carbon fibre reinforced and unreinforced silty clay samples based on CD tests

Fibre content (%)	Normal stress (kPa)	Peak shear strength (kPa)	Peak shear strength improvement (%)	φ (degrees)	c (kPa)
0	50	36.9		32.5	1.7
	100	68.1			
	200	132.2			
0.3	50	32.0	-13.2	32.2	3.5
	100	71.0	4.2		
	200	128.0	-3.1		
0.5	50	38.0	2.9	32.4	7.5
	100	73.0	7.2		
	200	134.0	1.4		
0.7	50	35.0	-5.1	31.3	4.0
	100	64.0	-6.0		
	200	126.0	-4.7		

displacement due to the combined development of mineral friction between adjacent soil particles with a part of fibre tensile strength mobilized by the relative movements of grains. The slightly lower values of

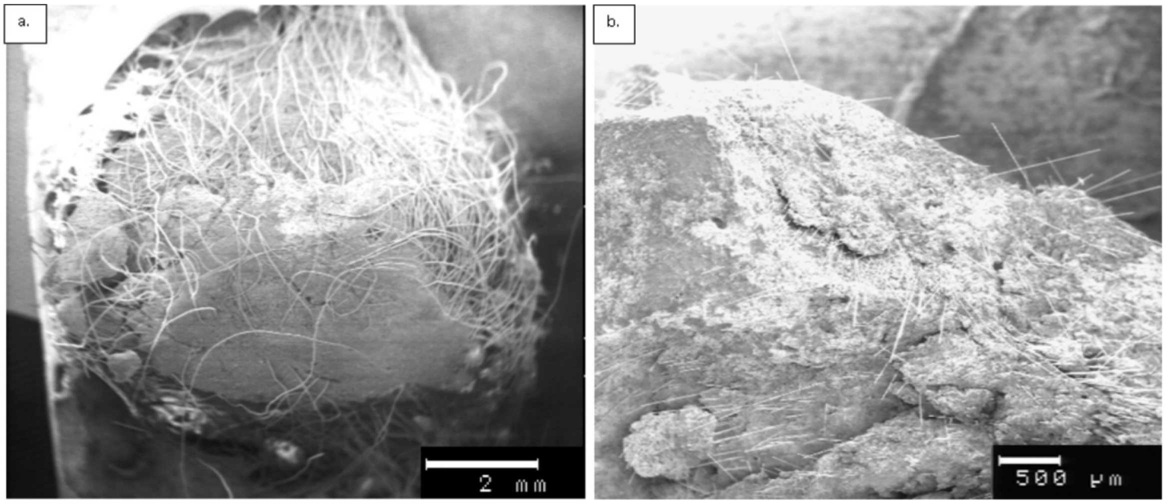


Fig. 7: SEM images of silty clay soil polypropylene fibre (left) and carbon fibre (right) composites at magnifications of, a) 9 times, b) 20 times

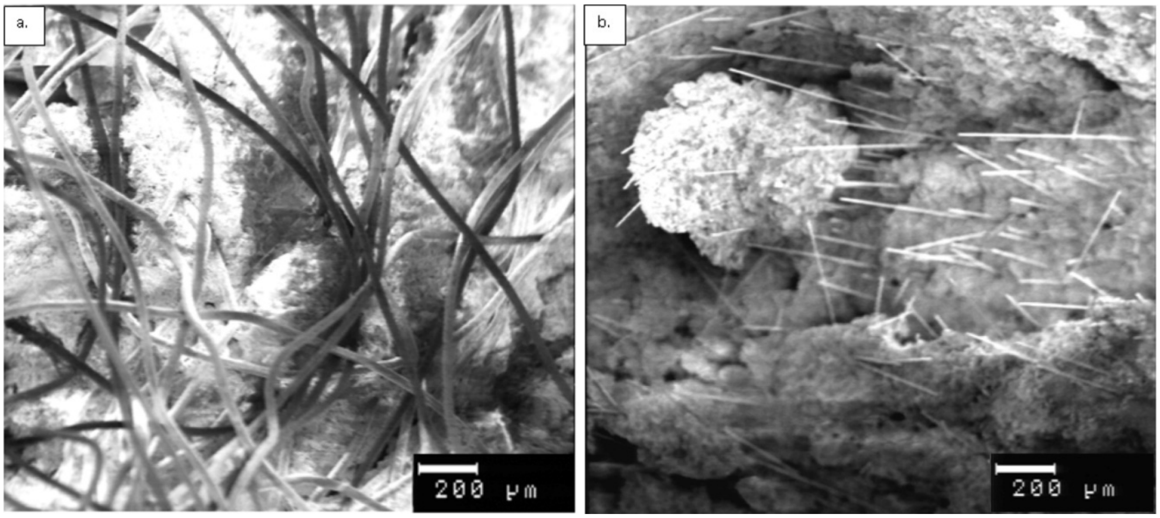


Fig. 8: Typical soil composite specimens showing random distribution of, a) polypropylene fibres, b) carbon fibres at magnification of 50 times

friction angle of F_2 fibre reinforced specimens in comparison with the ones of F_1 fibre reinforced specimens could be attributed to the smaller diameter of F_2 fibre, leading to less fibre-grains contact points (Sadek *et al*., 2010). The insignificant influence of carbon fibres on soil shear strength is probably owed to their high stiffness that restrains the activation of fibre-soil particles interaction as discussed in the following section.

Interface phenomena and micro mechanisms of the composite: Since the shear strength values of the silty clay soil outperformed the values obtained from the sandy silty soil only the macro-scale effect of the F_1 type of polypropylene fibres on the silty clay structure as well as the surface related microstructure of the carbon fibres were observed and analysed by Scanning Electron Microscopy (SEM).

Figure 7 and 8 show the general random distribution of the polypropylene and carbon fibres within the soil matrix. The polypropylene fibres are distributed discretely in the matrix and act like a three-dimensional network that interlock with the smaller in size clay grains. This interlocking effect is absent in the case of reinforcing the soil matrix with the carbon fibres. The polypropylene fibres with the silty clay form a coherent structure which restricts the displacement upon loading. The carbon fibres on the other hand qualitatively as shown from the SEMs do form a coherent matrix but with limited displacement restriction as seen from the shear tests. No deformation or breakage of carbon fibres was observed neither in the

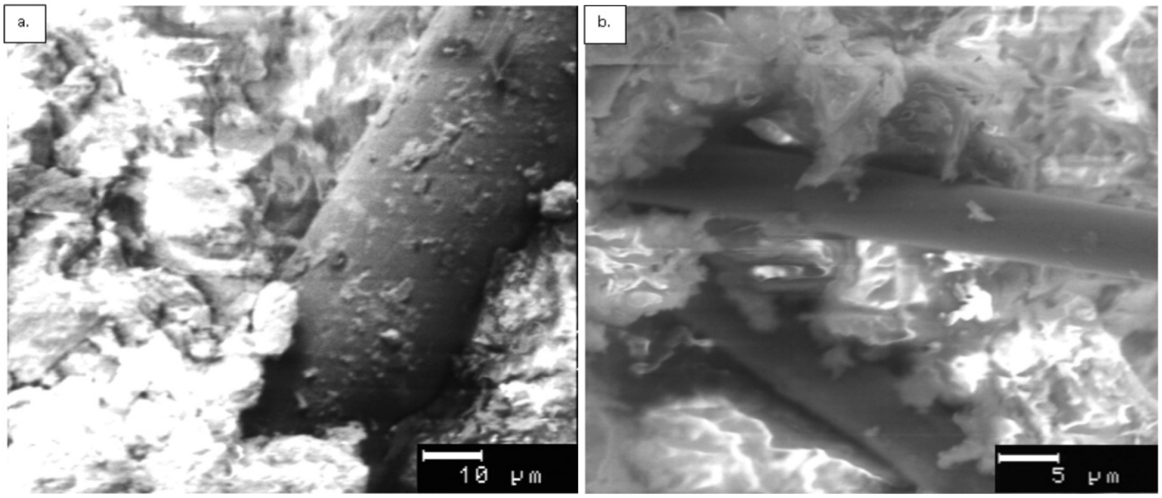


Fig. 9: SEM images of polypropylene (left) and carbon (right) fibre composites at magnifications of a) 500 times and b) 200 times, revealing the influence of the bond strength by the presence or absence of the clay remains

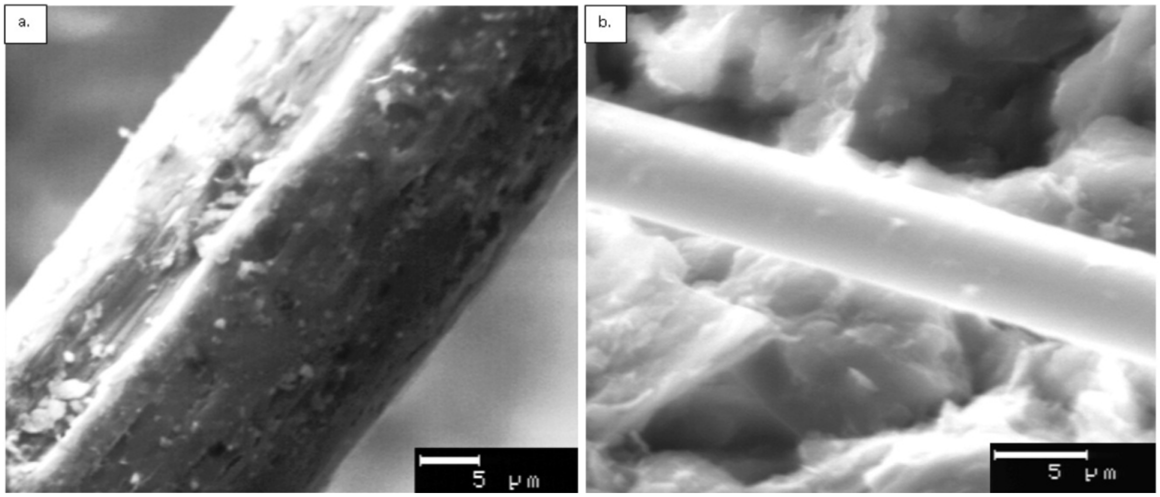


Fig. 10: SEM images of polypropylene (left) and carbon (right) fibre composites at magnifications of, a) 2000 times and b) 3000 times, showing the presence or absence of the characteristic pits and pores created from the clay grains during compaction and shearing

case of polypropylene fibres confirming in the latter case that the fibres can withstand tension within the matrix without yielding or significantly deforming.

More specifically, bond interfacial strength due to mechanical interlocking along friction at the interface seems to be the dominant mechanisms that control the reinforcement micromechanical benefit of the both carbon and polypropylene composites. Figure 9 show that the polypropylene fibre surfaces are attached by clay remains after the disturbance of the interfacial structure due to loading, indicating increased bond strength between the polypropylene fibres and the clay matrix. Examination of the carbon fibres as seen from the SEMs do not reveal any silty clay remains justifying the reduced bond strength as a subsequent to interfacial failure. Additionally, Fig. 10 shows some characteristic pits and grooves formed on the polypropylene fibre surface from the impacted hard clay particles, which abraded the fibre surface as shearing proceeded. During the consolidation stage local micro-forces acting on the hard clay particles are transferred to the "soft" ductile polypropylene fibres causing a local plastic deformation and even removal of a part of the surface layer (Tang *et al*., 2010). These pits result in an increase in fibre surface roughness and interfacial interlock resistance. Consequently, the interaction mechanism between fibres and soil matrix is improved. In the case of carbon fibres no such pits and grooves could be observed due to the higher hardness of such fibres compared to the polypropylene fibres preventing any hard clay particles to interact significantly with the fibre's surface. Moreover, the carbon fibres, having much higher stiffness than the polypropylene fibres, do not bend so to induce any wrapping effect and therefore to structurally and macroscopically introduce any type of interaction with the soil particles.

Evidently therefore, both the bending of the fibres induced by their adequate wrapping around the soil particles and the impaction of soil particles on fibre surface contribute significantly in the improvement of mechanical strength of the composites (Moraci and Gioffre, 2006; Racana *et al*., 2003). Subsequently, it can be also easily assumed that as the effective interfacial contact area between fibre and grains increases, the number and depth of the grooves formed from the penetration of hard particles into the polypropylene fibres increase, having as a result an extended plowing of the grains into fibre's body during shear process which gives a significant rise to interfacial strength and friction.

CONCLUSION

The experimental results developed in this study showed that the addition of polypropylene fibres in cohesive soils has a considerable effect on their shear strength. In particular, the shear strength of soils increases with the inclusion of fibres up to the optimum dose, beyond which it decreases or remains constant. Also, the improvement of the strength of FRSs is strongly dependent on the fineness of the grains evidencing the significant influence of the relative size between fibres and grains. Moreover, the addition of the fibres results in substantial increase of friction angle. On the other hand, cohesion does not change considerably with fibre content.

Another important result is that the drainage during shearing plays an important role in the mechanical response of the FRS and particularly the reinforcing effect is more obvious under un-drained shear. In addition, the strength of the composite is independent of the fibre mechanical indexes as monitored between two types of polypropylene fibres and one type of carbon fibre. Volume contraction also decreases by increasing the polypropylene fibre content under drained conditions whereas for high doses a clearly dilation behavior is observed. SEM images indicate that distributed fibres in the soil matrix are acting like a three-dimensional reinforcing network. Though, the impaction of soil particles on the different types of fibre surfaces seems to be the dominant factor controlling the interfacial strength and therefore the mechanical response of the whole mixture.

REFERENCES

Ahmad, F., F. Bateni and M. Azmi, 2010. Performance evaluation of silty sand reinforced with fibres. Geotext. Geomembranes, 28(1): 93-99.

Al Wahab, R.M. and H.H. Al-Qurna, 1995. Fiber reinforced cohesive soils for application in compacted earth structures. Proceedings of Geosynthetics '95, Nashville, Tennessee, pp: 433-446.

Al Wahab, R.M.A. and M.A. El-Kedrah, 1995. Using fibers to reduce tension cracks and shrink/swell in a compacted clay. Proceedings of the Geoenvironment 2000 ASCE, 1: 791-805.

Bauer, G.E. and A. Oancea, 1996. Triaxial testing of granular soils reinforced with discrete polypropylene fibers. Proceedings of the 1st European Geosynthetics Conference on Geosynthetics: Applications, Design and Construction. Rotterdam, pp: 407-410.

Casagrande, M.D.T., M.R. Coop and N.C. Consoli, 2006. Behavior of a fiber-reinforced bentonite at large shear displacements. J. Geotech. Geoenviron., 132(11): 1505-1508.

Casagrande, M.D.T., M.R. Coop and N.C. Consoli, 2007. Behavior of a fiber-reinforced bentonite at large shear displacements (Discussion closure paper). J. Geotech. Geoenviron., 133(12): 1635-1636.

Choubane, B., R.K. Ho and J.M. Armaghani, 1999. Full-scale laboratory evaluation of polypropylene fiber reinforcement of subgrade soils. Research Report No. 99-432, Florida Department of Transportation.

Consoli, N.C., J.P. Montardo, P.D.M. Prietto and G.S. Pasa, 2002. Engineering behavior of a sand reinforced with plastic waste. J. Geotech. Geoenviron., 128(6): 462-472.

Consoli, N.C., M.D.T. Casagrande, P.D.M. Prietto and A. Thome, 2003. Plate load test on fiber-reinforced soil. J. Geotech. Geoenviron., 129(10): 951-955.

Falorca, I.M.C.F.G., M.I.M. Pinto and G.L.M. Ferreira, 2006. Residual shear strength of sandy clay reinforced with short polypropylene fibres randomly oriented. Proceedings of the 8th International Conference on Geosynthetics. Yokohama, 4: 1663-1666.

Farrag, K.A. and P. Griffin, 1993. Pull-out Testing of Geogrids in Cohesive Soils. In: Cheng, S.C.J. (Ed.), Geosynthetic Soil Reinforcement Testing Procedures. ASTM STP 1190, Philadelphia, pp: 76-89.

Fishman, K.L. and S. Pal, 1994. Further study of geomembrane/cohesive soil interface shear behaviour. Geotext. Geomembranes, 13(9): 571-590.

Fredlund, D.G. and H. Rahardjo, 1993. Soil Mechanics for Unsaturated Soils. Wiley, New York.

Freilich, B.J., C. Li and J.G. Zornberg, 2010. Effective shear strength of fiber-reinforced clays. Proceeding of the 9th International Conference on Geosynthetics. Brazil, pp: 1997-2000.

Gray, D.H. and H. Ohashi, 1983. Mechanics of fiber reinforcement in sand. J. Geotech. Eng-ASCE, 109(3): 335-353.

Gregory, G.H. and D.S. Chill, 1998. Stabilization of earth slopes with fiber reinforcement. Proceedings of the 6th International Conference on Geosynthetics. Atlanta, pp: 1073-1078.

Ibraim, E. and S. Fourmont, 2006. Behaviour of sand reinforced with fibres. Proceedings of the Geotechnical Symposium in Roma. Netherlands, pp: 807-818.

Ibraim, E., A. Diambra, D.M. Wood and A.R. Russel, 2010. Static liquefaction of fibre reinforced sand under monotonic loading. Geotext. Geomembranes, 28(4): 374-385.

Kaniraj, S.R. and V.G. Havanagi, 2001. Behavior of cement-stabilized fiber-reinforced fly ash-soil mixtures. J. Geotech. Geoenviron., 127(7): 574-584.

Li, C., 2005. Mechanical response of fiber-reinforced soil. Ph.D. Thesis, University of Texas, Austin, USA.

Lopes, M.L. and M. Ladeira, 1996. Influence of the confinement, soil density and displacement rate on soil-geogrid interaction. Geotext. Geomembranes, 14(10): 543-554.

Maher, M.H. and D.H. Gray, 1990. Static response of sands reinforced with randomly distributed fibers. J. Geotech. Eng., 116(11): 1661-1677.

Michalowski, R.L., 1997. Limit stress for granular composites reinforced with continuous filaments. J. Eng. Mech., 123(8): 852-859.

Michalowski, R.L. and A. Zhao, 1996. Failure of fiber-reinforced granular soils. J. Geotech. Eng-ASCE, 122(3): 226-234.

Michalowski, R.L. and J. Cermak, 2003. Triaxial compression of sand reinforced with fibers. J. Geotech. Geoenviron., 129(2): 125-136.

Moraci, N. and D. Gioffre, 2006. A simple method to evaluate the pullout resistance of extruded geogrids embedded in a compacted granular soil. Geotext. Geomembranes, 24(2): 116-128.

Murray, J.J., J.D. Frost and Y. Wang, 2000. Behavior of a sandy silt reinforced with discontinuous recycled fibre inclusions. Transport. Res. Rec., 1714: 9-17.

Ozkul, Z.H. and G. Baycal, 2007. Shear behavior of compacted rubber fiber-clay composite in drained and undrained loading. J. Geotech. Geoenviron., 133(7): 767-781.

Pradhan, P.K., R.K. Kar and A. Naik, 2012. Effect of random inclusion of polypropylene fibers on strength characteristics of cohesive soil. Geotech. Geol. Eng., 30(1): 15-25.

Racana, N., M. Grediac and R. Gourves, 2003. Pull-out response of corrugated geotextile strips. Geotext. Geomembranes, 21(5): 265-288.

Rao, S.V.K. and A.M.A. Nasr, 2012. Laboratory study on the relative performance of silty-sand soils reinforced with linen fiber. Geotech. Geol. Eng., 30(1): 63-74.

Sadek, S., S.S. Najjar and F. Freiha, 2010. Shear strength of fiber-reinforced sands. J. Geotech. Geoenviron., 136(3): 490-499.

Shewbridge, S.E. and N. Sitar, 1990. Deformation-based model for reinforced sand. J. Geotech. Geoenviron., 116(7): 1153-1170.

Tang, C., B. Shi, W. Gao, F. Chen and Y. Cai, 2007. Strength and mechanical behavior of short polypropylene fiber reinforced and cement stabilized clayey soil. Geotext. Geomembranes, 25(3): 194-202.

Tang, C.S., B. Shi and L.Z. Zhao, 2010. Interfacial shear strength of fiber reinforced soil. Geotext. Geomembranes, 28(1): 54-62.

Tingle, J.S., S.L. Webster and R.L. Santoni, 1999. Discrete fiber reinforcement of sands for expedient road construction. Report GL 99-3, U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg.

Webster, S.L. and R.L. Santoni, 1997. Contingency airfield and road construction using geosynthetic fiber stabilization of sands. Report GL 97-4, U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg.

Zaimoglu, A.S. and T. Yetimoglu, 2012. Strength behavior of fine grained soil reinforced with randomly distributed polypropylene fibers. Geotech. Geol. Eng., 30(1): 197-203.

Ziegler, S., D. Leshchinsky, H.I. Ling and E.B. Perry, 1998. Effect of short polymeric fibers on crack development in clays. Soils Found. J. Appl. Clay Sci., 38(1): 247-253.

Zornberg, J.G., 2002. Discrete framework for limit equilibrium analysis of fibre reinforced soil. Geotechnique, 52(8): 593-604.