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Technical note

A comparison of the performances of polypropylene and rubber fibers in completely decomposed granite

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ABSTRACT

This fundamental study investigates how two very different types of fibers, very elongated polypropylene fibers with high tensile resistance, and larger rubber fibers with a smaller aspect ratio and low shear and Young's moduli affect the compression and shearing of a soil. The same host soil was used for both types of fibers, a well-graded decomposed granite. As well as providing a realistic base for the study with its well graded nature, the decomposed granite's tendency to contract upon shearing is used to highlight the underlying mechanisms causing any difference in behavior. The soil mixtures were prepared at an optimal fiber content for each kind. The general patterns of behavior of the reinforced soils, such as the stress-dilatancy behavior, and the normal compression and critical state lines, are compared. It is found that the specimens with rubber fibers are initially much less stiff than those with polypropylene fibers, so that they require larger deformations to reach failure. At failure, they can provide as much extra strength as polypropylene fibers if the rubber fiber-soil mixture has been consolidated to a low confining stress, although very much larger quantities are needed, even to the point of being unrealistic for engineering applications. At high confining pressures, the rubber fibers, which have become slack during compression, tend to lose in efficiency. The soil reinforced with polypropylene fibers develops consistently higher strength, but the compressive nature of the base soil has the effect of hindering their full mobilization as would be seen in a dilative soil.

1. Introduction

Adding discrete elements like fibers to soils with a view to improving their performance has been actively researched for two to three decades (e.g. Gray and Ohashi, 1983; Maher and Gray, 1990; Michalowski & Cermak, 2003; Consoli et al., 1998, 2005; Zornberg, 2008; Diambra et al., 2007; Silva dos Santos et al., 2010; Gregory, 2011; Hamidi and Hooresfand, 2013; Correia et al., 2015; Miranda Pino and Baudet, 2015; Madhusudhan et al., 2017). Fibers commonly used in previous studies were made of polypropylene, polyester or fiber glass, but there is an increasing trend, as part of a global effort for sustainable development, to use fibers made of recycled materials such as tire or plastic waste (e.g. Consoli et al., 2002), or natural fibers such as sisal or coconut coir (e.g. Sivakumar Babu et al., 2008).

Fibers made of polypropylene or polyester have been found to provide the soil with a higher strength but with larger deformation at failure in both clayey (e.g. Maher and Ho, 1994) and sandy soils (e.g. Consoli et al., 1998; Silva dos Santos et al., 2010). These fibers work principally in tension, and it might be expected that they therefore perform better in dilative soils, although it has been found that they can also be mobilized during isotropic compression by anchoring between the soil grains (Consoli et al., 2005). In situ, fibers have been used effectively to reinforce shallow foundation sublayers (e.g. Consoli et al., 2003) and thin soil veneers on shallow slopes (Zornberg, 2008), or for the repair of localized failed slopes (Zornberg, 2008). Extensive laboratory studies have allowed the behavior of polypropylene fiber-uniform sand mixtures to be

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successfully described within the Critical State Framework (e.g. Silva dos Santos et al., 2010). The database on fibers made of recycled material, on the other hand, is less complete, most existing research tending to focus on rubber granules, chips or shreds rather than "fibers" (e.g. Valdes and Evans, 2008; Lee et al., 2007, 2014; Fu et al., 2015, 2017). Fundamental research has however been undertaken to study the possibility of using rubber additions as reinforcement. The results have shown that rubber must be added in very much larger proportions than e.g. polypropylene fibers in order to provide some improvement on the strength of the soil, the quantities varying between 10 and 40% depending on the host soil and the type of rubber additions (e.g. Edil and Bosscher, 1994; Foose et al., 1996; Zornberg et al., 2004; Edinçliler and Ayhan, 2010). The initial stiffness during shearing reduces with rubber content, i.e. the strain at which peak strength is achieved increases, (e.g. Zornberg et al., 2004; Özkul and Baykal, 2007), while the compressibility also increases with rubber content (e.g. Youwai and Bergado, 2003; Lee et al., 2010). Their suitability as reinforcing material is therefore far from clear. In this technical note, the fundamental behavior of polypropylene fiber-soil mixtures and rubber fiber-soil mixtures are compared, with no attempt to recommend either as reinforcing material in the decomposed granite or other soils, but the comparison does illuminate the likely mechanisms involved.

There are significant differences between the properties and use of polypropylene fibers and rubber fibers. Small amounts of polypropylene fibers are generally enough to reinforce the soil, while we know that rubber shreds typically need to be added to the soil in very large proportions even to the point of being impractical for many applications. A rubber content of the order of 35% has been found to maximize the effect on the shear strength, beyond which the behavior changes from sand-dominant to tire shred-dominant (Zornberg et al., 2004). The effect is more pronounced when using shreds with a higher aspect ratio e.g. ratios of 8 or above, closer to a fiber shape, although much larger in size. The material polypropylene possesses very high tensile resistance and stiffness, while rubber has low shear and Young's moduli and deforms severely under loading. These differences make it difficult to extrapolate from one material to the next. Different materials have also not been used in the same soil so that a comparison might be made.

The results shown in the following were obtained using two types of fibers, polypropylene fibers and rubber fibers, added to the same host soil so that a comparison can be made. Given the very different fiber properties and quantities of fibers used for each type, comparing individual tests would not be very meaningful, so here the approach has been to identify similarities and differences within general patterns of fundamental behavior described by the Critical State framework, and more particularly the stress-dilatancy behavior, the normal compression and critical state lines.

2. Materials, testing apparatus and procedures

The base soil for the tests was a completely decomposed granite **(CDG)** from Hong Kong. Polypropylene (PP) and rubber fibers (RF) were added to the CDG as described below.

2.1. Materials

The soil was obtained at Mt. Beacon, Kowloon Tong, Hong Kong. It is a well-graded completely decomposed granite containing about 20% fines. The main components of the soil are quartz, potassium feldspar and mica, with some kaolinite present in the clay fraction, giving a plasticity index of 16%. The particle size distribution of the soil is given in Fig. 1. The maximum dry density determined by Proctor compaction was 18.9 kN/m^3 for an optimum water content of 11%. A complete description of the behavior of the CDG within the Critical State framework is available in Madhusudhan and Baudet (2014). The choice of completely decomposed granite as host soil is that being well graded, it may be more representative of many natural soils than the uniform soils typically used in research. One aspect to highlight is that its contractive nature during compression and shearing will hinder rapid mobilization of the fibers, therefore emphasizing the different mechanisms by which the two types of fibers may interact with the soil.

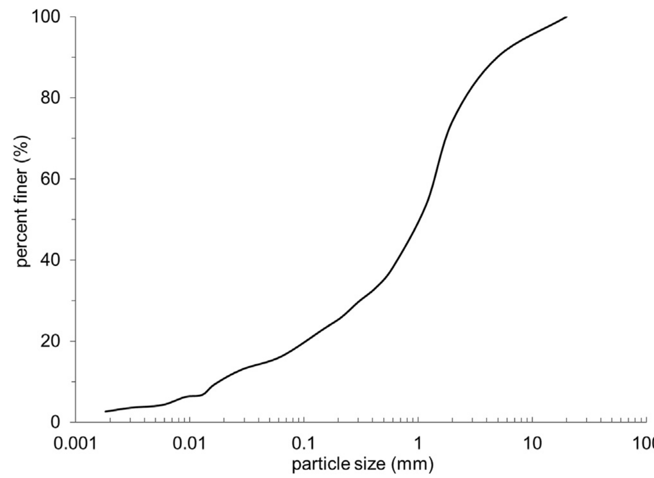

Fig. 1. Particle size distribution of the completely decomposed granite.

The polypropylene fibers used (Fig. 2(a)) were similar to those used by Silva dos Santos et al. (2010) and purchased from a commercial company. The rubber fibers, also called buffings, are byproducts of the tire re-treading industry and therefore consist entirely of recycled material (Fig. 2(b)). Their high aspect ratio compared to shreds or chips should be beneficial, and also should allow a more straightforward comparison with the polypropylene fibers. The properties of the two types of fiber are reported in detail later. The two sets of fiber-soil mixtures were prepared at very different fiber contents but which had been shown to provide the best performance for the decomposed granite for each fiber type (Fu et al., 2017; Madhusudhan et al., 2017). A quantity of 0.3% PP fibers by weight was used, which was based on previous studies (Silva dos Santos et al., 2010; Madhusudhan et al., 2017). The quantities of rubber used for reinforcement are typically much higher (e.g. Edinçliler and Ayhan, 2010; Zornberg et al., 2004): in this study, 30% rubber fibers by weight were added to the decomposed granite. This amount was based on the study by Fu et al. (2017) who showed, albeit on a poorly graded soil, that the performance of rubber-soil mixtures improves with increasing content of rubber, but that it becomes very impractical to prepare soil mixtures with more than 30% rubber content.

2.2. Testing, apparatus and procedures

Triaxial compression tests were carried out on normally consolidated specimens of dimensions 60 mm × 120 mm or 76 mm × 152 mm at The University of Hong Kong and the City University of Hong Kong. Additional isotropic high pressure tests were performed at University College London on the unreinforced and PP-reinforced CDG in order to determine their normal compression and critical state lines. All shearing tests were strain controlled.

For both PP- and RF-fiber soil mixtures, the soil was first mixed at the optimum water content, then the fibers were mixed in. This