Behavior of plate tests bearing on fiber-reinforced sand

Comportement de la plaque tests portant sur fiber-sable renforcé

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ABSTRACT

Field tests are uncommon in fiber-reinforced soil researches. The polypropylene fibers mixture on a compacted residual sandy soil can increase the bearing capacity response to be used as a base of shallow foundations, when compared with non-reinforced soil. Past research has demonstrated that inclusion of fibers significantly improves the engineering response of soils. A number of factors such as fiber content, orientation of fibers with respect to the shear surface, and the elastic modulus of the fiber were each found to influence the contribution of fibers to the shear strength. The present work is aimed at a fundamental understanding of the 90% relative density on the behavior of a plate bearing test on a compacted sandy soil-polypropylene fiber stratum, when compared to a non-reinforced layer, including an investigation of the performance at large displacements and the determination of the vertical displacement level where the reinforcement will present influence in strength and deformability characteristics for the new material. The fiber inclusion occasion a drastic change in load-settlement behavior, conferring for the new material an increasing in strength and stiffness characteristics, when compared with non-reinforced sand. The fiber inclusion change the failure mechanisms observed for non-reinforced sand. The lateral expansion is contained by the fibers, increasing the horizontal loadings and the fiber-reinforced sand bearing capacity. This improvement of soil behavior due to fiber introduction suggests the potential application of fiber-reinforcement for landfill final covers, embankments over soft soils and other earthworks that may suffer excessive deformation.

RÉSUMÉ

Les essais sur le terrain sont rares dans fiber-sol renforcé recherches. Le mélange de polypropylène fibers sur un résiduel de sable compacté le sol peut augmenter la capacité portante réponse à être utilisé comme base de fondations, en comparaison avec les non-sol renforcé. Les recherches antérieures ont démontré que l'inclusion de fibers améliore sensiblement la réponse de l'ingénierie des sols. Un certain nombre de facteurs tels que fiber contenu, l'orientation de fibers à l'égard de la surface de cisaillement, et le module d'élasticité de la fiber ont été trouvés à l'influence de fibers contribution à la résistance au cisaillement. Le présent travail vise à une compréhension fondamentale de 90% de la densité relative sur le comportement d'une plaque d'essai portant sur un sol de sable compacté-fiber couche de polypropylène y compris une enquête de la performance à grande déplacements et la détermination de la verticale d'un niveau où le renforcement présentera influence de la force et la déformabilité des caractéristiques du nouveau matériel. L'inclusion fiber occasion, un changement radical en charge de règlement comportement, conférant pour le nouveau matériel de plus en plus en force et la rigidité caractéristiques, en comparaison avec les non-renforcée de sable. L'extension latérale est contenue par la fibers, l'augmentation de la charge de l'horizontale et la fiber-sable renforcé la capacité portante. Cette amélioration du comportement des sols due à l'introduction fiber suggère l'application éventuelle de renforcement fiber-finale à l'enfouissement couvre, remblais sur sols mous et d'autres travaux de terrassement qui souffrent mai déformation excessive.

Keywords: Footings/foundations; reinforced soils; sands; failure; bearing capacity.

1 INTRODUCTION

Field tests are uncommon in the area of fibre-reinforcement of soils. Consoli *et al*. (2003) were among the first to demonstrate the improvement in behaviour in an *in situ* plate load test on a silty sand soil resulting from inclusion of fibres in the soil. The plate load tests carried out by Consoli *et al*. (2003) on the fibre-reinforced soil were performed to relatively high bearing pressures, and gave a noticeable stiffer response than that carried out on the non-reinforced soil. Other important work was performed by Crockford *et al.* (1993), who evaluated the gain in the lifetime of a pavement resulting from fibre inclusion. Regarding laboratory tests, Gray & Ohashi (1983) studied the mechanics of fibre-reinforcement in cohesionless soils, and showed that inclusion of fibres increased peak shear strength and ductility of soils under static loads. A number of factors such as fibre content, orientation of fibres with respect to the shear surface, and the elastic modulus of the fibres were each found to influence the contribution of fibres to the shear strength. Later work by many researchers (e.g. Gray & Al-Refeai 1986; Maher & Gray 1990; Maher & Ho 1993; Consoli *et al*. 1998, 1999, 2002, 2005; Zornberg 2002, Michalowski & Cermák 2003, Heineck *et al*. 2005, Casagrande 2005), has improved understanding of the mechanisms involved and the parameters affecting the behaviour of fibre-reinforced soils under static loading conditions in the laboratory.

The present work is aimed at a fundamental understanding of the behaviour of plate load tests bearing on a compacted fibre-reinforced sand stratum, when compared to a non-reinforced sand layer. This study includes an investigation of the performance of the plate tests at large displacements and the determination of the amount of settlement required for the fibres to have an effect on the load-settlement response, as well as the effect of the fibre-reinforcement on the kinematics of failure.

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The results presented are part of a comprehensive joint testing program being carried out by the Federal University of Rio Grande do Sul (UFRGS) and University of Passo Fundo (UPF), located in southern Brazil, to verify the improvement in the behaviour of shallow foundations on sandy soil due to fibre reinforcement.

2 EXPERIMENTAL PROGRAM

2.1 *Materials*

The sand used in the testing was obtained from the region of Osorio near Porto Alegre, in southern Brazil. The soil is classified [ASTM D 2487-93 (1993)] as non-plastic uniform fine sand (SP) and the specific gravity of the solids is 2.63. Mineralogical analysis showed that sand particles are predominantly quartz. The grain size is entirely fine sand with an effective diameter (D_{50}) of 0.16 mm, and uniformity and curvature coefficients of 1.9 and 1.2, respectively. The minimum and maximum void ratios are 0.6 and 0.9, respectively.

Polypropylene fibres were used throughout this investigation to reinforce the soil. Their average dimensions were 24 mm in length and 0.023 mm in diameter, with a specific density of 0.91, a tensile strength and elastic modulus of 120 MPa and 3 GPa, respectively, and a linear strain at failure of about 80 %.

2.2 *Plate Load Tests*

The plate load tests were carried out using a 0.30 m diameter smooth circular rigid steel plate, 25.4 mm in thickness, resting on the top of non-reinforced and fibre-reinforced sand. The soil material was prepared by mixing, in a rotating drum mixer, dry sand with fibres, and then adding water to achieve a water content of 12%. For the fibre-reinforced samples, the fibre content was 0.5% of the dry sand weight. The tests were conducted on samples compacted within a wooden box, 2.8 m × 2.8 m in plan dimensions, and 1.4 m high, with a soil thickness of 1.2 m, which is equivalent to 4 times the plate diameter. The soil was placed in 12 consecutive lifts, each 0.1 m thick, with each layer being compacted using a vibratory plate, to relative densitie of 90%.

The load was applied through a system comprising a hydraulic jack, a reaction beam, and a load platform, and measured using a calibrated load cell. The loading system had a capacity of 200 kN. The displacements of top of the plate were measured using three LVDTs spaced equally around the periphery of the plate (Figure 1). Another LVDT was positioned 100 mm outside the plate, to determine the external displacements of the soil surface. The LVDTs were fixed to a reference beam and supported on external supports. The data from the load cell and LVDTs were logged by a data acquisition system. Pressure cells were inserted in the side walls of the box at mid-height. These registered only insignificant stresses during the tests, showing that the square box was sufficiently large to have no effect of finite box size.

The load was applied in equal increments of not more than one-tenth of the estimated ultimate bearing capacity. Each increment was maintained for at least 30 minutes, and until the following criterion was achieved:

$$L_n - L_{n-1} \leq 0.05 \cdot (L_n - L_1) \quad (1)$$

where L_n is the average LVDT reading (on the top of the plate) at a specified time *t* (15 sec, 30 sec, 1 min, 2 min, 4 min, 8 min, 15 min, 30 min, 1 hour and so on, after stage loading appliance), L_{n-1} is the immediately-previous reading, and L_1 is the first reading of the stage of loading taken just after stage loading appliance, according to Brazilian standard NBR-12131 (1991), which is in accordance with the standard ASTM D 1194-94 (1998). When the LVDTs reached their limit, they were reset at the end of a loading stage, allowing settlement measurements greater than 50 mm.

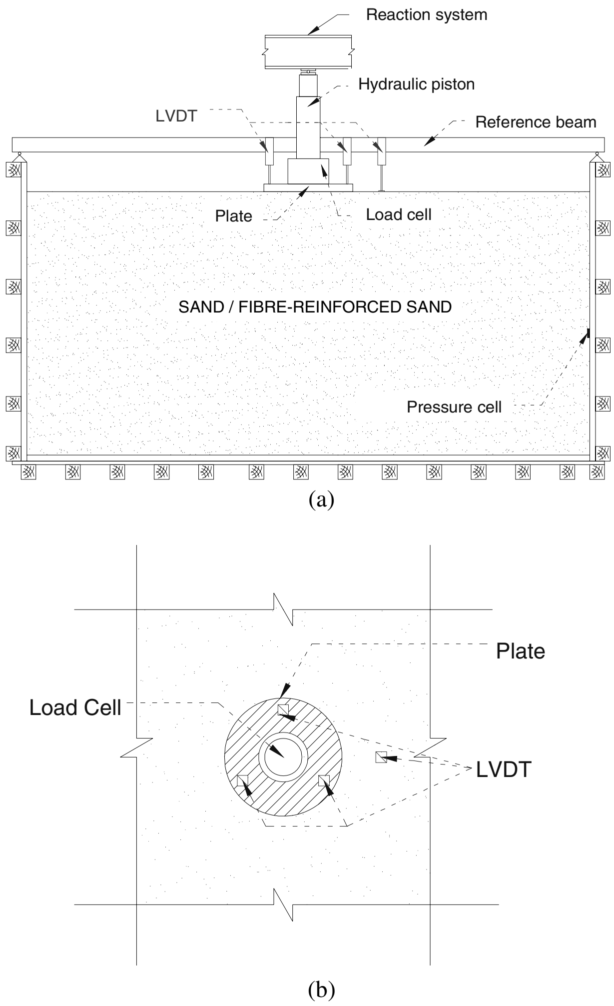


Figure 1. Test setup: (a) cross section and (b) plan view.

3 RESULTS AND ANALYSIS

The results obtained from the tests in non-reinforced and fibre-reinforced sand are shown in Figure 2, for relative densities of 90%. Inclusion of fibres in the sand has resulted in a change in the shape of the load-displacement curves: the non-reinforced cases show reasonably well-defined ultimate loads (‘failure’), but the fibre-reinforced cases show loads continuing to increase at the ends of the tests, even where the total settlements were substantial. The response could therefore be described as being more ‘ductile’ or as showing ‘strain hardening’ characteristics.

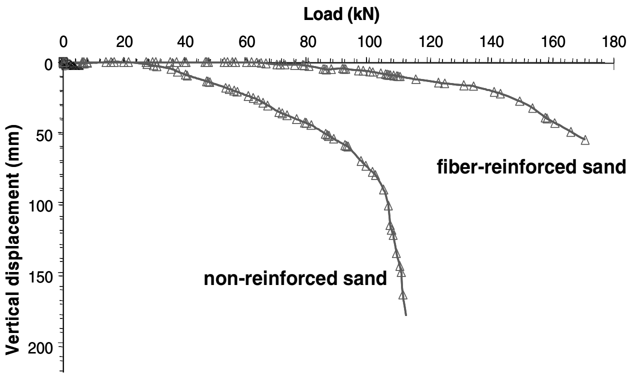
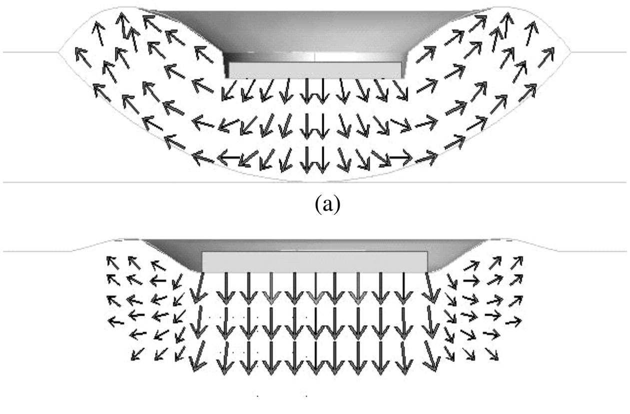


Figure 2. Load-settlement behaviour observed for non reinforced sand and fiber-reinforced sand.

Following completion of each test, the plate was carefully removed, and vertical boreholes were excavated below the loaded area, as an aid in determining failure mechanisms for each case. By combining this information with the measurements of plate settlement and ground surface settlement (or heave) and the observed surface deformation patterns, it was possible to construct a picture of the likely deformation mechanisms in the ground for each case. These are shown in Figure 3 for (a) non-reinforced sand and (b) the fibre-reinforced sand. For the fibre-reinforced case, the fibres seemed to redistribute the stresses over a broader area, acting in a manner somewhat similar to plant roots.



(a)

(b)

Figure 3. Field of displacements suggested after interpretation of vertical displacements measured in the top of the plate and in the top of the tested material, 100mm outside the plate border: (a) sand, D_R = 90%; and (b) fibre-reinforced sand, D_R = 90%.

The failure patters in the non-reinforced cases can be classified in the terminology of Vésic (1975) as 'punching shear'. However, inclusion of fibres in the sand resulted in a radical change in failure mechanisms observed. This behaviour is attributed to interaction between the fibres and the sand around and below the plate. For the very dense fibre-reinforced case (D_R = 90%), the mechanism suggests that lateral expansion of the sand is contained by the fibres acting in tension, thereby increasing the confining stresses, resulting in a very significant increase in bearing capacity for this case. Another fact observed that confirms the fibre-reinforced sand mobilisation outside of the plate area is that the radial fissures that appear in non-reinforced sand have disappeared for the fibre-reinforced sand.

The expansion of the sand out of the plate is reduced because of the fibre-reinforcement, the vertical upward heave expansion is drastically reduced, even for loads 50% higher than the non-reinforced soil failure load.

It has been shown by many authors (e.g. Maher & Gray 1990, Zornberg 2002, Heineck et al 2005) that the fibres in fibre-reinforced sand actually work in tension and not in shear. The tensile restraint produced by the fibres tends to act like an effective confining pressure, which increases the frictional component of the strength. In effect, the fibres tend to act to suppress dilation (e.g. Michalowski & Cermák 2003) in dense sands, such that shear deformation occurs in a manner analogous to undrained shearing; in this latter case, the tendency for dilation results in generation of negative pore pressure, and hence an increase in effective stress, which acts to suppress dilation. The degree to which dilation is suppressed by the fibres is probably quite low, but, as will be shown later, it is still sufficient to give a significant increase in effective stress, and hence in shear strength.

From the load-settlement curves presented previously, it is possible to evaluate the absorbed energy in each of the plate tests, this being obtained by the integration of the area under the load-settlement curve. The absorbed energy for fibre-reinforced cases was greater than for the corresponding non-reinforced cases. The increase in absorbed energy was around 127% (at a settlement of 200 mm).

4 CONCLUDING REMARKS

The following observations and conclusions are made regarding the influence of the relative density on the behaviour of plate tests bearing on polypropylene fibre-reinforced and non-reinforced sandy soil:

1. From the plate load tests carried out in the present research, it can be concluded that inclusion of fibres in the sand caused a drastic change in plate load-settlement behaviour, when compared to the non-reinforced sand, conferring on the composite material superior strength and stiffness characteristics compared with non-reinforced sand;
2. The inclusion of fibres changes the failure mechanisms observed for non-reinforced sand. Another detail observed that confirms the fibre-reinforced sand mobilisation outside the plate area is that the radial fissures that are manifest in non-reinforced sand have disappeared for the fibre-reinforced sand;
3. The effect of fibre inclusion on bearing capacity and stiffness, and the sensitivity of that effect to relative density seems to fit with the idea that fibres have the effect of tending to suppress dilation;
4. The fibre-reinforced sand shows the ability to maintain strength (or even continue to increase strength) with ongoing deformation, suggesting a very ductile material. Thus, this material might potentially be used in other earthworks, such as part of cover liners of municipal solid waste landfills, which suffer huge differential settlements, as well as in embankments over organic soft soils, which suffer excessive deformation due to consolidation. In both cases, this new geo-material might suffer huge differential displacements without opening fissures or deteriorating.

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