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EXPERIMENTAL EVIDENCES AND ANALYTICAL EXPRESSION OF ANISOTROPIC SHEAR STRENGTH FIBER-REINFORCED SOILS

Murari Prasad Panda
Aryan Institute of Engineering & Technology, Bhubaneswar

ABSTRACT

This paper alludes on the shear strength of soils supported with short arbitrarily conveyed filaments, which is a new and viable ground improvement strategy. The shear strength of built up soils is normally anisotropic as a result of the method of arrangement and compaction of the dirt with strands. As of late, in light of an enormous exploratory proof acquired straight by the creators or from writing, Lirer at el. (2011) has been proposed a straight forward articulation of the disappointment envelope of fiber supported soils. In the paper, the aftereffects of some triaxial tests did on sandy examples built up with short strands put with various plane of direction have been utilized to adjust the disappointment envelope presented by Lirer et al. (2011) to consider anisotropy.

KEYWORDS: soil improvement, polypropylene fibre, laboratory tests, anisotropy.

INTRODUCTION

Many experimental researches conducted on fibre-reinforced materials have demonstrated that the addition of discrete fibres improves the mechanical behaviour of granular soils, increasing strength and ductility and reducing the post peak-strength loss. The distributed discrete fibres act as a spatial three-dimensional network to interlock soil grains. Therefore, they can be considered an interesting alternative in the case of superficial layers or embankments to be improved.

Several experimental studies ([1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12 and 13]) were conducted to explore the effect of various parameters on the shear strength of soils reinforced with randomly distributed fibres. The macroscopic effect of reinforcement is governed by fibres content w_f, fibres aspect ratio ρ (defined as the ratio between the length L_f and diameter d_f of the fibre, $\rho=L_f/d_f$), fibres orientation, geometrical and mechanical characteristics of the fibres, as well as by soil intrinsic (grading, mineralogy, grain shape) and state (density and applied stresses) properties.

Traditionally, the approach used in the design of fibre-reinforced soil structures assumes that the addition of fibres leads to an increase in the shear strength of the 'homogenised' composite reinforced mass which should be expressed via a non linear formulation. As a matter of fact, non linearity clearly results from the experimental data ([5, 9 and 12]), being ruled by the evolution of the fibre to grains interaction mechanism: at small confining stresses, such interaction is mostly mutual sliding, while at higher confining stresses fibres yielding becomes more and more relevant. In the typical engineering applications, however, discrete fibres are used for shallow reinforcements, and so fibres sliding is the most important micromechanical interaction mechanism.

Different formulations are nowadays available to express the non linear shear strength envelope ([14, 3, 10 and 12]). Even though the fibre to grains relative dimension also plays a relevant role, as clearly stated in some of the previously mentioned works ([3, 8]), only recently it was explicitly included in a possible formulation of the shear strength envelope of the composite material by Lirer *et al.*, 2011 ([12]).

Such an envelope is defined as the sum of two terms: one relative to the natural soil (represented by the soil stress ratio η or the friction angle φ), and a non linear one related to the effect of fibres and stress state. By means of some micromechanical considerations (explained in detail in [12]), the effect of fibres is represented by a single parameter β that takes into account the fibre content, the geometrical properties of fibres and the fibre-grain relative dimension, defined as:

$$\beta = \sqrt{w_f \cdot \rho \cdot \frac{L_f}{d_{50}}} \tag{1}$$

where w_f is the fibre content (defined as the ratio between the weight of fibres W_f and the dry weight of soil W_s, w_f=W_f/W_s), ρ is the fibres aspect ratio, and d_{50} is a representative grain diameter (fro the sake of simplicity, it was assumed that a single diameter represents soil grading).

The expression of the failure envelope for fibre reinforced soils proposed by Lirer *et al.*(2011) is:

$$\eta_r = \eta \left(1 + 0.00004 \cdot \beta \cdot \frac{\sigma_y^{0.85}}{p_a^{0.65} \cdot p'^{0.2}} \right) \tag{2a}$$

where η is the stress obliquity ratio (η=q/p', were q and p' are respectively the deviatoric and mean stress invariant) of the natural soil, $\sigma_{y,f}$ is the fibre tensile strength, p_a is the atmospheric pressure (introduced for dimensional problems).

Eq. (2a) can be also written in terms of friction angle of the reinforced soil φ_r as:

$$\varphi_r = \sin^{-1}\left(\frac{3 \cdot \sin(\varphi) \cdot \left(1 + 0.00004 \cdot \beta \cdot \frac{\sigma_{y,f}^{0.85}}{p_a^{0.65} \cdot p'^{0.2}} \right)}{3 + \sin(\varphi) \left(0.00004 \cdot \beta \cdot \frac{\sigma_{y,f}^{0.85}}{p_a^{0.65} \cdot p'^{0.2}} \right)} \right) \quad (2b)$$

Even though Eqs. (2) have been written based on an oversimplified interpretation of the true micromechanical interaction mechanism between grains and fibers, they have proven able to predict the shear strength of a large variety of fiber reinforced soils measured in triaxial tests (Lirer et al., 2011).

For a given confining stress (for instance, p'=50 kPa), eq. (2b) can be easily adopted to calculate the shear strength increment given by the addition of fibres to two different soils (sand and gravel). Fig. 1 reports the values of the friction angle φ_r predicted by eq. (2b) for different soil gradations and different values of the natural soil friction angles. It can be observed that, for a given value of fibre content and aspect ratio, the addition of fibres is more effective in fine grained soils (sand) than in coarse soils (gravel).As expected, for a given soil, φ_r increases with the aspect ratio of fibres and with fibre content.

What is new is that, for a given friction angle of the natural soil, the shear strength of the reinforced soil is higher for the finer soil, with differences increasing with ρ: comparing (Fig. 1) for instance the friction angle of reinforced silt and sand (for φ=30° of the natural soil) or that of reinforced sand and gravel (for φ=35° of the natural soil). This effect is generated by eq. (2b) as a consequence of the fibre to grains scale effect, and no other expression of the shear strength envelope available in literature is able to reproduce it.

Being eqs. 2 obtained by processing experimental data from triaxial compression tests on compacted specimens in which fibres are mostly laying in the direction of the major tensile strains (horizontal fibres, θ=90°), the values of φ_r shown in Fig. 1 are the maximum ones. For such a reason, the proposed expression need to be modified to take into account the influence of the angle between the preferred plane of orientation of the fibres and the unknown direction of the major principal stress.

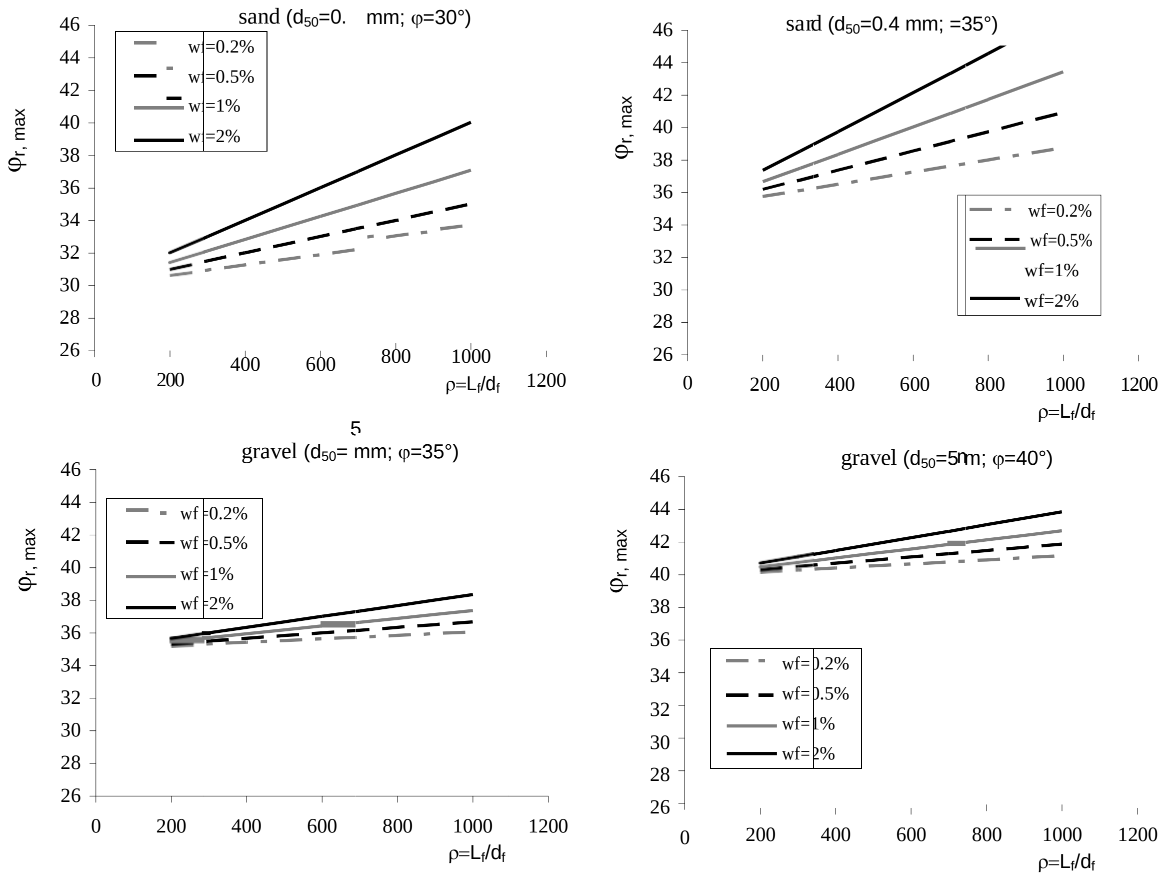

Figure 1: Friction angles of fibre-reinforced soils (φ_r) (eq. 2b).

The distribution of fibre orientation in practical applications of reinforced soils is usually anisotropic because of the techniques of placement and compaction of the soil with fibres. In typical construction conditions, the horizontal plane is the preferential bedding plane, and the fibre orientation distribution can be described as a function of the inclination angle θ to the horizontal. Obviously, fibres in the direction of largest extension contribute in the most effective way to the strength of the composite material, whereas the fibres under compression have an adverse effect. Therefore, to be effective, the bedding plane of fibres must be inside the tensile strains domain, schematically shown in Fig. 2.

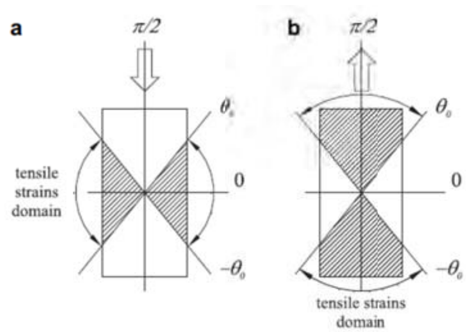

Figure 2: Domains of tensile strain orientation for compression (a) and extension (b), (after[10]).

An effort to consider the anisotropy in the mechanical behaviour of the fibre/reinforced soils has been done by some authors (e.g. [15]). Based on an elliptical distribution of fibres (Fig. 3), Micaloswki ([15]) developed a failure criterion in which the shear strength under plane-strain conditions is described by a function dependent on the in-plane mean stress and the inclination of the major principal stress to the preferred fibres orientation plane (θ). Fig. 3 shows that the strength of the reinforced soils significantly changes with the anisotropy of the material (represented by the ratio ζ between the two axes of an elliptical distribution).

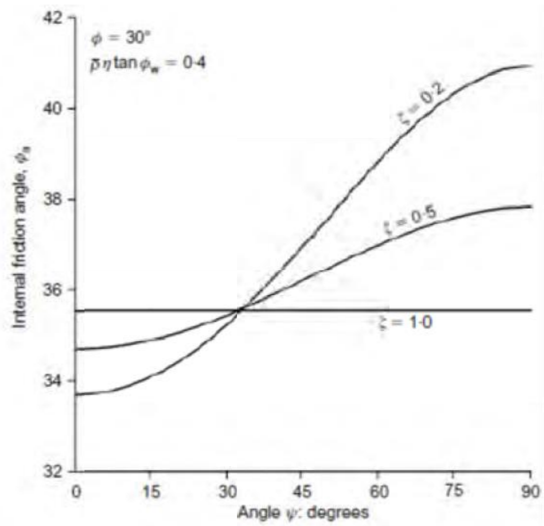

Figure 3: Internal friction angle as a function of the major principal stress inclination to the preferred fibre orientation plane (ψ) for different aspect ratio of the distribution ζ (after [15]).

According to Micaloswki ([15]), for the lower values of θ the addition of fibres may even reduce the soil strength.

Diambra et al ([10]) have proposed an alternative approach to take into account an anisotropic distribution of fibres, based on reasonable assumptions on the behaviour of the fibres. Their model has the advantage of being independent on the model considered to describe the mechanical behaviour of the un-reinforced soil, and is conceived to simulate the behaviour of the composite material also in stress conditions ar from failure.

However, most of the approaches available to take anisotropy into account lack of experimental evidences. This paper will present some laboratory experiments carried out to quantify the effect of the fibre orientation on the shear strength of reinforced soils, whit the final goal to modify the equation (Eqs. 2) proposed by Lirer et al. [12], to take into account anisotropy.

EXPERIMENTAL ACTIVITY

Test materials and specimens preparation

The laboratory activity was carried out on specimen of a non-plastic uniform fine sand (European Standard, 2004) reinforced with polypropylene fibres. The soil and fibre properties are reported respectiv ly in Tab. 1 and Tab. 2. Reinforced samples were prepared by hand mixing dry soil, water and fibres (fibre content w_f=0.5%). Fibres were added progressively in the horizontal

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plane (Fig. 4 a,b). Samples were compacted by wet tamping in five layers into a split mould (L= 150 mm, B=150 mm, H=300 mm) up to a relative density $D_{r,0}$=50% (Fig. 4b).

Reinforced samples were freezing (Fig. 4 c) for 2 days: after that the some specimens were retrieved from the frozen sample. In particular, by choosing different cutting plane (Fig. 4 d,e) of the sample, it was possible to recover specimens with fibres orientation (described as a function of the inclination angle θ to the vertical) ranges between 0° (vertical fibres) to 90 ° (horizontal fibres).

(a) sample preparation (*b*) sample preparation (*c*) frozen sample

(*d*) sample cutting (*e*) sample cutting (*f*) sample cutting

(*g*) specimen trimming (*h*) specimen trimming (*i*) reinforced specimen

Figure 4: Specimen preparation.

Table 1: Physical properties of the natural soil

Maximum diameter, d_{max} (mm)	Mean diameter d_{50} (mm)	Uniformity index Cu	Specific gravity Gs	Maximum void index e_{max}	Minimum void index e_{min}
2	0.8	2.3	2.72	0.60	0.45

Table 2: Properties of the polypropylene fibres

Specific gravity, G_f	Fiber length, L_f (mm)	Fiber diameter, d_f (mm)	Aspect ratio $\rho=L_f/d_f$	Tensile strength, $\sigma_{y,f}$ (MPa)
0.91	24	0.023	1043	120

Experimental program

Some drained triaxial tests (Tab. 3) were carried out on both un-reinforced and reinforced frozen specimens in a stress-strain controlled Bishop cell. Three triaxial tests on natural soil (S1, S2 and S3) have been performed to quantify the increase in the soil shear strength given by the addition of fibres. Eleven tests have been carried out on fibre-reinforced specimens.

The thawing of the reinforced specimens was carried out in the triaxial apparatus (in about 24 hours) imposing a low isotropic effective stress (σ'_c=20 kPa) in drained conditions, with a back pressure of 30 kPa. In principle, under such a low effective stress level, extremely small volumetric deformations of the soil skeleton have to be expected. Upon thawing, specimen saturation (Skempton parameter B≥98%) was guaranteed by water flow under a very low hydraulic gradient.

After saturation, specimens were isotropically consolidated up to a defined stress σ'c and then a monotonic stress path was applied up to the end of the tests (more or less at an axial strain ε_a=20%).

Table 3: Experimental programme

	Name test	Stress path	Confining stress σ'c (kPa)	Relative density Dr (%)	Fibre content w_f (%)	Fibre orientation θ (°)
	S1		50			
	S2		100			-
	S3		200			
	FS1					90
	FS2		50			30
	FS3					60
Natural soil	FS4	CID		50	-	30
	FS5		100			60
	FS6					90
	FS7					0
	FS8		200			30
	FS9					60
	FS10					90

Analyses of the laboratory results

The results of the drained triaxial tests carried out on the natural soil are reported in Fig. 5a: specimens show a ductile behaviour in the stress-strain plane and their shear strength (represented by the maximum value of the stress obliquity ratio η_{max}=1.6) doesn't depend on the stress state.

Some results of triaxial tests on reinforced specimens (tests carried out with a confining stress equal to 100 kPa) are plotted in Fig. 5b: the increase in shear strength due the fibre addition is clear. As expected, fibres in the direction of largest extension (θ=90°) contribute in the most effective way to the strength of the reinforced material.

The ultimate reinforced friction angles (measured at axial strain ε_a=20%) measured in all the triaxial tests are plotted versus fibre orientation θ in Figure 5c: it can be noted that the shear strength of reinforced soil depends on both the fibre orientation and the stress level. Consistently with published experimental evidence, the shear strength of the reinforced soil decreases as the preferred plane of orientation of the fibres departs from the major tensile strains direction (θ<90°).

INTERPRETATION OF THE EXPERIMENTAL RESULTS

As previously showed, anisotropy reduces the reinforced soil friction angle depending on the value of fibre orientation. Considering the experimental evidences, it is reasonable to assume that the reduction in friction angle should be smooth for bedding angles just a bit smaller than θ=90°, getting sharper and sharper as the angle θ tends to zero. As a starting hypothesis, it can be considered that for θ=0°, the fibres have no effect on the behaviour of the reinforced soil, even though the experimental results (Fig. 5c) and some literature evidences (Fig. 2) suggest that in such a case they could even result into a value of φ_r smaller than that of the natural soil.

A simple way to incorporate in eq. (2b) the effect of anisotropy in the terms just described is by the adoption of a non linear anisotropy reduction function f(θ) of the second term of the second member of the equation.

$$\eta_r = \eta\left(1 + 0.00004 \cdot f(\theta) \cdot \beta \cdot \frac{\sigma_{y,f}^{0.85}}{p_a^{0.65} \cdot p'^{0.2}}\right) \quad (3)$$

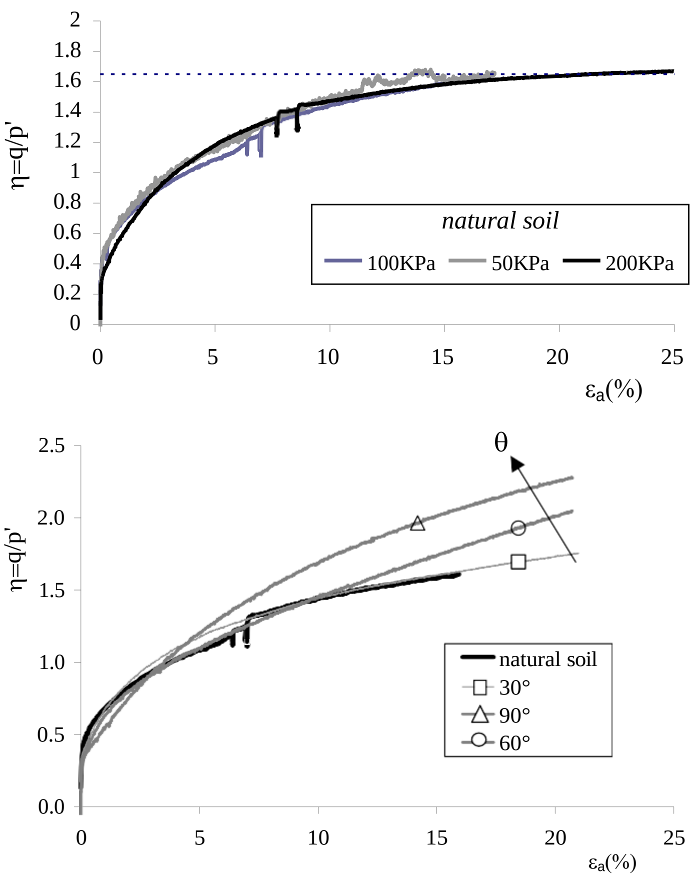
The function that gives the better fitting with the experimental results obtained in this work is :

$$f(\theta) = 0.6 \cdot \sinh(\theta) \quad (4)$$

Introducing eq. (4) in eq. (3), a more general form of friction angle of the anisotropic reinforced soil is obtained :

$$\varphi_r = \sin^{-1}\left(\frac{3\cdot\sin(\varphi)\cdot\left(1+0.00004\cdot(0.6\sinh\theta)\cdot\beta\cdot\frac{\sigma_{y,f}^{0.85}}{p_a^{0.65}\cdot p'^{0.2}}\right)}{3+\sin(\varphi)\left(0.00004\cdot(0.6\sinh\theta)\cdot\beta\cdot\frac{\sigma_{y,f}^{0.85}}{p_a^{0.65}\cdot p'^{0.2}}\right)} \right) \qquad (5)$$

Figure 6 reports the predicted (eq. 5) and measured values of φr for the tests carried out in this work or retrieved from the literature. As it can be noted in Fig. 6, few data refer to specimens reinforced with fibres not placed in the horizontal plane (θ ≠ 90°). The overall agreement between measured and predicted friction angles is satisfactory, since the experimental results obtained on different soils, different fibres and stress levels are well predicted by eq. (5).



(*a*)

(*b*)

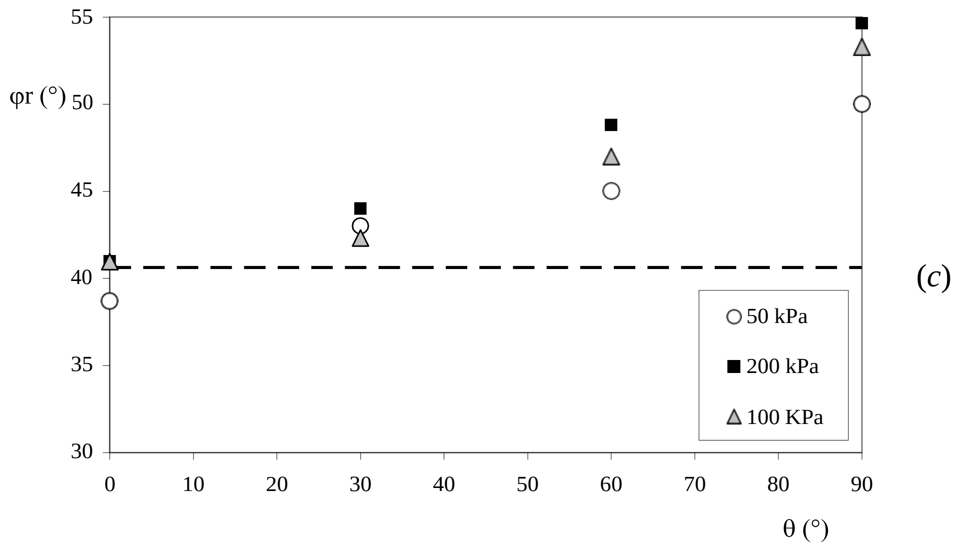


Figure 5: Experimental results: a) shear strength of natural soil; b) shear strength of reinforced soils (at a confining stress of 100 kPa); c) ultimate reinforced friction angle (measured at axial strain ε_a=20%) versus fiber orientation θ.

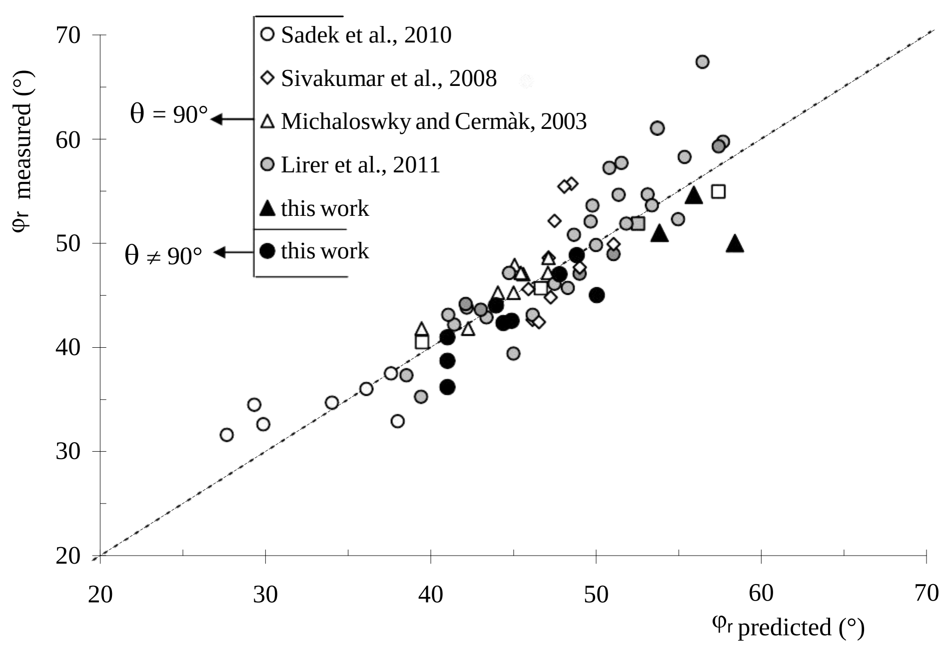


Figure 6: Comparison between measured and predicted (eq. 5) reinforced friction angles φr.

CONCLUDING REMARKS

Some drained triaxial tests have been carried out to analyse the rule of fibre orientation in the shear strength of a sandy reinforced soil. The experimental results were used to calibrate an expression of the failure envelope of fibre reinforced soils which takes into account both the fibre-grain relative dimension and the effect of anisotropy.

The proposed expression shows that:

- for a given value of fibre content and aspect ratio, the addition of fibres is more effective in fine grained soils than in coarse soils;
- for a given friction angle of the natural soil, the shear strength of the reinforced soil is higher for the finer soil (with differences increasing with ρ); this effect of the proposed expression cannot be obtained with any of the available models, being related to the 'scale effect';
- the shear strength of the reinforced soils decreases as the preferred plane of orientation of the fibres departs from the major tensile strains direction ($\theta<90°$). Consistently with published experimental evidence, this effect becomes relevant for value of θ significantly smaller than 90°.

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