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Abstract

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Evaluation of coalwash as a potential structural fill material for port reclamation

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ABSTRACT

Coalwash is a granular waste by-product that results from the processing of coal. While its potential use as fill material for port reclamation has been recognised, the effect of particle breakage on its geomechanical performance has not been investigated. This paper presents an experimental study of the stress-strain behaviour and associated breakage of compacted coalwash. The characterization of basic index properties is first presented and stress-strain response is investigated using standard undrained triaxial tests over a wide range of effective confining stresses in line with the expected performance criteria of structural fill materials for port reclamation. Furthermore, to account for the effect of moisture variation on particle breakage, alternate wetting and drying cycles on coalwash aggregate was performed. Substantial particle degradation was observed after 25 cycles of wetting and drying. Results show that while the compacted coalwash conforms to typical structural fill criteria in terms of shear strength, the excessive deformation associated with change of particle size distribution due to particle breakage may render the material unsuitable in practice.

Keywords: coalwash, critical state line, particle breakage, particle degradation, undrained shearing

INTRODUCTION

Coalwash is a by-product of the washing process of coal and is produced at over a hundred million tons per year (Armitage, 2012). This waste material generally contains coarse-grained coal reject (coalwash) and fine-grained coal tailings in proportion between 89:11 and 67:33 by weight (Davies, 1992). The material is readily available in the vicinity of coal washerys and its use as structural fill has important economic and environmental advantages (Leventhal and de Ambrosis, 1985; Indraratna et al., 1994). Although significant ongoing advances in understanding basic responses of coalwash have been made, research in this area is still in progress (Kettle, 1983; Williams and Morris, 1990; Montgomery, 1990 ; Skarżyńska, 1995; Hegazy et al., 2004 and Fityus et al., 2008). One of the factors that can adversely affect the granular material deformation behaviour is the particle size distribution and associated breakage (Kikumoto et al., 2010). More data on change of particle size distribution is needed to determine appropriate modelling approaches and allow assessment of material behaviour under different conditions.

Various researchers (Been et al., 1991; Yamamuro and Lade, 1996 and Bedin et al., 2012) showed that the change of particle size distribution (PSD) effects the critical state line (CSL). In particular, the grading state index was related to the position of the CSL for granular material (Wood and Maeda, 2008). Since coalwash is generally a weak material, a study on the effect of PSD in relation to stress-strain behaviour is necessary to evaluate the material in port reclamation applications.

The effect of stockpiling coalwash is reported to cause particle degradation over time (Skarżyńska, 1995) with variation in moisture content a significant factor causing particle degradation leading to a broader PSD. From this study, it has been revealed that Dendrobium coalwash (Dendrobium is an underground black coal mine located near Wollongong NSW) has large particle degradation potential under wetting and drying cycles.

Recently, Rujikiatkamjorn et al. (2012) demonstrated coalwash suitability as structural fill material based on drained behaviour and it has been used in the Illawarra region of NSW (McIntosh and Barthelmeß, 2012). For port reclamation conditions, the suitability of coalwash as fill material should be assessed based on placement condition and expected field stresses. For typical port conditions, the fill material is at or below sea level (i.e. submerged) and short term loading is expected due to handling of containers or goods. Hence, critical shear strength evaluation should be carried out under undrained condition. This paper aims to provide a contribution to the fundamental understanding of undrained shearing behaviour and associated particle breakage of compacted coalwash and also, the degrading potential under moisture variation through alternate wetting and drying cycles.

COALWASH CLASSIFICATION

The material selected for this study is a Dendrobium coalwash. It has been used extensively as structural fill in the Illawarra region of NSW, Australia. The particle size distribution of the coalwash sample selected for the 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; thus, it can be classified in accordance with Unified Soil Classification System as Clayey SAND(SC). For the sake of comparison, the curve representing the coalwash (Rujikiatkamjorn et al., 2012) is also shown in Fig.1.

The change of particle size distribution (PSD) was quantified using the method proposed by Indraratna et al., 2005. The arbitrary boundary of maximum breakage is based on the sample PSD after shearing (Fig.1). The minimum particle size is considered to be 0.01mm and the maximum to be 5 mm, which corresponds to 95% passing of the RC100 compacted sample. Breakage index (B) is defined as a ratio between the area loss caused by shift in PSD (region A) and area enclosed between initial PSD and arbitrary boundary (region A+C) as shown in Fig.1. The compaction induced breakage during sample preparation at various compaction efforts is expressed as a breakage index (B_c) shown in Table 1.

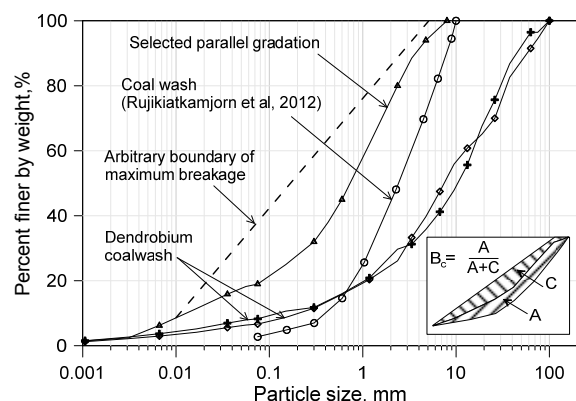


Figure1. Selected PSD.

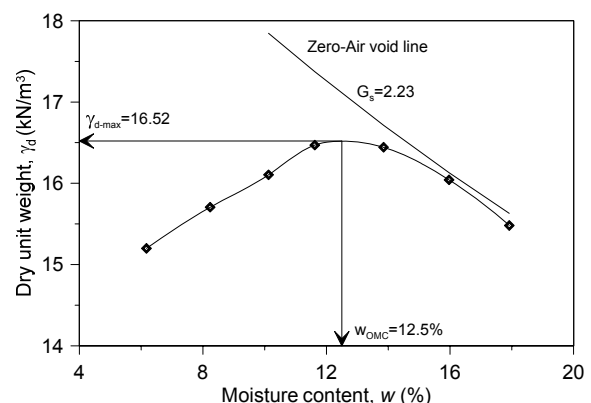


Figure 2. Dry unit weight - Moisture relation.

The loose unit weight of coalwash is measured as 9.6 kN/m^3 in accordance with ASTM D4254-00(2006)e1, which corresponds to a void ratio of 1.28 and relative compaction (RC) of 58%. The permeability of compacted coalwash was measured for the expected field confining stress which ranges between 20-80 kPa. The permeability of compacted coalwash under 50 kPa confining stress was measured between 4.8×10^{-5} and $2.4 \times 10^{-7} \text{ cm/sec}$ for RC levels of 85% and 100%, respectively (Table 1). The permeability linearly decreased between RC85 and RC95, with a sharp decrease noticed between RC95 and RC100. The permeability for RC less than 90% are comparable to silty sand, whereas the permeability for RC95 and RC100 approach silt and clay ranges (Look, 2007).

SAMPLE PREPARATION

The coalwash material was oven dried to 50°C . Upon mixing with the required amount of water, any visible lumps were disaggregated and the mixture stored inside a sealed plastic bag under constant temperature and humidity overnight to allow for moisture equilibration. The compaction characteristics were established using the standard Proctor compaction test (Australian Standard 1289.5.1.1, 2003).

For an applied energy level equivalent to standard Proctor, the maximum dry unit weight (γ_{d-max}) and the optimum moisture content (w_{OMC}) were 16.5 kN/m³ and 12.5% respectively (Fig.2).

Table.1: Properties of compaction coalwash sample.

Relative compaction, RC	85%	90%	95%	100%
Dry unit weight, γ_d (kN/m ³)	14.0	14.8	15.7	16.5
Specific volume, v	1.56	1.48	1.40	1.33
Particle breakage, B_c	0.113	0.145	0.190	0.239
Permeability, k (cm/sec)	4.8×10^{-5}	2.2×10^{-5}	9.3×10^{-6}	2.4×10^{-7}

Different compaction energies were considered to explore a range of placement conditions. Although the applied energy was varied during sample preparation, a moisture content of 10% was maintained to resemble practical compaction conditions. A moisture content of 10% was selected because it corresponded to the average moisture content recorded at the stockpile of a field trial site in Port Kembla NSW. Four different compaction energies (85.1 kJ/m³, 170.3 kJ/m³, 340.6 kJ/m³ and 681.1 kJ/m³) were considered corresponding to RC85, RC90, RC95 and RC100, respectively. The samples were compacted in a 50 mm diameter and 101.5 mm high mould following the procedure described by Heitor et al. (2013). The dry unit weight, specific volume and particle breakage during compaction (B_c) are given in Table.1. A nearly linear increase in particle breakage with increasing RC was observed.

A series of standard undrained triaxial tests were performed to evaluate the stress–strain and particle breakage behaviour of the compacted coalwash. A summary of the testing program is given in Table 2. The test comprises three stages: saturation, consolidation and shearing. During the saturation stage, CO₂ was first used to displace air in the void space and then, a back pressure of 150 kPa was applied. This procedure consistently yielded Skempton's B-value of greater than 0.98. Following isotropic compression to the desired effective confining stress, undrained shearing was conducted at a constant strain rate of 0.1 mm/min.

Table.2: Summary of test program.

Test ID	Relative compaction, RC (%)	Axial strain (%)	Effective confining stress, p' (kPa)	Test ID	Relative compaction, RC (%)	Axial strain (%)	Effective confining stress, p' (kPa)
U1	85	18	15	U10	95	18	200
U2	90	18	25	U11	95	18	400
U3	90	18	50	U12	95	18	600
U4	90	18	100	U13	100	18	50
U5	90	18	200	U14	100	18	100
U6	90	18	400	U15	100	18	200
U7	90	18	600	U16	100	18	400
U8	95	18	50	U17	100	18	600
U9	95	18	100	-	-	-	-

UNDRAINED TRIAXIAL TESTING

Undrained monotonic shearing tests were carried out on compacted coalwash prepared at different relative compaction. In order to investigate the effect of varying initial confining stress (σ'_3), undrained shearing was performed at different initial confining stresses. The undrained shearing results corresponding to 90% relative compaction are reported in Fig.3. The deviator stress (q), excess porewater pressure (Δu) and volume change (ϵ_v) results are plotted against axial strain (ϵ_1) in Figs. 3a, 3b and 3c, respectively. With the increase in confining stress, the deviator stress response increased sharply and reached a peak within 1.3% axial strain and then decrease with increasing axial strain, whereas excess pore water pressure increased dramatically within 3-6% of axial strain and remained constant. For instance, the sample with initial confining stress ($\sigma'_3 = 100$ kPa) reached a peak deviator stress of 85 kPa at axial strain of 0.8% and showed a strain softening response with

increasing axial strain and then attained a stable value of 23.7 kPa at axial strain of 18%. While the excess pore water pressure rose to just over 85 kPa at 5% of axial strain and remained constant with increase in axial strain. This behaviour is identical to dense sand under high stresses (Been et al., 1991).

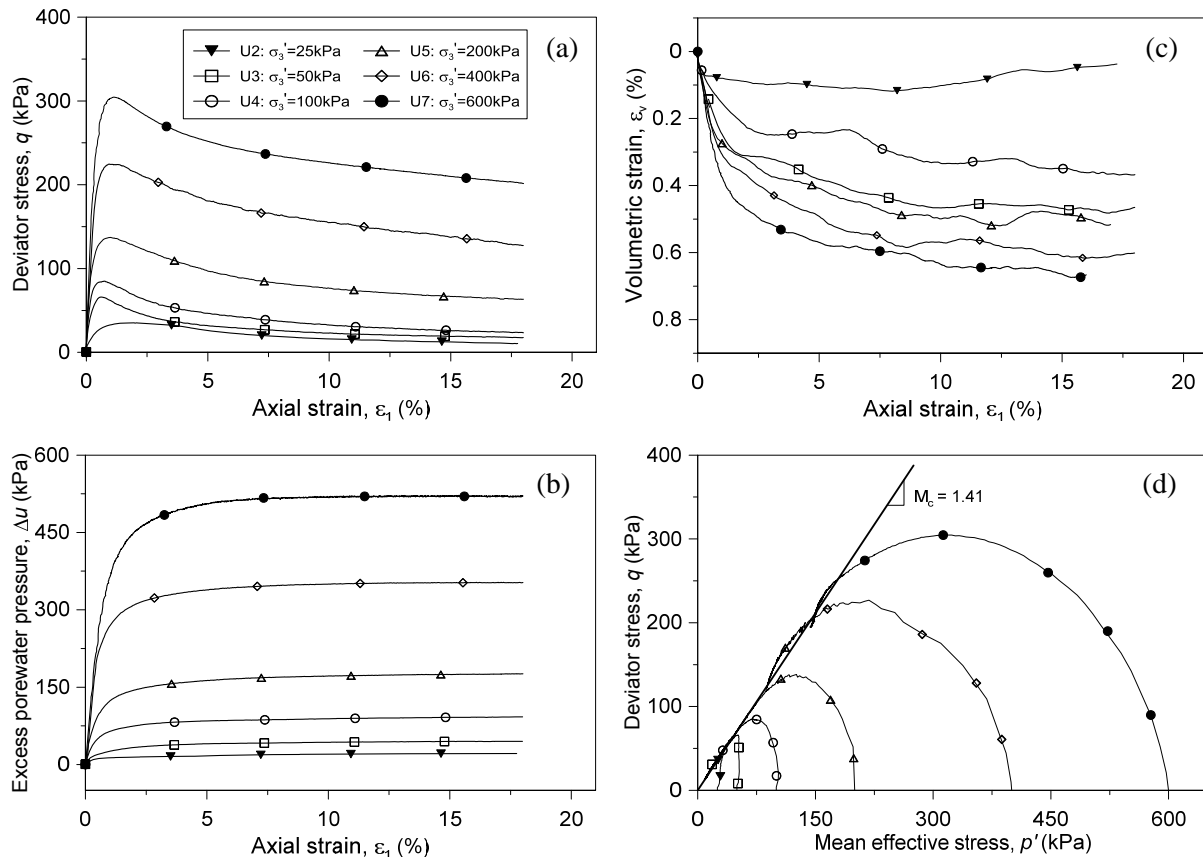


Figure 3. Stress-strain response of compacted coalwash (RC90: U2-U7.)

The volumetric strain responses, shown in Fig. 3c, during undrained shearing is possibly associated with the effect of breakage, pore fluid compression (Garga and Zhang, 1997) and the progressive saturation of the micro pores of coalwash (Lu and Do, 1992). Typically, undrained shearing of fine grained materials yields no volumetric strains, but for coalwash, being a dual porosity material, this is not the case. The volumetric strains measured are mainly associated with a contraction response (i.e. water intrudes the micro pores as the pore water pressure increases). Slight dilation was observed after 8% axial strain for low confining stress ($\sigma_3' = 25$ kPa).

The corresponding stress-paths in the deviator stress plotted against mean effective stress are depicted in Fig.3d. It is evident that sample reached the critical state at a very early stage of the tests and then went on to develop a strain-softening response. Even though the tests were conducted under different initial confining stresses and void ratios, the stress-paths show a similar behaviour. The best fit through the final points of the tests corresponds to a critical state line ($M_{cs} = 1.41$) which is estimated to have a friction angle ϕ'_{cs} of 34.8 degrees.

PARTICLE BREAKAGE DUE TO SHEARING

After the undrained shearing, the tested sample PSDs were analysed and the total particle breakage (B_t) due to shift in PSD incurred during both compaction and shearing is determined, shown in Fig.4. The results show that the particle breakage is dependent on the mean effective stress. Particle breakage is very significant not only during the preparation of the sample, but also during compression and shearing stages. A semi-logarithmic bi-linear relationship can be defined with inflexion at mean effective stress of 127 kPa (critical breakage stress). While a small increase in breakage for $p' < 127$ kPa was observed once the critical breakage stress ($p'_{cb} = 127$ kPa) was exceeded, significant breakage occurred.

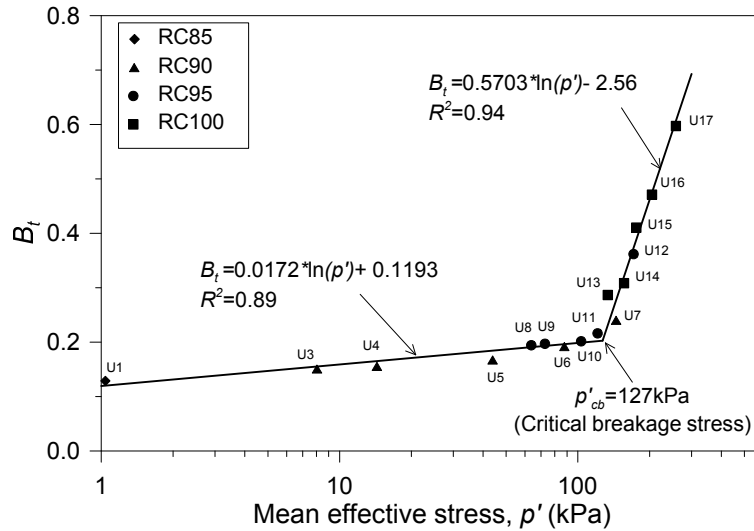


Figure 4. Total particle breakage after undrained shearing.

CRITICAL STATE LINE

On the basis of testing Dendrobium coalwash, some interesting aspects of the critical state of this material are identified. The undrained stress path of compacted coalwash under different initial confining stress states (Fig.3d) clearly indicates that the stresses reached the critical state. The void ratio and mean effective stress at critical state are plotted in the $e - \ln p'$ plane in Fig. 5. The critical state line of coalwash can be defined in three semi-logarithmic linear segments (A-C) having two transitions in the compression slope at $p' = 127$ kPa and 189 kPa. It appears that a unique critical state line under undrained shearing exists and is independent of the stress path and initial compaction state. The critical state parameters of the coalwash, such as void ratio, compression slope and mean effective stress are given in Table.3.

Table.3: Critical state line parameters.

Critical state line	Void ratio, e	Compression slope, λ	Mean effective stress, p' (kPa)
Segment A	0.57-0.362	0.043	1-127
Segment B	0.362-0.267	0.250	127-189
Segment C	<0.267	0.087	> 189

For the sake of comparison, the critical state line of other granular materials such as sand and other mining wastes are also shown in Fig. 5. It is interesting to notice that coalwash has a lower critical breakage stress (p'_{cb}). This is defined as the stress level at which the first transition in compression slope occurs. In addition, while a single transition in slope of the CSL for other granular materials has been attributed to particle breakage or crushing from a qualitative standpoint, i.e., gold tailings at $p'_{cb} = 225$ kPa (Bedin et al., 2012), Erksak sand at $p'_{cb} = 1.3$ MPa (Been et al., 1991) and Cambria sand at $p'_{cb} = 4$ MPa (Yamamuro et al., 1996), limited studies have quantitatively shown this is to be associated with a larger incidence of breakage.

Segment A of the critical state line follows a conventional semi-logarithmic linear response where the volumetric strain has mainly occurred due to particle rearrangement resulting from sliding and rotation. The compression slope (λ) of segment A is observed as 0.043. On exceeding the critical breakage stress ($p'_{cb}=127$ kPa), an aggravated particle breakage commences (as seen from Fig.4) and a steeper semi-logarithmic linear response is observed within the stress range of segment B, purporting that particle breakage was the main mechanism that resulted in large volumetric strain. This segment has shown a higher compression slope ($\lambda=0.25$) compared to the other segments. In segment C, where the stress range is larger than the second transition at $p'=189$ kPa, the volumetric strain response has reduced although the particle breakage pattern remains the same (i.e., Fig.4-tests U15, U16 and U17). This suggests that in this stress range, particle breakage may not significantly influence the deformation as suggested by Russell and Khalili (2002). This might be because the size of the broken particle is much larger than the surrounding void space.

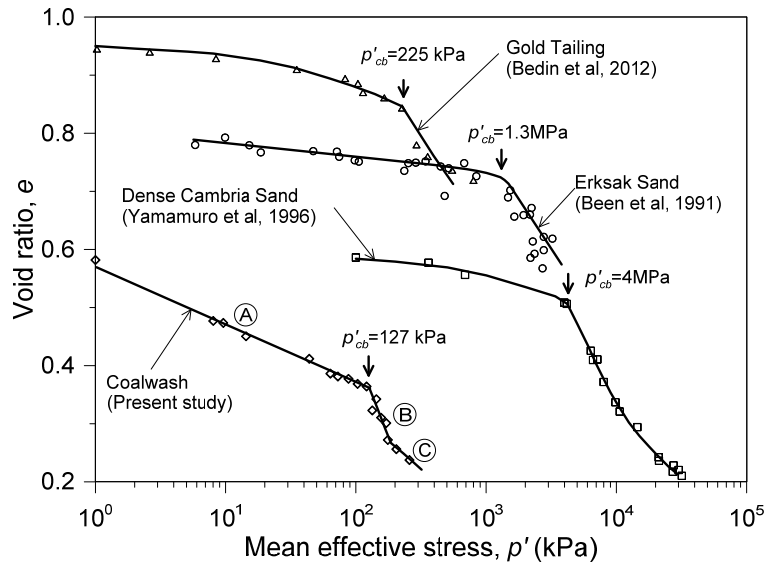


Figure 5. Comparison of critical state line in $e-\ln p'$ space of coalwash (undrained shearing) with other granular materials.

PARTICLE DEGRADATION DUE TO ALTERNATE WETTING AND DRYING

Past research studies indicate that the coal mining waste material undergoes substantial particle degradation leading to a shift in particle size when subjected to seasonal climatic wetting and drying processes (Hauss and Heibum, 1990 and Skarżyńska, 1995). For instance, Skarżyńska reported a substantial shift in the PSD due to weathering between new fill and a 30 year old stockpile (Fig. 6a). The causes for the degradation of this material is associated with the physical disintegration caused by variation of moisture content and temperature (i.e. seasonal climatic variations), and by water dispersion of the clay minerals and other constituents. In port conditions where the material is used in the tidal zone, it will be subjected to frequent wetting and drying and thus it is important to investigate the particle degradation under moisture variation using alternate wetting and drying cycle tests.

Some aggregates of gravel size between 25 and 45mm were used in this study. A wetting stage involving submerging coalwash for 8 hours was followed by drying stage in a 60°C oven for 16 hours. The change of PSD after 12 and 25 cycles of alternate wetting and drying are shown in Fig.6b. The PSD results show that the coalwash has large degradation potential under moisture variation which is consistent with the results of other coal mining waste (Skarżyńska, 1995, Fig.6a). The photographic illustration of the coalwash sample at the beginning and final stages of the wetting and drying test is shown in Fig.6c and 6d respectively. It can be easily observed that there is a significant PSD change.

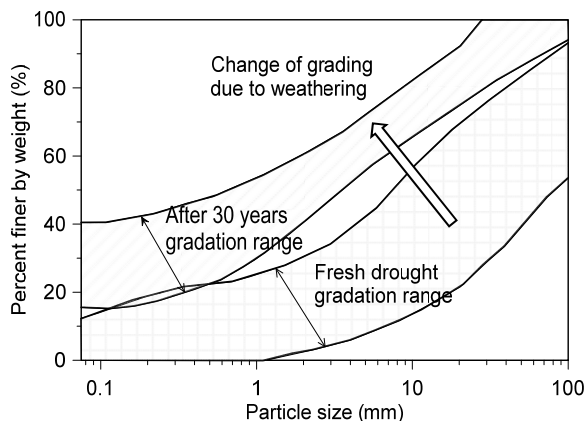


Figure 6(a). Change of PSD of coal rejects due to weathering. (data from Skarżyńska, 1995)

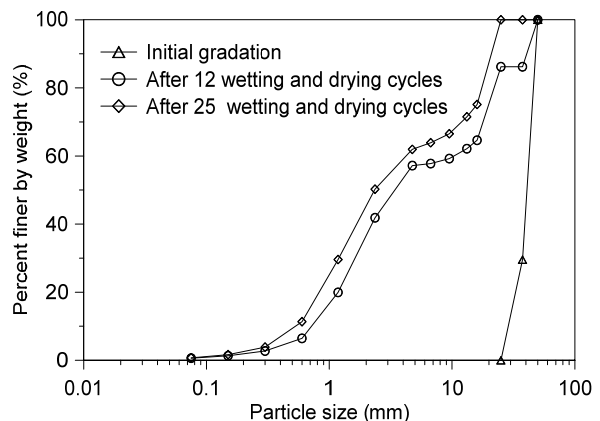


Figure 6(b). Change in PSD due to alternate wetting and drying of coalwash.



Figure 6(c). Coalwash before wetting and drying cycle.



Figure 6 (d). Coalwash after 25 cycles of wetting and drying cycle.

The substantial particle degradation observed in the alternate wetting and drying test shows that the material may be prone to cause excessive deformation due to particle degradation when used at the tidal zone. While from a shear strength standpoint, coalwash can be considered suitable for use as structural fill for water front structures under saturated conditions (i.e., $\phi'_{cs} \geq 30$ degrees, Philip and James, 2011), at the tidal zone the excessive degradation may limit its application.

CONCLUSION

The suitability of coalwash as structural fill material for port reclamation was investigated through a series of undrained triaxial shearing tests and by assessing particle degradation potential. The experimental results of undrained tests reveal that the compaction energy and associated initial grading can significantly influence on the stress-strain behaviour. The deviator stress under undrained shearing reached a peak value for the confining stress up to 600 kPa within 1.3% axial strain, followed by a strain softening response and a stable stress at around 18% axial strain. The critical state values of $p' - q$ show a linear relationship with a stress ratio of 1.41. The critical state line in $e - \ln p'$ space for coalwash under undrained conditions has three semi-logarithmic linear segments with transition at stresses of 127 kPa and 189 kPa, wherein a definite change in compression slope is observed. While the experimental trends observed for the total breakage index (B_t) with mean effective stress show similar pattern to that of the CSL in the lower mean effective stress levels but differ quite considerably for larger mean effective stresses. The observed additional breakage in undrained shearing could have possibly resulted from high stresses and be due to increase of fluid pressure in the micro pore structure of coalwash particles. In the event that the applied stress in port reclamation applications exceed the coalwash critical breakage stress (127 kPa), aggravated breakage will occur that can indeed lead to excess volume change during service.

Alternate wetting and drying cycle testing simulating port conditions within a tidal zone shows excessive particle degradation. From a shear strength standpoint coalwash can be considered suitable as structural fill for mean effective stress conditions under the critical breakage stress. However, in the tidal zones excessive degradation is likely to limit its suitability and performance in service.

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