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Technical note

The effect of the particle size distribution on the mechanics of fibre-reinforced sands under one-dimensional compression

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ABSTRACT

Seven reconstituted sands of different mineralogies and different particle size distributions, from uniform to well-graded and coarse to fine, were tested under one-dimensional compression, with and without reinforcement by discrete fibres. The compressibility, the particle breakage and the associated change in particle shape were examined in the sands with and without reinforcement. Each reconstituted sand was found to have a unique normal compression line. The compressibility increased with increasing uniformity and with larger mean diameters, thus coarse uniform sands were found to be the most compressible. They also underwent more breakage of particles, which was more significant in the weaker carbonate sands. At the grain scale, the addition of fibres seemed to reduce the amount of particle breakage in the soil, more significantly in well-graded sands. A unique NCL was found for each fibre-reinforced sand, parallel to that of the corresponding non-reinforced sand. A strong correlation was found between the ability of the fibres to prevent particle breakage and their ability to limit changes in particle shape.

1. Introduction

The use of fibres as a means of reinforcing soil has been shown to provide an increase in the strength and ductility of the host soil, the latter in particular in stabilised soils (e.g. Hamidi and Hooresfand, 2013; Nasr, 2014; Correia et al., 2015). Several researchers have contributed to the understanding of the mechanics of soil reinforced with discrete fibres (e.g. Gray and Ohashi, 1983; Heineck et al., 2005; Consoli et al., 2005; Silva Dos Santos et al., 2010). As a result, there is a large database available on the influence of properties of both the host soil (particle size, density, gradation, shape) and the fibres (length, aspect ratio) on the behaviour of fibre-soil mixtures. Most of this research focused on the benefits of adding fibres to the shearing strength of the host soil and how it could be predicted (e.g. Michalowski and Cermak, 2003; Lirer et al., 2011). The behaviour of fibre-reinforced soils under compression has been less studied. Consoli et al. (2005) found that unique isotropic normal compression lines (NCL) exist for non-reinforced and for fibre-reinforced sands, parallel to each other, with the NCL for the reinforced soil lying above the NCL for the pure soil. Similar results were found by Silva Dos Santos et al. (2010) from isotropic compression tests on fibre-reinforced and pure fine sand. They also analysed the mechanics at particle level and found that fibre-reinforced sands underwent less breakage than the non-reinforced sands. However, the amount of breakage was very small since the sand particles' mineralogy consisted mainly of quartz, and it was not quantified.

Studies on the influence of the particle size distribution, i.e. particle size and gradation, on the fibre-reinforced soil behaviour exist but they are predominantly based on the shearing behaviour of the soil. For example, Maher and Gray (1990) found that in uniform fibre-reinforced sands, the value of confining stress at which the mechanism of reinforcement changes from slipping to yielding of the fibres is larger than that in well-graded sands. Michalowski and Cermak (2003) determined that when the fibre content is low, the gain in shear strength due to fibre reinforcement is more significant in fine sand than in coarse sand, but at higher fibre content, the tendency was found to be reverse as the reinforcement performed better in the coarse sand. Existing work on the compression behaviour of fibre-reinforced soils can only be found for uniform soil, such as e.g. Osorio sand used by Consoli and co-workers. There is evidence however that a change in grading can affect the behaviour of pure granular soils at both the microscopic

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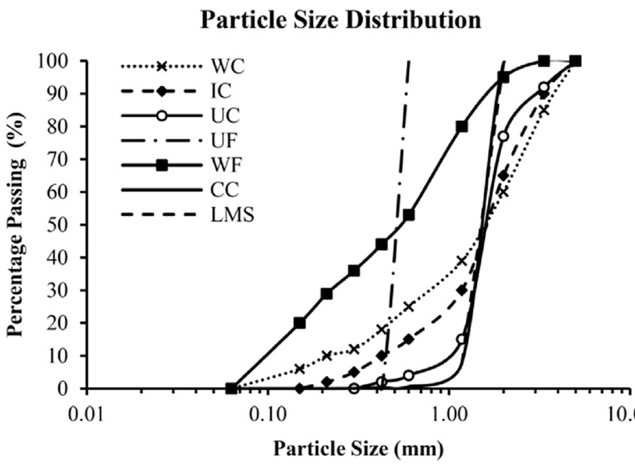

Fig. 1. Particle size distribution of the host sands.

and the macroscopic scale (e.g. Altuhafi and Coop, 2011). This paper examines the effect of the host soil characteristics on the performance of the fibre reinforcement. The one-dimensional behaviour of sands of various particle size distributions, with and without fibre reinforcement, is presented. The effects of the grading and the strength and shape of the soil grains on the compressibility of the soils, and on the underlying mechanics at the grain scale (e.g. particle breakage, change in particle shape) are discussed.

2. Materials, testing apparatus and procedures

The tests were carried out on reconstituted completely decomposed granite, coral sand and limestone.

2.1. Materials

Complete decomposed granite (CDG) from Hong Kong was used to reconstitute five sands at different gradations. Hong Kong CDG is a residual soil with particles made mostly of quartz and feldspar. It is well graded in nature, with about 15% of the particles passing a 63 micron sieve. The natural CDG was sieved, separated into different sizes of particles, and specimens were created according to the proportions necessary to obtain the particle size distributions shown in Fig. 1. Two well-graded (W), two uniformly graded (U) and one intermediate graded (I) soils were created, pivoting around two different mean sizes, coarse (C) and fine (F). Their coefficient of uniformity and their mean diameter are listed in Table 1. A specific gravity of 2.65, found from previous study, was used for the computation of the specific volumes. Two carbonate sands composed predominantly of calcium carbonate were also tested, a uniform coarse coral sand (CC) of natural origin and a uniform coarse crushed limestone (LMS). Their particle size distributions are also shown in Fig. 1, and their coefficient of uniformity and mean diameter are presented in Table 1. Their specific gravity was measured as 2.73 and 2.72 for the coral sand and limestone respectively. Scanning electron micrographs of the different sand particles in Fig. 2: the CDG and limestone have solid structures (Figs. 2a and b) and are quite round in shape, while the coral sand grains are more elongated and contain a large quantity of internal voids (Fig. 2c). These voids should make the soil particles more susceptible to breakage under loading and the overall soil much weaker.

Table 1
Coefficients of uniformity (C_u) and mean diameters (D_{50}) of the host sands.

Material	C_u	D_{50} (mm)
WC	9.43	1.60
IC	4.47	1.60
UC	1.48	1.60
UF	1.36	0.42
WF	7.30	0.42
CC	1.37	1.56
LMS	1.37	1.56

Polypropylene fibres similar to those used by Silva Dos Santos et al. (2010) were mixed into the soil as reinforcement. The fibres have the following properties: 27 mm in length and 0.023 mm in diameter, with a specific gravity of 0.91, a tensile strength and elastic modulus of 120 MPa and 3 GPa respectively.

2.2. Oedometer tests

A fixed 50 mm diameter and 20 mm high oedometer apparatus was used to evaluate the mechanical behaviour of the sands under compression, both non-reinforced (NR) and reinforced (R). The specimens were loaded to a maximum vertical effective stress of 8.1 MPa. Five initial values of specific volume were computed independently. Two initial specific volumes were computed from the initial water content and the initial measurements, measured by calliper and by the oedometer dial gauge. Two initial specific volumes were back-calculated from the final specific volume which was found from the final water content and dimensions measured again by calliper and by dial gauge. A last computation was made using the volumetric strain, the final degree of saturation and the final water content. The volumetric strain at the end of testing was found to be 20% ± 5%, irrespectively of the soil type or the presence of reinforcement. Values within a range of ±0.03 from a mean value were retained; other values outside this range were discarded. Table 2 shows an example of values computed for the CDG sand. This ensured a good accuracy of the location of the compression curves and therefore a better ground for exploring their convergence to a unique normal compression line. In the case of the reinforced specimens the fibres were considered as part of the solid phase and the same procedure as described above was used to calculate the void ratio.

2.3. Sample preparation

The specimens were prepared at varying densities to be able to evaluate the compressible behaviour of the specimens. The two main densities tested were loose and dense, and in some cases some intermediate specimens were also tested.

For the non-reinforced sands, an initial loose state was achieved by filling the ring with the usage of a teaspoon as slowly as possible and with a minimal drop distance. Specimens in dense and intermediate states were poured in 3 layers, tamping after each layer to achieve the required density. In the better graded specimens, in order to avoid segregation and sedimentation of the fine particles, the mixtures were stirred before placing in the apparatus.

The preparation of the reinforced specimens was done in a way similar to that proposed by Michalowski and Zhao (1996). Here a quantity of 0.3% or 0.5% fibres by mass (indicated on the figures) was added to the host soil. The specimens were prepared in at least five layers of dry soil, adding in-between two layers a portion of fibres that had been previously detangled. They were then mixed taking caution not to produce any clogging between fibres, until the sand layers and the fibre layers were not visible anymore and the soil-fibres composite was uniformly distributed. Finally, a water content of 6–8 % was added to ensure adequate bonding between the fibres and the particles, and a final mix was done, again with