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Shear strength of a fibre-reinforced clay at large shear displacement when subjected to different stress histories☆

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A B S T R A C T

The topic of fibre-reinforced soil has been introduced and studied increasingly in the past few decades. However, the shear strength response of fibre-reinforced clay soils with different initial void ratio values when subjected to large shear displacement has not been explored in the literature. The purpose of this study is to evaluate the shear strength responses of fibre-reinforced clay soils when remoulded with relatively small and large initial void ratio and subjected to large shear displacement. In order to exclude the composition variability of the fibre-reinforced samples when subjected to various normal effective stresses, a series of multi-stage reverse drained direct shear test was undertaken with four reverse cycles of ±7 mm, ±7 mm, ±7 mm and +14 mm to achieve an accumulative horizontal shear displacement up to 56 mm that is 93% of the sample dimension. The first stage of the testing programme was carried out on soil samples consolidated at normal effective stress of 600 kPa and unloaded to 50 kPa, followed by 4 shear cycles at normal effective stresses of 50, 100 and 200 kPa, respectively. The results of these tests confirmed significant effective stress ratio improvement with fibre reinforcement, even at large shear displacement to the fourth cycle. However, the rate of improvement decreased with normal effective stress and initial void ratio. Based on the experiments carried out in this study, the optimum fibre content to increase the shear strength of the clay soil with initial void ratio of 0.64 was found to be 0.25% with 140%, 81% and 23% increase in the stress ratio over that of the unreinforced soil at normal effective stresses of 50, 100 and 200 kPa, respectively. The second stage of the testing programme was conducted on a set of samples consolidated and sheared at normal effective stresses of 50, 100 and 200 kPa, respectively. The optimum fibre content was found to be related only to the initial void ratio of the soil, irrespective of the stress history of the soil and the applied normal effective stress. The shear stress ratio of the fibre-reinforced clay soils at large shear displacement was found to be relatively independent of the stress history of the soil. For all soil samples tested in this study, the stress ratio at 200 kPa normal effective stress was found to remain between 0.45 and 0.60.

1. Introduction

Soft clay soils found in the construction of infrastructure projects such as highway embankments typically possess low shear strength, stiffness and bearing capacity resulting in excessive settlements (Du et al., 2014; Jiang et al., 2016). A number of soil improvement techniques has been introduced and practiced to improve the engineering properties of soft clay soils. Short discrete fibres are increasingly prevalent as classical tension resisting elements in geotechnical engineering practice, particularly for improving the mechanical behaviour of weak soils. The technique

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of soil reinforcement using randomly distributed fibres has been extensively studied in recent years. The fibre-reinforced soil behaves as a composite with a relatively coherent matrix (Jamsawang et al., 2015; Mirzababaei et al., 2017). Fibre reinforcement leads to an increase in the soil strength by interlocking soil particles, improving strain resistance and by preventing from formation of continuous planes of weakness at failure (Ahmad et al., 2010). A body of experimental data exists on the shear strength of fibre-reinforced coarse grained soils examining the stress-strain relationships under monotonic loading (Maher and Gray, 1990; Al-Refeai, 1991; Heineck et al., 2005; Diambra et al., 2007; Chen and Loehr, 2008; Hamidi and Hooresfand, 2013; Li and Zornberg, 2013; Miranda Pino and Baudet, 2015; Ajayi et al., 2016). Several investigations have also been targeted towards understanding the mechanical behaviour of fibre-reinforced fine grained soils using triaxial compression tests, unconfined compression strength tests, ring and direct shear tests and 1D-consolidation tests (Estabragh et al., 2012; Botero et al., 2015; Yi et al., 2015; Chen et al., 2015; Nguyen and Indraratna, 2016). A few studies have also been undertaken to evaluate cyclic loading scenarios (Festugato et al., 2013a,b; Sadeghi and Beigi, 2014). Consoli et al. (2002) reported that fibre-reinforced sand gains a superior ultimate strength incorporating increased internal friction angle in the drained condition and larger dilation compared to unreinforced sand with an insignificant change in the initial stiffness and ductility of the soil. Fibres increase the shear strength parameters of the granular soil subjected to compression by confining the soil particles solely through their tensile features. However, fibres are not effective in triaxial extension loading tests due to shortcomings in the specimen preparation methods that force fibres to align in a preferred sub-horizontal orientation relatively perpendicular to the direction of loading (Diambra et al., 2010).

The stress-strain behaviour of fibre-reinforced soil is usually in the form of strain-hardening with no apparent failure (Mirzababaei et al., 2013b). Heineck et al. (2005) similarly reported no strength deterioration of fibre-reinforced sand even at very large horizontal displacements up to 250 mm. Therefore, limit equilibrium, statistical analysis and failure criteria techniques that have been used to investigate the shear strength of fibre-reinforced soils may not adequately capture the behaviour of fibre-reinforced soil at very large strains (Romero, 2003). To reach the residual state, a very large shear displacement in one direction is required to orientate the clay particles face-to-face and parallel to the direction of the shear stress. To overcome the limitation on the shear displacement in the currently available shear test apparatus, drained multiple reverse direct shear test or drained ring shear test have been successfully undertaken for determining the residual shear strength of stiff clays, shales and mudstones (Bishop et al., 1971; Stark and Eid, 1994; Mesri and Huvaj-Sarihan, 2012). In multiple reverse drained direct shear test, a prismatic soil sample is consolidated under an initial normal stress and subsequently is sheared forward and then backward at a sufficiently slow forward shear displacement rate until a residual state is measured. However, in drained ring shear test, a relatively thin annular soil sample is sheared slowly and continuously in one direction while the cross-sectional area of the shear surface during shear remains unchanged.

Skempton (1985) stated that the drained residual shear strength is one of the most important strength parameters in assessing the stability of slopes with a pre-existing shear surface. After sufficient shear displacement in the drained condition, the plate-like clay particles are predominantly aligned face-to-face and orientated parallel to the direction of the shear. In such cases, the shear strength reaches the residual shear strength and then remains constant with progression of the shear displacement (Mesri and Shahien, 2003). Heineck et al. (2005) investigated the shear behaviour of fibre-reinforced sand at very large strains using ring shear tests, triaxial tests and bender element tests and concluded that fibre reinforcement does not influence the behaviour of the soil at small strains, but significantly improves the ultimate strength up to very large strains. Consoli et al. (2007) studied the mechanical behaviour of fibre-reinforced sands using ring shear tests and reported no strength deterioration at markedly large shear displacements, but observed breakage of the fibres into shorter lengths. Casagrande et al. (2006) also evaluated the shear strength of fibre-reinforced bentonite at very large shear displacement using ring shear test and reported a peak shear strength at 1 mm displacement followed by constant strength up to 50 mm and subsequent strength deterioration to shear displacements of 180 mm.

Past research on the shear strength of fibre-reinforced clay soils at large shear displacements is therefore very limited. This research aims to evaluate the drained shear strength of an expansive clay soil at large shear displacement using multi-stage reverse direct shear test. In this study, the impact of initial void ratio, as well as stress history, on the shear strength of the fibre-reinforced clay soil at large shear displacement is investigated.

2. Materials

The soil sample was collected from Sarina township in Central Queensland of Australia. The sample is classified as a highly plastic clay, according to the Unified Soil Classification System (USCS) with an activity ratio of 0.50 and specific gravity of 2.71. The grain size analysis of this soil indicated that it contained 93.3% clay particles with liquid limit and plastic limit of 74% and 27%, respectively. The maximum dry unit weight and optimum moisture content of the soil were determined using the modified Proctor compaction test. The soil properties are presented in Table 1. Short virgin polypropylene monofilament fibres with length of 19 mm, thickness of 32 μm, specific gravity of 0.91 and tensile strength of 600 MPa were used in this study.

3. Soil sample preparation

The procedure mentioned in AS 1289.6.2.2–1998 was used to prepare cohesive soil samples for direct shear test. Saad et al. (2012) showed that preparing fibre-reinforced soil samples in multiple layers improves the uniform distribution of the fibres within the sample and maintains the desired soil density along the sample. Unreinforced clay soil samples were prepared in a 60 mm square shear box in five equal layers of approximately 5 mm each, using a static compression method. The surface of each layer was scarified for better bonding with the successive layers. For the fibre-reinforced soil sample, in order to maintain a consistent fibre distribution within the sample, the desired amount of soil and fibre for each sample was divided into five equal portions, mixed with each other and compacted in the shear box similar to that of the unreinforced clay soil.

4. Experimental program

In traditional shear tests, each specimen is subjected to a stage of consolidation followed by shearing and hence it supplies a single stress versus strain curve and, accordingly, a single stress state point on the failure envelope. To adequately identify the failure envelope and extract the shear strength parameters, a minimum of three specimens must be consolidated at increasing normal effective stresses and sheared respectively. Difficulties arise in preparing identical homogeneous clay soil samples with the same initial void ratio and moisture content. In the case of fibre-reinforced clay soil,