Influence of Particle Breakage on the Geomechanical Behaviour of Compacted Coalwash

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ABSTRACT: Coalwash is a waste material that results from coal mining operations. While its potential use as structural fills has been recognised in past research studies, the effects of particle breakage on the geomechanical performance of the material have not been investigated. This paper presents an experimental study of compacted coalwash tested under saturated conditions and over a wide range of stresses. The results indicate that particle breakage has a strong influence on the geomechanical behaviour of coalwash. Furthermore, the influence of particle breakage on the critical state behaviour was also analysed. While the results confirmed that coalwash is a suitable structural fill material in terms of its shear strength, its excessive deformation associated with particle breakage must be considered in order to meet specific performance criteria.

1 INTRODUCTION

Coal washer reject is a by-product from coal washing process and is produced at over a hundred million tons per year in Australia (Armitage, 2012). This waste material generally contains both fine grained coal tailings and coarse grained coal rejects (coalwash) in a weight proportion between 11:89 and 33:67 (Davies, 1992). This material is readily available near coal washerys and has environmental and economic advantages when used as structural fill (e.g. Leventhal and de Ambrosis, 1985; Indraratna et al., 1994). Despite advances in research on the characterisation of its behaviour, only limited studies have focussed on the quantification of breakage and its impact on the stress strain behaviour (Kettle, 1983 and Fityus et al., 2008). One of the important factors that can significantly affect the deformation of granular material is the particle size distribution (PSD) and associated breakage (Kikumoto et al., 2010). Thus, it is important to study the effects of changes in PSD to determine the appropriate modelling approaches in order to assess material behaviour under different conditions.

The effects of change in particle size distribution on critical state line (CSL) have been studied by various researchers (Been et al., 1991; and Yamamuro and Lade, 1996), and in particular, the position of the CSL as related to the grading state index of granular material (Wood and Maeda, 2008). Since coalwash has a large breakage potential (Rujikiatkamjorn et al., 2013), studying the effects of particle size distribution in relation to variations in its critical state to evaluate whether the material meets common performance criteria, is very important.

This paper will describe the behaviour of compacted coalwash and its associated particle breakage under drained shearing for different compaction states.

2 COALWASH CLASSIFICATION

The material selected for this study is a coalwash sourced from Dendrobium (an underground black coal mine located near Wollongong, NSW, Australia). The particle size distribution (PSD) of the sample of coalwash selected for this study is shown in Fig.1 and includes 6% gravel, 75% sand, 17% silt and 2% clay. The sample had a plasticity index of 10.7%, a liquid limit of 27.7% and a specific gravity of 2.23, so it was classified as clayey sand(SC), in accordance with the Unified Soil Classification System.

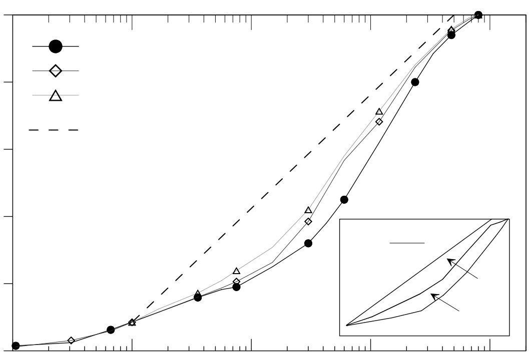

Fig. 1 Selected particle size distribution

The particle breakage due to a change in the particle size distribution (PSD) was quantified using the method presented in Kaliboullah et al., 2015. A typical PSD results of specimen after compaction and shearing and the method to estimate particle breakage is shown in Fig.1, where A is area enclosed between initial and current PSD, C is the area enclosed between current PSD and the arbitrary boundary of particle breakage. The compaction induced breakage while the specimen was being prepared at different compaction efforts is expressed as the breakage index (B_c), and are given in Table 1.

Table 1. Properties of compacted coalwash specimen

Relative compaction, RC	95%	100%
Dry unit weight, γ_d (kN/m^3)	15.7	16.5
Specific volume, v	1.40	1.33
Particle breakage, B_c	0.190	0.239

3 SPECIMEN PREPARATION

The coalwash material was oven dried to 50°C. After mixing with the required amount of water the mixture were stored overnight inside a sealed plastic bag under a constant temperature and humidity to allow for moisture equilibration. The compaction characteristics were determined using the standard Proctor compaction test (Australian Standard 1289.5.1.1, 2003), is shown in Fig.2. For an applied standard Proctor energy level, the maximum dry unit weight ($\gamma_{d\text{-}max}$) and the optimum moisture content (w_{OMC}) were 16.5 kN/m^3 and 12.5% respectively.

Different compaction energies were investigated to explore a range of placement conditions. The moisture content was 10% because it corresponded to the average moisture content recorded at the stockpile of a field trial site at Port Kembla (NSW, Australia). Two different compaction energies (340.6 kJ/m^3 and 681.1 kJ/m^3) that corresponded to relative compaction (RC) levels of 95 and 100%, respectively were investigated. The compaction state of test specimen (i.e., dry unit weight and moisture content) that correspond to RC95 and RC100 are shown in Fig.2. Following the procedure described by Heitor et al.(2013), the specimens were compacted in a 50 mm diameter by 101.5 mm high mould. The dry unit weight, specific volume, and particle breakage during compaction (B_c) are given in Table 1.

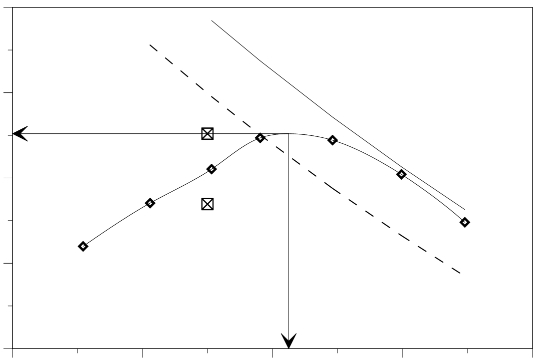

Fig. 2 Compaction state of test specimen (Modified after Kaliboullah et al., 2015)

A series of standard drained compression triaxial tests were conducted to evaluate the stress–strain and particle breakage behaviour of the compacted coalwash. A summary of the testing program is listed in Table 2. The test consisted of three stages: saturation, consolidation, and shearing. During the saturation stage, air in the void space was displaced using CO_2, followed by a back pressure of 150 kPa. This procedure consistently attained Skempton's B-value of more than 0.98. The desired effective confining pressure was applied through isotropic compression, followed by drained shearing at a constant strain rate of 0.1 mm/min in accordance with ASTM D7181-11.

Table 2. Summary of test program

Test ID	RC (%)	Axial strain (%)	Effective confining pressure, σ'_3 (kPa)
D6, D7	95	40	50,100
D9	95	20	200
D11, D12, D14, D15	100	20	50,100, 200,400

4 DRAINED TRIAXIAL TESTING

Drained monotonic shearing tests were carried out on compacted coalwash prepared at different relative compaction levels, and for a range of initial effective confining pressures (i.e. 50-400kPa). The drained shearing results corresponding to RC100 are shown in Fig.3. The deviator stress (q), and volume change (ε_v) results are plotted against axial strain (ε_1) in Figs. 3a and 3b, respectively. At an effective confining pressure of up to 100 kPa, the deviator stress increased sharply and reached a peak within 1.6% of axial strain, and then decreased with increasing axial strain which indicated a strain softening behaviour. For instance, the specimen with an initial effective confining pressure (σ'_3 = 50 kPa) reached a peak deviator stress of 242.8 kPa at 1.4% axial strain, followed by a strain softening response with increasing axial strain, and then attained a stable value of 145.4 kPa at an axial strain of 18%. A predominant strain hardening behaviour was observed for confining pressures larger than 100 kPa, and this reached its peak value before 18% axial strain.

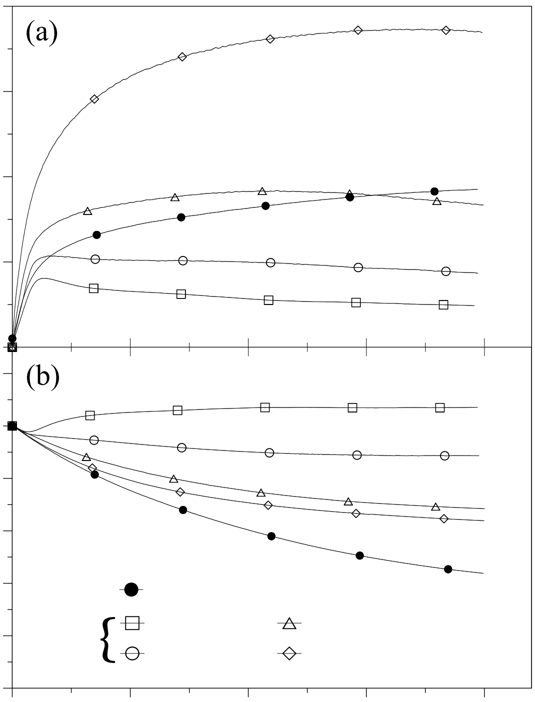

Fig. 3 Stress-strain response of compacted coalwash

The volumetric strain responses during drained shearing shown in Fig. 3b, mainly showed dilation for low effective confining pressure up to 50 kPa, but mainly contraction for higher effective confining pressures. For instance, up to 50 kPa, the effective confining pressure on the specimen showed a strong dilation within 5% axial strain, and then reached a stable value at 10% axial strain. The stress-strain response of RC95 specimen at effective confining pressure of 200kPa is shown in Figs.3a and 3b for comparison. Larger volumetric strains were recorded despite observing comparable stress levels at 20% axial strain.

The specimens prepared at RC100 reached a constant volume and stress condition at 18% axial strain, i.e. they reached a critical state. The stress ratio (q/p') at the critical state stress condition indicated a friction angle ϕ'_{cs} of 35°. On this basis alone, the coalwash may be classified as a suitable fill material with a critical state friction angle exceeding 30° (Philip and James, 2011).

5 PARTICLE BREAKAGE

The tested specimen PSDs were analysed after drained shearing. The total particle breakage (B_t) due to a shift in PSD caused by compaction and shearing is plotted in Fig.4a. These results showed that particle breakage depends on the mean effective stress and relative compaction. Particle breakage was very significant, not only while the specimens were being prepared, but also during the compression and shearing stages. A semi-logarithmic linear relationship can be defined between mean effective stress and total particle breakage. It can also be observed that each RC level defined an unique line and different RC levels resulted in almost parallel lines. The upward shift of RC100 was largely due to compaction induced breakage.

6 CRITICAL STATE LINE

The drained shearing of compacted coalwash under different initial effective confining pressure (Fig.3) indicated that the stresses reached a critical state. The specific volume and mean effective stress at this critical state are plotted in the v – ln p' plane in Fig. 4b. The family of critical state lines (CSL) for relative compaction levels of 95 and 100% defined a linear relation in the semi-logarithmic v – ln p' plane. The specific volume at p' = 1 kPa of CSLs was graphically found to be 1.64 and 1.62 for RC95 and RC100 respectively. The observed compression slope of the CSL was 0.06 for an RC level of 95 and 100. The particle breakage results validates the hypothesis by Wood and Maeda (2008), that the shift in critical state line is caused to change in particle size distribution.

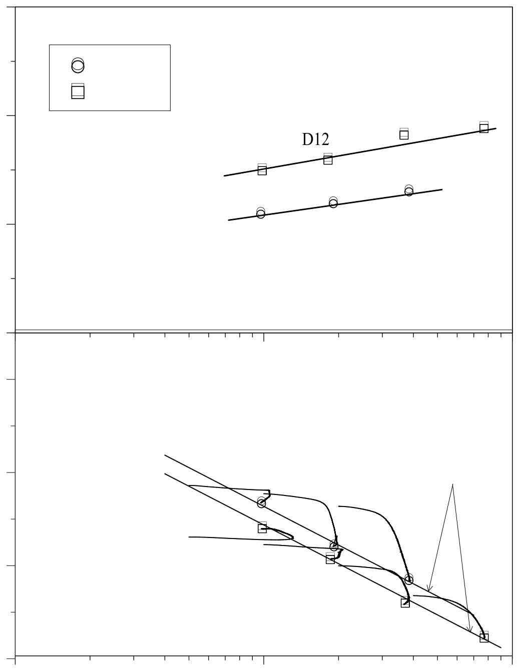

Fig. 4 (a) Total particle breakage after drained shearing; (b) Critical state of compacted coalwash

7 CONCLUSIONS

The suitability of coalwash as structural fill material was investigated through a series of drained triaxial shearing tests and by assessing particle breakage. The experimental results of drained tests revealed that the compaction energy and associated initial grading can influence the stress-strain behaviour quite significantly. The deviator stress under drained shearing reached a peak value for an effective confining pressure up to 100 kPa within 1.6% axial strain followed by a strain softening response, whereas a strain hardening response was observed for higher effective confining pressures. The critical state stress condition showed a linear relationship between deviator stress and mean effective stress with a friction angle of 35^o. The critical state line in v - lnp' space for coalwash under drained conditions showed a semi-logarithmic linear relation and two parallel lines appeared for the two RC levels. Extensive particle breakage is observed during compaction and shearing. The results displaying the total breakage (B_t) and mean effective stress relationship explains the cause for the shift in critical state line for different RC samples. Based on this study, coalwash can be assessed as suitable for structural fill from a shear strength point of view, but the effects of relative compaction and particle breakage must be considered for accessing its stress strain behaviour in order to meet specific field performance criteria.

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