Cyclic shear response of fibre-reinforced cemented paste backfill

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In order to investigate techniques to improve tailings backfill stability in stopes, the cyclic shear response of fibre-reinforced cemented mine tailings was studied. Cyclic simple shear tests were conducted on fibre-reinforced and non-reinforced cemented mine tailings. The tailings, produced from gold mining, are classified as sandy silt with traces of clay. Portland cement (5%) and polypropylene fibres (zero and 0.5%) were added to the material. Under monotonic shear conditions, the addition of fibres confers hardening behaviour to the cemented material. Under shear strain controlled cyclic conditions, fibres increased the shear stress values of the cemented samples after successive load cycles. The agreement of the strength envelopes of both monotonic and cyclic stress paths, under different cyclic loading conditions, allows the use of the same strength parameters of mixtures analysed under different loading conditions.

KEYWORDS: reinforced soils

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NOTATION

C_c	coefficient of curvature
C_u	coefficient of uniformity
d_{tex}	unit of measure for linear mass density of fibres (g/10 000 m)
d_{10}	effective diameter
d_{50}	mean diameter
G_s	specific gravity
γ	shear strain
Δu	pore pressure increment
$\sigma'_v \text{ initial}$	initial effective vertical stress
σ'_v	effective vertical stress
τ	shear stress
$\tau_{\text{cyc max}}$	cyclic maximum shear stress
$\tau_{\text{cyc max}}/\sigma'_v \text{ initial}$	maximum cyclic shear stress to initial effective vertical stress ratio

INTRODUCTION

Paste backfill is the process whereby full stream tailings are combined with small amounts of cement and water before being used to fill previously mined voids in an open stope mining situation. In order to contain the material in a stope (i.e. stopping it from flowing into nearby mine workings), containment barricades are constructed in the stope drawpoint (Helinski *et al.*, 2007).

The mining process usually includes exposure of a face of these stopes, which can reach heights of over 80 m in many cases. The backfill therefore has to be self-supporting as well as able to resist dynamic loading, should it occur. The potential for dynamic loading to

induce liquefaction is usually only a concern during the first few days after placement because, thereafter, the self-desiccation process (Helinski *et al.*, 2007) results in development of negative pore water pressures. Failures of backfilled stopes are not unknown. Between December 2003 and December 2004, there were reportedly at least six paste fill barricade failures worldwide, with each of these failures resulting in an inrush of fill to the mine workings (Helinski *et al.*, 2006).

It is now well known that randomly distributed tensile inclusions, such as polypropylene fibres, incorporated into soils improve their mechanical behaviour (e.g. Consoli *et al.*, 2009, 2010a, 2011a, 2011b) and could potentially improve cemented paste backfill (CPB) shear response. The relevant mechanism is that the stress is transferred from the soil to the tensile inclusions, mobilising their tensile strength and imparting this resisting force to the soil, thus leading to an improvement in load-carrying capacity of the material. Consoli *et al.* (2010a) showed that fibre insertion causes an increase in the unconfined compression strength of a cemented silty sand. However, the influence of fibre inclusion on the mechanical behaviour of CPBs has not been previously discussed. CPB material is significantly different from conventional reinforced cemented sand – it usually has a wider particle size distribution (because full plant tailings are used), it has a lower solids content than natural or compacted sands (because it is placed hydraulically) and it is likely to be subjected to significantly higher shear stresses as a consequence of the exposure of high vertical faces, as mentioned earlier.

According to Wijewickreme *et al.* (2005), the preponderance of laboratory studies on mine tailings has not been performed using cyclic simple shear equipment and the studied stress paths therefore do not simulate the cyclic rotation of principal stresses that takes place during earthquake loading. Previous studies (Arthur *et al.*, 1980; Wijewickreme & Vaid, 1993) showed that most soils experience deformations due to changes in the magnitudes of principal stresses and also to changes in their directions. The variation of shear stresses under cyclic conditions

Manuscript received 29 June 2012; first decision 30 July 2012; accepted 10 December 2012.

Published online at www.geotechniqueletters.com on 15 January 2013.

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Fig. 1. Particle size distribution of mine tailings

along with changes in the direction of principal stresses is achieved during cyclic direct simple shear tests (Wijewickreme *et al.*, 2005). Vaid & Finn (1979) considered the direct simple shear test as the most appropriate for the simulation of earthquake loading conditions. Therefore, through a series of undrained cyclic direct simple shear tests results, the fibre reinforcement of a CPB was evaluated to further understand the cyclic response of fibre-reinforced cemented mine tailings.

MATERIALS AND METHODS

Mine tailings

The studied tailings, produced from gold mining, are classified as sandy silt with traces of clay. The particle size distribution of the material is presented in Fig. 1 ($d_{10} = 3 \mu\text{m}$, $d_{50} = 17 \mu\text{m}$, $C_u = 10$, $C_c = 0.63$). The specific gravity (G_s) of the material is 2.72 and its mineralogical composition is presented in Table 1.

Cement

For sample preparation, general Portland cement (Type II) was used as the cementing agent. The cement content, defined as the mass of dry cement divided by the dry mass of soil, was 5%. The use of 5% of cement was chosen considering international experience with cemented soils (Consoli *et al.*, 2007, 2010b; Mitchell, 1981). This is the value used in all production backfilling of stopes at the mine site from which the tailings were obtained.

Fibres

Monofilament polypropylene (extensible) fibres were used to reinforce the cemented mine tailings. Their average

Fig. 2. Schematic illustration of direct simple shear test procedure: (a) sample prior to test; (b) consolidation; (c) shear strain application; (d) shear stress measurement; (e) 'actual' conditions imposed on sample

dimensions were 50 mm length and 0.1 mm ($d_{\text{tex}} = 100$) diameter, with a specific gravity of 0.91, tensile strength of 120 MPa, elastic modulus of 3 GPa and linear strain at failure of 80%. The fibre content used in the experiments was 0.5% by weight of dry solids. Previous studies (Consoli *et al.*, 2004, 2009, 2011b) have shown that these fibre characteristics optimise workability and improve the mechanical behaviour for different types of soil. As no other study has ever been carried out on fibre-reinforced mine tailings, these characteristics were taken as the initial reference, and worked satisfactorily. Technically, the amount chosen is applicable in a real situation as it has been applied by Consoli *et al.* (2012) in a pilot treatment in the field.

The direct simple shear test

The direct simple shear test is well known and widely used for measuring the strength and stiffness of soil. It is preferred by some because it is the only laboratory test that subjects a soil sample to constant-volume plane-strain conditions and allows principal stress rotation – conditions that are often representative of stress states in typical field situations such as the mode of shearing adjacent to a pile shaft (Randolph & Wroth, 1981) or under an offshore

Table 1. Chemical composition of the studied mine tailings

Mineral	Chemical composition	Amount: %
Quartz	SiO_2	29
Muscovite	$(\text{K}, \text{Na})\text{Al}_2(\text{Si}, \text{Al})_4\text{O}_{10}(\text{OH})_2$	24
Albite	$\text{NaAlSi}_3\text{O}_8$	25
Calcite	CaCO_3	1
Dolomite	$\text{CaMg}(\text{CO}_3)_2$	17
Orthoclase	KAlSi_3O_8	4

gravity-base platform (Andresen *et al.*, 1979). Doherty & Fahey (2011) describe the distinct direct simple shear test apparatus used and available worldwide.

The results obtained in the present work were obtained using a UWA-type simple shear apparatus (Mao & Fahey, 2003). In this type of apparatus, to impose plane-strain conditions, the sample height is fixed, which, coupled with the constant-volume conditions imposed by the pore fluid, prevents any change in cross-sectional area (Doherty & Fahey, 2011). Figure 2 shows a schematic illustration of the test procedure with the conditions imposed on the sample.

Sample preparation and test procedure

The weights of moist mine tailings and cement necessary for sample preparation were determined with an accuracy of 0.01 g. The two materials were mixed in a mechanical blender for about 10 min. When employed, the mass of

fibres was determined with an accuracy of 0.001 g and manually incorporated into the cement-backfill mixture after its preparation. The mixtures were prepared in amounts to produce the samples and allow two measurements of moisture content. The moisture content after treatment was always similar, approximately 28.5%. The mix was then poured into disposable plastic moulds and placed inside a humidity chamber at $22 \pm 2^\circ\text{C}$, where they remained for 14 days before the test. As the samples were prepared in saturated condition and the moisture content was similar, all specimens' unit weight was similar, approximately 19.7 kN/m^3 . The samples were produced to dimensions of 102 mm diameter and 102 mm height to achieve the minimum ratio between the smallest sample dimension and the largest fibre dimension of 2. Immediately prior to testing, the samples were stripped from the moulds and, using a thin-walled hollow cylinder, reduced to dimensions of 100 mm diameter and 50 mm height. They

Fig. 3. Monotonic shear response of non-reinforced cemented mine tailings under 100 kPa of initial effective vertical stress

were then placed in the equipment, where a latex membrane was used to allow application of back pressure.

The test procedure involves placing the sample between rigid cylindrical top and bottom heads with edge protuberances to ensure adequate sample fitting. A thin latex membrane (0.5 mm) envelops the sample. Consolidation pressures are radially applied through the membrane by increasing confining pressure, and vertically through the head. Thus, independent control of horizontal and vertical stresses is allowed, as in triaxial testing.

The stages of the direct simple shear test are similar to those of a triaxial test. Initially, a flow of water is established through the sample to expel possible air bubbles. Increments of confining pressure and back pressure are then applied to the sample up to a satisfactory B parameter (at least 0.97; Skempton (1954)). The sample is consolidated and, finally, shearing is started.

RESULTS

Monotonic shear response

Monotonic simple shear tests were carried out to establish a reference for comparison with the cyclic results. The tests were performed under undrained conditions with a displacement rate of 0.1 mm/min, equivalent to a constant shear strain rate of about 0.2%/min.

Figure 3 presents the monotonic shear test results for non-reinforced material. For 100 kPa of initial effective vertical stress, the non-reinforced cemented matrix presented a peak shear stress of about 90 kPa around 11% shear strain. There is a pore pressure increase of about 40 kPa and a vertical effective stress reduction of the same magnitude.

The monotonic shear test results for fibre-reinforced material are shown in Fig. 4. The addition of fibres to artificially cemented mine tailings confers on the material a

Fig. 4. Monotonic shear response of fibre-reinforced cemented mine tailings under 100 kPa of initial effective vertical stress

Fig. 5. Cyclic shear response of non-reinforced cemented mine tailings under 50 kPa of initial effective vertical stress and $\pm 2.5\%$ of controlled shear strain

very pronounced hardening behaviour, which provides for higher shear deformation and greater strength. For 20% shear strain, the shear stress was about 110 kPa. Furthermore, the values of pore pressure increments and effective vertical stress reductions reach a threshold, around 30 kPa, where the prior compression trend changes to expansion up to the end of the test.

Strain controlled cyclic shear response

The strain controlled cyclic simple shear tests were also performed under undrained conditions. The same frequency of 0.1 Hz was used for all cyclic tests. Under such conditions, the equipment imposes a specified displacement and, as the main response, measures the values of shear stresses. The tests were terminated only when the limit of the data acquisition system (1500 cycles) was achieved.

Figure 5 shows the results of the cyclic test on the non-reinforced cemented mine tailings sample under an initial effective vertical stress of 50 kPa and controlled shear strain (γ) of $\pm 2.5\%$.

Strain controlled cyclic simple shear tests were also carried out on non-reinforced CPB samples under 100 kPa of initial effective vertical stress and controlled shear strains of $\pm 2.5\%$, $\pm 4.5\%$ and $\pm 7.0\%$. Figure 6 summarises these results. The increase of initial effective vertical stress, as expected, increases the shear strength. The increase of imposed shear strain increases the shear stress values achieved in the initial load cycles, to the detriment of the reduced levels of shear stresses for the later cycles. The composite develops greater strength by deforming more and, the higher the strain level, the greater the damage to the cemented matrix structure. Over successive load cycles, the shear strength decreases gradually and, for later cycles, is higher for lower strain levels.

Fig. 6. Ratio of cyclic maximum shear stress to initial effective vertical stress $\tau_{cyc\ max}/\sigma'_{v\ initial}$ versus number of cycles of strain controlled tests under 100 kPa and 50 kPa of initial effective vertical stress for non-reinforced cemented mine tailings (a) and fibre-reinforced cemented mine tailings (b)

Figure 7 shows the results of the cyclic test on the reinforced cemented mine tailings sample under an initial effective vertical stress of 50 kPa and controlled shear strain (γ) of $\pm 2.5\%$. Strain controlled cyclic simple shear tests were also carried out on reinforced CPB samples under 100 kPa of initial effective vertical stress and controlled shear strains of $\pm 2.5\%$, $\pm 4.5\%$ and $\pm 7.0\%$. Figure 7 summarises the results from these tests. The increase of initial effective vertical stress, as expected, increases the shear strength. The increase of shear strain levels again increases the shear stress values achieved in the initial load cycles, to the detriment of the reduced levels of shear stresses for the later cycles.

Cyclic shear behaviour comparison

Comparison of the cemented samples' cyclic behaviour was performed by normalising the maximum cyclic shear stresses ($\tau_{cyc\ max}$) by the initial effective vertical stress of each test ($\sigma'_{v\ initial}$).

For each test, with a different strain imposed during shearing, curves were adjusted to relate the ratio of maximum cyclic shear stress and the initial effective vertical stress ($\tau_{cyc\ max}/\sigma'_{v\ initial}$) with the number of cycles. Figure 6(a) groups such curves for the tests carried out under the initial effective vertical stress of 100 kPa and 50 kPa on non-reinforced cemented mine tailings and Fig. 6(b) on fibre-reinforced cemented mine tailings.

For the higher strain levels of $\pm 4.5\%$ and $\pm 7.0\%$, the fibre addition slightly increased $\tau_{cyc\ max}/\sigma'_{v\ initial}$ from the start of the termination point when compared with the non-reinforced material. For the lowest studied strain level of $\pm 2.5\%$, the addition of fibres caused a stress ratio reduction for the initial cycles but did not affect the stress ratio values for the later cycles as compared with the non-reinforced material. As for static loads, the fibre reinforcement performance is more effective for higher cyclic strain levels.

The increase of shear strain levels increases the shear stress values achieved in the initial load cycles, to the detriment of the reduced levels of shear stresses for the later cycles. For the first cycles, the reinforced sample develops greater strength by deforming more and, for the final cycles, the higher the strain level, the greater the damage to the cemented matrix structure. Over successive load cycles, the shear strength decreases gradually and, as shown in Fig. 6, for the later cycles, is higher for lower strain levels. However, for the later cycles, the shear stress values of the fibre-reinforced cemented material, for different strain levels, are similar. The damage to the cemented bonds is compensated by the existence of fibres that absorb and redistribute the loads.

Stress paths and strength envelopes

From the simple shear tests results, the strength envelopes of the different materials and their strength parameters are defined. For comparison, the stress paths of monotonic and cyclic tests are grouped, as well as the strength envelopes. The stress paths are presented and the strength envelopes are defined in the effective vertical stress (σ'_v) and shear stress (τ) space. Thus, the effective friction angle can be directly determined from the slope of the strength envelope and the cohesive intercept from the intercept of the envelope with the axis of the shear stress.

Figure 8 presents such an analysis for both the non-reinforced cemented mine tailings (Fig. 8(a)) and the fibre-reinforced cemented mine tailings (Fig. 8(b)). The stress paths of the tests performed under distinct load conditions – monotonic and cyclic – reach the same strength envelopes. The effective internal friction angle of the non-reinforced material is 49° and that of the reinforced material is 45° . The cohesion intercept of both materials is zero.

The agreement of the same strength envelopes to stress paths of monotonic and cyclic tests is remarkable.

Fig. 7. Cyclic shear response of fibre-reinforced cemented mine tailings under 50 kPa of initial effective vertical stress and $\pm 2.5\%$ of controlled shear strain

FINAL REMARKS

From the results of a series of monotonic and cyclic simple shear tests on fibre-reinforced cemented mine tailings, the following conclusions can be drawn.

- Under cyclic shear strain controlled load conditions, the increase of initial vertical effective stress increases shear strength.
- The increase of shear strain levels increases the shear stress values achieved in the initial load cycles, to the detriment of the reduced levels of shear stresses for later cycles.
- The composite develops greater strength by deforming more, and the higher the strain level, the greater the damage to the cemented matrix structure. Over successive load cycles, the shear strength decreases gradually and, for the later cycles, is higher for lower strain levels.

For the later cycles, the shear stress values of the fibre-reinforced cemented material, for different strain levels, are similar. Disintegration of the cement matrix is compensated for by the existence of fibres that absorb and redistribute the loads.

- The agreement of the same strength envelopes to both monotonic and cyclic stress paths, under different cyclic loading conditions, allows the use of the same strength parameters of mixtures analysed under different loading conditions.

Acknowledgement

The authors wish to express their gratitude to Brazilian Research Council CNPq/MCT (Project PNPD #558474/2008-0) for financial support.

Fig. 8. (a) Strength envelope, shear strain controlled cyclic test ($\sigma'_{v \text{ initial}} = 100$ kPa, $\gamma = \pm 4.5\%$) and monotonic test ($\sigma'_{v \text{ initial}} = 100$ kPa) stress paths on non-reinforced cemented mine tailings. (b) Strength envelope, shear strain controlled cyclic test ($\sigma'_{v \text{ initial}} = 100$ kPa, $\gamma = \pm 7.0\%$) and monotonic test ($\sigma'_{v \text{ initial}} = 100$ kPa) stress paths on fibre-reinforced cemented mine tailings

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