Comparative study of two biggest mineral wastes in South Africa for mine reclamation: A geotechnical study.

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Abstract

Laboratory investigations were conducted on two mineral wastes to assess their geotechnical properties for mine backfilling. Composite Coal Fly Ash (CFA) sludge recovered from CFA and acid mine drainage (AMD) reaction (ratios 1:2 and 1:3) and gold mine tailings (GMT) with 3 % cement were evaluated at varying curing ages. Both samples showed favourable characteristics for use in mine reclamation. However, solid/liquid ratios should be maintained to ensure maximum strength. The results show that CFA can be recommended for mine reclamation due to it geotechnical properties. The use of GMT is possible, however blending with higher percentages of cement should be considered.

Keywords: Coal Fly Ash, Gold Mine Waste, Geotechnical Characterisation, Backfilling

1. Introduction

South Africa generates approximately 70% mineral waste annually from its mining activities (DEA 2012). Waste generated from gold mining alone accounts for 47% of the total mineral waste generated in South Africa. This percentage excludes ~30 MT CFA that is accumulated annually from electricity generating and liquid fuel production (Du Plessis *et al*. 2013). Small percentages of this waste are beneficially utilized in South Africa, with huge amounts stored in tailings and ash dams (Mashifana 2018; Van der Merwe *et al*. 2011).

Underground mine backfilling has become an integral part of mine reclamation in most parts of the world. Backfilling provides ground support and regional stability, thus reducing subsidence and improving ore recovery (Der Verleihung 2009; Potgieter 2003). A wide range of backfilling methods has been assessed; these methods include rock backfill, hydraulic backfill, cemented backfill and silica alumina-based backfill (Sheshpari 2015; Sivakugan *et al*. 2015). The methods considered for backfilling often make use of mineral waste (waste rock and tailings) in conjunction with small proportions of binders such as cement to improve the properties of the backfill material (Lokhnde 2005). The use of mineral waste in mine backfilling provides an effective means of disposal due to cuts in storage costs and a reduced environmental footprint.

Previous studies on viability of using CFA and GMT in mine backfilling (Kruger and Krueger 2005; Yilmaz 2011) were encouraging and very few studies of this nature were carried out in South Africa. Realising the consequences of mineral waste disposal and the opportunity thereof for use in mine reclamation, this study aims at assessing the properties of GMT and CFA for mine backfilling purposes.

2. Materials

Class F CFA was collected in dry state from the hoppers of a coal fired power station in Mpumalanga. GMT used in the study was a composite sample collected from one the tailings dams of a gold mine in west rand basin, South Africa. The sample was obtained using an auger from a depth of 0.5 m to 5 m to ensure that the non-oxidised layer was represented to the best of our ability. Mine water used in the co-disposal with CFA was collected from an old abandoned coal mine located in Emalahleni, Mpumalanga Province. Samples were collected following the standard procedure described in DWAF (1996). Water samples were kept cooled en-route to the laboratory and subsequently stored in a refrigerator at 4 ºC for analysis. Lafarge CEM II 52.5N (at 3%) was used as an additive for GMT during geotechnical testing to improve the properties of the material. Geotechnical tests conducted for CFA and GMT are presented in Table 1. The samples were remoulded to 95% maximum dry density (MDD) and cured in moisture over a 7, 28 and 56 days curing period and at a room temperature of about 23 °C.

Table 1 *Geotechnical tests conducted for CFA and GMT*

Tests Conducted	Standard method
Grain size distribution	ASTM D422-63
Atterberg limit	ASTM D4318
Modified proctor test	ASTM D1557
Permeability test	BS 1377 part 6
Unconfined compression strength	ASTM D2166
Box shear test	ASTM D2166

3. Results and discussions

4.1. Grain size distribution

Figures 1 and 2 show the grain size distribution curves of CFA and GMT. The ash consists of grain size fractions ranging from 0.01 mm to 0.1 mm. These range fractions, according to Das (2006), are similar to silt soils and show a potential for pozzolanic reaction as reported by Paya *et al*. (2001) and Jatuphon *et al*. (2005). The coefficient of uniformity (Cu) and the coefficient of curvature (Cc) for CFA could not be determined due to the particle size distribution of the material.

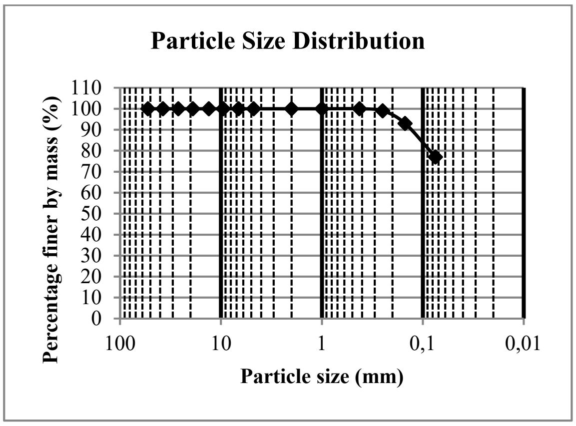

Figure 1 *Particle size distribution of CFA.*

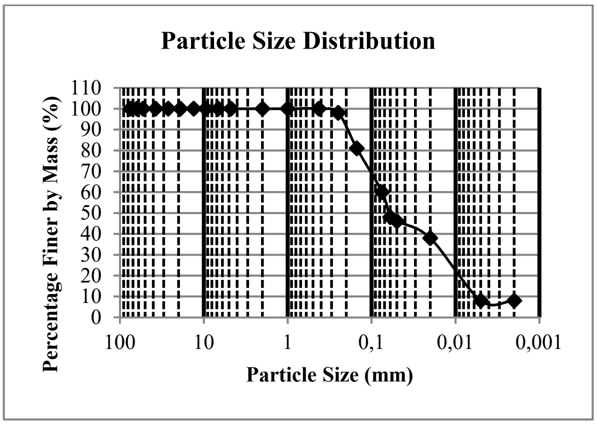

Figure 2 *Particle size distribution of GMT.*

The particle size distribution obtained for GMT is composed of 52% sand, 40% silt and 8% clay fractions with ranges of 0.01mm to 1 mm. The Cu for the tailings was 12mm comparable to well graded sand. The Cc for the tailings was 0.5 outside the range for well-graded sands. Upon the addition of the 3% cement, the particle size composition changed to 21% sand, 67% silt and 12% clay fractions resulting in more silt fractions. The Cc value was also adjusted to 2.6 providing for categorisation under well-graded sand.

4.2. Atterberg limits

Atterberg tests revealed that both materials were non-plastic consequently, the liquid limit and plastic index could not be determined. According to Bartle (2000), non-plastic soils have an inherent shear resistance to sliding with the addition of water and can lose 50% shear strength because of water floating on top contrary to clays that lose 99.5% of their total shear resistance to sliding due to drainage.

4.3. Compaction characteristics

The compaction characteristics of CFA and GMT are given in Table 2.

Table 2 *Compaction characteristics of CFA and GMT*

Properties	CFA 1:2	CFA 1:3	GMT	GMT with 3% cement

MDD (kg/m³)	1192	1183	1588	1555
OMC (%)	34.1	33.3	14.9	10.4

Both CFA samples exhibited lower MDD and higher OMC compared to GMT. MDD values recorded for CFA, according to Geliga and Ismail (2010), Das (2011) and Sabat (2015) are typical for soils with silt particle sizes. The MDD of GMT was originally 1588 kg/m^3 and decreased to 1555 kg/m^3 upon the addiction of cement. High OMC values recorded for CFA according to Gimhan *et al.* (2018) are attributed to higher air void content, which Pandian (2004) places at 5% to 15% compared to 1% and 5% of soils. Addition of cement to GMT also reduced the OMC of the material, similar to the trends noted by Al-Khafaji (2015) due to chemical reactions between the molecules of cement, clay and water. The compaction results obtained for the CFA and GMT qualifies the use of these materials in civil works, based on the Indian Road Congress (IRC) compaction specifications.

4.4. Permeability characteristics

Table 3 presents the values of the coefficient of permeability (k) for compacted CFA and GMT.

Table 3 *Values of permeability at a normal stress of 100 kPa*

Samples	Initial void ratio (e)	Coefficient of permeability (m/s)	Dry density (kg/m³)	Initial degree of saturation
CFA 1:2 (0 curing)	1.008	3.7E-08	1101	80.6
CFA 1:2 + 3% cement (7 days)	1.053	3.9E-08	1077	76.0
CFA 1:2 + 3% cement (28 days)	0.985	8.0E-08	1114	79.7
CFA 1:2 + 3% cement (56 days)	0.973	7.9E-08	1108	80.7
CFA 1:3 (0 curing)	1.009	6.2E-08	1100	79.5
CFA 1:3 + 3% cement (7 days)	1.032	9.1E-08	1087	79.1
CFA 1:3 + 3% cement (28 days)	1.030	1.2E-07	1088	78.9
CFA 1:3 + 3% cement (56 days)	1.022	1.2E-07	1095	79.3
GMT (0 curing)	0.933	3.8E-07	1417	38.8
GMT + 3% cement (7 days)	0.932	2.9E-07	1382	31.8
GMT + 3% cement (28 days)	0.932	9.0E-07	1382	27.7
GMT + 3% cement (56 days)	0.861	9.0E-07	1434	21.6

The coefficient of permeability for CFA and GMT increased with curing age and cement addition. The coefficient of permeability of the ash was observed to be in the range of silt material and the GMT in the range of silt sand. The coefficient of permeability range of CFA is attributed to the uniform silt particles, which form larger inter-particle voids, contributing to increased permeability. Similarly, the addition of cement to GMT increased the fine fractions, resulting in larger inter-particle voids responsible for increased coefficient of permeability (Prashanth *et al.* 2001). Studies by Dungca and Jao (2017) on ash showed decreasing permeability with curing age and addition of more fines. The slight increase in permeability noted for the ash with increasing curing age was erratic; however, the permeability ranges noted were within the accepted range for embankments and backfilling (Heindel and Noyes 1997).

4.5. Compression characteristics- Unconfined compressive strength (UCS)

The measure of resistance to external loading for CFA and GMT at 0, 7, 28 and 59 days of curing is presented in Table 4. The UCS of CFA and GMT samples (without cement and curing) was low compared to the composites samples (Table 4). The curing age together with the addition of fines appears to have significant impact on the strength of both materials.

Early high strength recorded for the GMT could be attributed to the well grading of particles that resulted in artificial cementation. By the 56th day of curing, both materials showed improved strengths, which indicates the benefits of cement addition and curing age to the strength properties, as noted by Lee *et al.* (2016). Tatt and Ali (2004) made similar observations; the authors also noted that the compressive strength of soils increases upon cement addition and age of curing. The strain variables achieved at these compressive strengths are an indication of the stiffness of the samples.

Table 4 *Unconfined compressive strength for CFA and GMT*

Samples	Compressive strength (kPa)	Axial strain at max. (%)
CFA 1:2 (0 curing)	79	1.32
CFA 1:2 + 3% cement (7 days)	126	1.14
CFA 1:2 + 3% cement (28 days)	178	1.13
CFA 1:2 + 3% cement (56 days)	383	0.77
CFA 1:3 (0 curing)	111	1.33
CFA 1:3 + 3% cement (7 days)	144	1.76
CFA 1:3 + 3% cement (28 days)	155	1.67
CFA 1:3 + 3% cement (56 days)	419	1.21
GMT (0 curing)	129	1.96
GMT + 3% cement (7 days)	315	1.49
GMT + 3% cement (28 days)	386	1.14
GMT + 3% cement (56 days)	412	0.89

4.6. Shear strength characterisation- Box shear

The shear strength values for CFA and GMT are presented in Figures 3 and 4.

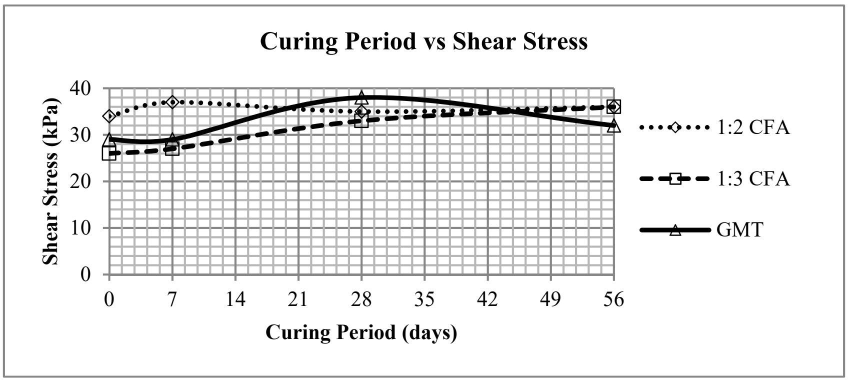

Figure 3 *Relationship between curing period and shear stress.*

The values of the angle for internal friction (φ) were recorded to be 34º, 26º and 29º for CFA 1:2, CFA 1:3 and GMT respectively at the initial stages of the experiment. An increase in the φ was noted until the 56th day of curing for CFA 1:2 and CFA 1:3 because of initial cementation and a long-term pozzolanic reaction. The effect of curing was observed until the 28th day for GMT due to the saturation of the samples with moisture, resulting in the loosening of particles, these observations coincide with observations made by Hasan (2012). Values of cohesion for CFA started low and improved with increasing curing age and increasing solid fractions as noted by Uchaipichat and Limsiri (2011). For both materials, an increase in cohesion was noted after 7 days of curing, followed by a slight decrease at 28 days and a significant increase at 56 days. Studies conducted by Moayed *et al.* (2011) corroborate the observations made in this regard.

Based on φ and c recorded for the two samples, it may be concluded that CFA composites have a higher capacity to withstand shear stress, while the tailings show moderate capacity. The ability of both materials to withstand shear stress qualifies the use of these materials in mine backfilling. However, blending with the higher percentages of cement should be explored to ensure maximum shear strength.

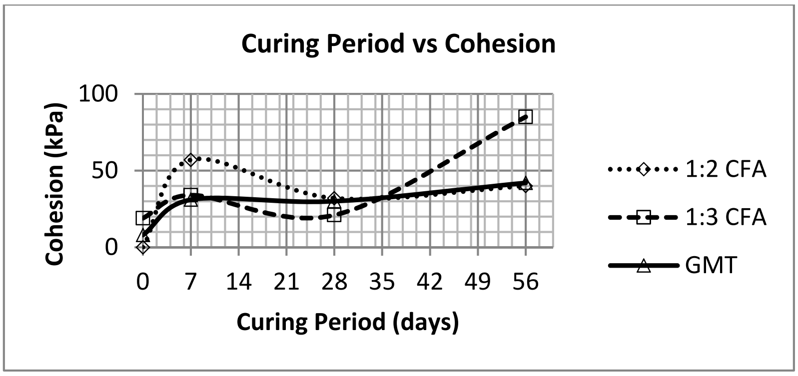

Figure 4 *Relationship between curing period and cohesion.*

4. Conclusions

GMT and CFA composites yielded appreciable geotechnical properties suitable for application in mine backfilling; with the only drawback being the permeability properties of the material, which showed increased permeability with age of curing. It is therefore advised that the addition of a wider variety of percentages of cement be evaluated to improve the permeability properties of the material and to further ascertain its geotechnical properties.

5. Acknowledgements

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