Shear Behaviour of Compacted Gold Mine Tailings and Gold Mine Tailings Composite for Possible Use in Mine Backfilling

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Abstract

Utilisation of gold mine tailings (GMT) in mine reclamation requires a thorough understanding of its geotechnical characteristics. In this paper, a detailed experimental study carried on compacted gold mine tailings and gold mine tailings composite of varying curing ages is presented. Strength characteristics were investigated using consolidated drained (CD) and consolidated undrained (CU) triaxial tests under different confining pressures. The results obtained from the test showed that GMT composites exhibited higher strengths compared to untreated tailings. CD shear test revealed that GMT has a moderate capacity to withstand shear stress while the CU test showed an occurrence of static liquefaction.

Keywords: Gold Mine Tailings, Shear Strength, Box Shear Test, Triaxial Test

Introduction

For more than a century, South Africa's mining sector has played a pivotal role in the economic development of the country. Like many other mining jurisdictions, it is faced with a legacy of negative environmental and societal impacts. The severity of mining impacts on the environment and society has been observed in most areas where there are abandoned mines, with the most severe impacts noted in the eMalahleni coalfields and the Witwatersrand goldfields.

The Witwatersrand goldfields has over 270 gold mine tailings (GMT) covering an estimated area of 400 km^2 (AngloGold Ashanti 2004; Oelefse *et al.* 2009). A fraction of the tailings is beneficially utilised in mine backfilling, albeit in small quantities (Mashifana 2018; Van der Merwe *et al.* 2011). In the Witwatersrand goldfields, gold mining although not the only mineral resource mined is associated with several environmental issues, such as subsidence caused by underground voids, contamination of soils and water resources due to seepages from mine residue stockpiles and deposits (Sanmiquel *et al*. 2018). Given the prevailing environmental degradation in the Witwatersrand Basin, underground mine backfilling using mine waste was proposed as the most suitable rehabilitation method (Kleinhans and Van Rooy 2016).

Underground mine backfilling provides ground support and regional stability, thus reducing subsidence (Der Verleihung 2009; Potgieter 2003). Backfills can be classified as uncemented or cemented. Uncemented backfill materials include hydraulic fills, sand fills, aggregate fills and rock fills, whereas the most common cemented backfills are cemented paste fills, cemented hydraulic fills, and cemented rock fills (Sheshpari 2015; Sivakugan *et al.* 2015). Typically, backfills are prepared using waste rock, mill tailings, quarried rock, sand, and gravel. The most commonly used material is the waste rock and mill tailings due to their abundance in mining regions. Cemented backfills use low concentrations of cement (Lokhande 2005; Belem and Benzaazoua 2008), usually 3% to 7% in dry weight, which represents 50 to 75% of the backfill cost (Grice 2001).

The physical and chemical characteristics of the backfill are crucial in the selection of filling material and may influence the mechanical properties of a backfill (Hefni and Hassani 2020). Research into backfills has shown that cemented paste fills are the best option for backfilling due to their competitiveness and strength development.

In this study, the shear behaviour of GMT under laboratory conditions was assessed for use in cemented paste backfilling. The use of GMT in mine backfilling provides effective means of waste storage, resulting in the minimisation of environmental degradation.

Materials and experimental investigations

Representative GMT samples in a wet state were collected from a tailings storage facility on a gold mine in the Witwatersrand goldfields. The samples were obtained using an auger from a depth of 0.5 m to 5 m to ensure that the non-oxidised layer was represented. Representative samples of the GMT were prepared to form a homogenous sample. As part of sample preparation, the homogeneous sample was air dried at room temperature for 48 hours and a composite sample (GMT and cement) was generated to determine the shear strength characteristics.

Lafarge CEM II 52.5N (at 3%) and tap water were used in all mixes in the test series during the geotechnical testing protocol. The samples investigated were remoulded to 95% maximum dry density (MDD) and cured in moisture obtained during moulding over a 7, 28 and 56 days curing period at a room temperature of about 23 °C. The static strength characteristics of the sample were thoroughly studied using consolidated drained (CD) and consolidated undrained (CU) triaxial test with pore water measurements to determine strength characteristics. During the test series, all samples were tested under different confining pressures of 50, 100 and 200 kPa. The influence of various parameters on the shear strength characteristics was also noted.

Results and discussions

Strength characteristics are crucial for materials used for engineering construction. The strength properties of the materials are affected by variations in the density, particle size distribution and confining pressure. Consolidated drained (CD) and undrained triaxial tests were carried out under confining pressures of 50, 100 and 200 kPa on GMT. The test was performed as per ASTM D3080 to determine the shear strength characteristics of GMT. The samples were tested at a relative density of 2.209 to study their compaction behaviour. Mohr-Coulomb total strength parameters, namely, cohesion (c) and angle of shear resistance (φ) were determined.

Material characterisation

Important geotechnical properties like particle size distribution, atterberg limits, compaction characteristics, permeability and compression characteristics of the tailings were previously determined and are tabulated in Table 1 (Gcasamba *et al.* 2019). From the test results, it can be observed that the particle size of the tailings is medium to course size which is ideal for paste fills (Landriault 2001). Atterberg limits revealed that the tailings are non-plastic, which is an indication of soils with inherent shear resistance to sliding in fluvial conditions (Bartle 2000). The compaction characteristics of the tailings provide an opportunity to be used in mine backfilling. The coefficient of permeability showed permeability in a range of silt to sand soils. The tailings have a compressive strength within the recommended range between 200 kPa to 5000 kPa (Fall and Benzaazoua 2003).

Consolidated drained and consolidated undrained triaxial test results

Consolidated drained and undrained triaxial test results for GMT under different confining pressures are presented in Figures 1 and 2 respectively. During the test series, consolidation at all confining pressures took place rapidly and was completed in 5 minutes. The development of pore water pressure in the

Table 1 *Geotechnical properties of GMT and GMT composites (Gcasamba et al. 2019).*

	Particle size (mm)	Atterberg limits	Compaction (kg/m^3)	Permeability (m/s)	Compression (kPa)
GMT	Sand to silt	Non plastic	1588	3.8E-07	129
GMT composites (7 days)	Silt to sand	Non plastic	1555	2.9E-07	315
GMT composites (28 days)	-	-	-	2.9E-07	386
GMT composites (56 days)	-	-	-	9.0E-07	412

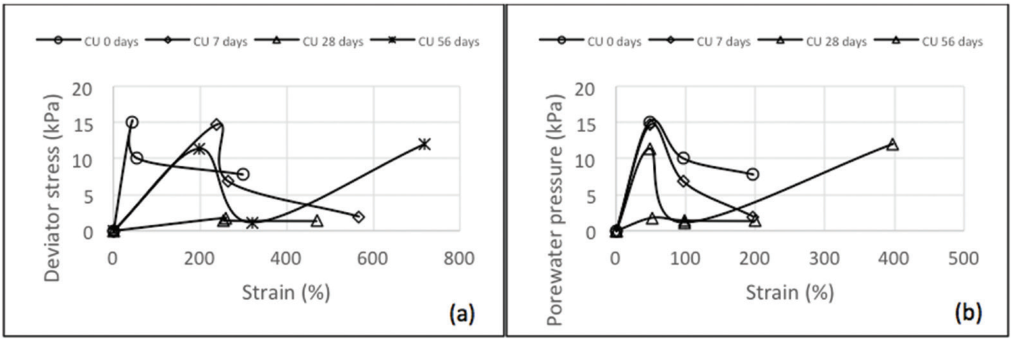

Figure 1 Results of CD test: (a) Deviator stress vs. axial strain, (b) Pore water pressure vs. axial strain.

tests shows a correlation with volume changes of the sample. Samples exhibiting contraction in the CD test series were observed to develop positive pore water pressures in the CU test series. Whereas samples exhibiting dilation in the CD test developed negative pore water pressure. The degree of negative pore water pressure was noted to decrease with increasing confining pressures, similarly, dilation decreased with increasing confining pressure. An increase in contraction was observed in CD tests with the increase in confining pressure and developments in pore water pressure increased with increasing confining pressure in the CU test. The development of liquefaction in CU tests was noted corresponding to the development of high pore water pressure and increased confining pressure.

It was observed that the axial strain at failure increases with an increase in confining pressure. It was also observed that the peak value for pore water pressure rise increases with an increase in confining pressure. The deviator stress attained peak value at an axial strain of 11.39, 4.57, 4.78 and 4.13 following a 0, 7, 28 and 56 days of curing for the CD test (figure 1a). At the axial strains of 15.5, 14.67, 1.8 and 12.03 a peak in deviator stress was obtained during the CU test following the different ages of curing; followed by a sharp decline due to static failure (Figure 2a).

The liquefaction behaviour noted during the CU test may be due to high variabilities of effective stress. Hakam (2016) noted the liquefaction susceptibility of soils. The author noted that soils under high effective stress, are easier to liquefy than soils under low effective stress. The same effect was noted during the CU test, liquefaction corresponded with the high effective stress.

Shear strength parameters in response to varying curing ages are presented in table 2. It was observed that the strength parameters corresponding to CD tests are comparable with the strength parameters from the CU tests except for cases where static liquefaction was observed.

At the initial stage (no cement and zero days of curing) of the shear test, the results

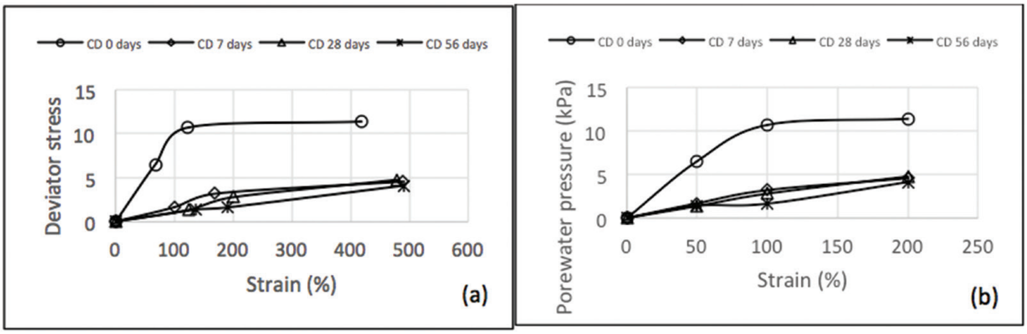

Figure 2 Results of CU test: (a) Deviator stress vs. axial strain, (b) Pore water pressure vs. axial strain.

revealed minimum values of the angle of internal friction (φ), recorded at 27° and 30° respectively for CD and CU tests. An increase in the angle of internal friction was noted until the 28 days of curing for CD tests followed by a slight decrease by the 56 days of curing. During the CU test, an increase in φ was noted until the seventh day. After the 28 and 56 days of curing, the angle of internal friction was recorded at 0° due to static failure. Based on the results, the effect of curing on the φ of the tailings was observed during the CD test whereas the effects of curing during CU tests was negligible.

Similarly to the angle of internal friction, values of cohesion were minimal at zero cement addition and curing and improved with increasing curing periods and cement addition for CD while the opposite was observed for CU tests, as noted by Uchaipichat and Limsiri (2011). An increase in cohesion was noted until the 56 days for the CD tests while an increase in cohesion during CU tests was observed until the 7 days of curing. Studies conducted by Moayed *et al.* (2011) corroborate the significance of cement on cohesion and the angle of internal friction. The authors noted the significant increase in these shear properties of soils with cement addition.

Conclusions

The results obtained from the consolidated drained shear test indicate that the tailings have a moderate capability to withstand shear stress and could be suitable for civil works. The CU test, however, showed an occurrence of static liquefaction indicating the possibility of liquefaction when used in civil works. Similarities in shear strength characteristics were observed during the previous shear tests conducted using box shear (Gcasamba *et al.* 2019) and the CD test. The shear box results showed improved shear strength characteristics with the age of curing and cement addition. The values of cohesion ranged from 8 to 42 and 12 to 107 respectively for the box shear test and CD test. Similarly, the angle of internal friction during both tests improved with the age of curing and cement addition. The shear strength results for both tests are an indication of a highly cohesive material. Contrary, the CU test showed minor effect of curing and cement addition, at 28 days of curing, static liquefaction was observed during the CU test series. These results are an indication that in a loose state, the undrained stress path will result in liquefaction, although in a dense state, liquefaction may be prevented due to the tendency of materials to dilate during drainage as a result of pore water pressure. Further studies on the liquefaction resistance of the tailings before utilisation, especially in earthquake-prone areas is necessary.

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***Table 2** Consolidated drained and undrained triaxial shear strength parameters.*

	State	CD test		CU test	
		Cohesion (kPa)	Angle of internal friction (°)	Cohesion (kPa)	Angle of internal friction (°)
GMT	Compacted	12	27	8	30
GMT composites (7 days)	Compacted	91	33	11	33
GMT composites (28 days)	Compacted	89	37	0	0
GMT composites (56 days)	Compacted	107	29	0	0

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