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Compaction and Strength Testing of Industrial Waste Blends as Potential Port Reclamation Fill

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ABSTRACT

This paper reports on preliminary laboratory geotechnical investigations conducted to explore the compaction and unconfined compression strength (q_u) behaviour of granular waste mixtures of coal wash (CW) and steel furnace slag (SFS). Compaction was conducted under relatively dry and submerged conditions. Proctor compaction test results show that the higher the SFS content, the greater the maximum dry density of mixtures, while the optimum moisture content (OMC) is rather constant. However, for mixtures compacted at their OMC, q_u decreases with increasing SFS content. In contrast, for mixtures compacted under submergence and cured in seawater for up to 28 days, q_u increases with both the SFS content and curing time. The preliminary findings suggest that CW-SFS mixtures have good potential as fill for port reclamation. However, two different mixtures, in terms of SFS content, should be used for dry and submerged fills.

Keywords: coal wash, compaction, curing time, port reclamation, steel furnace slag, submergence

1 INTRODUCTION

In New South Wales (NSW), Australia, more than 10 million tonnes of industrial waste are produced annually. Lack of suitable landfill space and shortage of natural earth aggregates have highlighted the urgency of finding innovative ways of reusing and recycling industrial by-products. In this context, the use of locally available granular wastes, such as coal wash (CW) and steel furnace slag (SFS), as reclamation fill for the offshore expansion of the existing outer harbour of Port Kembla near Wollongong would be an effective way of disposing of these industrial wastes and reducing the demand for quarried fresh aggregates and dredged marine sands.

Recycling of granular waste material produced by the coal and steel industries is environmentally prudent. Nevertheless, the rational evaluation and quantification of its construction potential as an effective port reclamation fill offers a significant challenge, considering the material heterogeneity, its vulnerability to breakage and collapse, and the lack of current knowledge of its performance under both relatively dry and submerged loading conditions.

The improvement of the heterogeneous waste materials of CW, in terms of geotechnical properties, has been conducted in the past (Indraratna et al. 1994, Kamon 1997, Pusadkar and Ramaswamy 2005). Indraratna et al. (2012) showed that properly compacted CW has good potential as effective fill for embankments and port reclamations. However, compressive strength for CW specimens compacted under dry conditions is much greater than that measured for specimens compacted under submerged conditions. In contrast, to date there no previous study exists on compaction and shear strength properties of mixtures of CW and SFS, neither under dry nor submerged conditions. Such a study is fundamental for indentifying an optimum waste mixture as effective fill for port reclamation.

Chemical stabilisation is a suitable method for improving the bearing capacity and the strength of compacted CW, as shown by Okagbue and Ochulor (2007) who investigated the effectiveness of ordinary Portland cement (OPC) in the stabilisation of Nigerian coal reject. On the other hand, Poh et al. (2006), using SFS fines as a stabiliser for fine-grained (cohesive) soils, reported that a percentage of 15-20% of SFS fines and a long curing period may be required in order for the treated soils to show remarkable improvements in terms of strength (i.e. unconfined compression strength, UCS), volume stability and durability. According to Shi (2004), the chemical composition and mineralogy of SFS is similar to that of OPC. Therefore, like pozzolanic materials, SFS is expected to form strength-enhancing products while reacting spontaneously with water. Yet, the potential of SFS as stabiliser for improving the compressive strength of CW, especially in the presence of seawater, has not been studied yet.

In this paper, preliminary laboratory geotechnical investigations are performed to explore the compaction and strength behaviour of CW-SFS as potential fill for port reclamation under dry and submerged conditions. The effects of SFS content on the strength properties of CW-SFS blend materials compacted under dry and submerged conditions and the capability of SFS as a stabiliser for improving the strength of CW-SFS mixtures with curing time in seawater are evaluated and discussed based on UCS test results. Yet, for a comprehensive geotechnical characterisation of CW-SFS mixtures, additional laboratory investigations are currently being performed to properly evaluate shear properties (friction and cohesion) and collapse potential of these granular waste blends.

2 TEST MATERIALS AND PROCEDURE

The two granular wastes used in this study include CW and SFS. CW supplied by BHP Billiton-Illawarra Coal is a well-graded, dark coloured and heterogeneous material with varying constituents including coal. On the other hand, SFS supplied by ASMS is produced in a basic oxygen system (BOS). Particle size distribution curves for CW and SFS tested samples are shown in Figure 1. Soil classification, based on the unified soil classification system (USCS), is presented in Table 1..The average specific gravity (G_s) for CW is 2.13, while that of SFS is 3.48.

Table 1. Soil classification and specific gravity of CW and SFS tested in this study

Waste material	G_s	% gravel	% sand	% fines	Classification (USCS)
CW	2.13	42.6	39.6	17.8	Silty sand, sand-silt mixture
SFS	3.48	44.7	53.8	1.5	Well-graded sand, gravelly sand

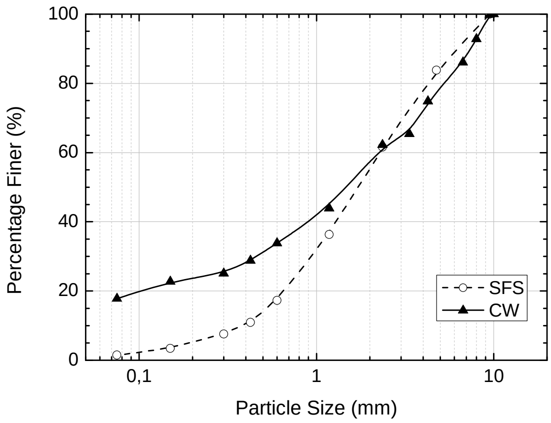

Figure 1. Particle size distribution curves for CW and SFS samples used in this study

Mixtures. In this study, various mixtures were prepared by varying the ratio in weight of CW to SFS. Compaction was conducted under relatively dry and submerged conditions, while compressive strength (q_u) was evaluated by UCS tests.

Dry conditions. Several samples were compacted in three layers of equal volume into a 1 L mould by dropping a 24.5 N hammer from a height of 305 mm (i.e. using standard Proctor compaction energy per volume of about 600 kJ/m^3). Each layer was subjected to 25 blows. To evaluate the maximum dry density (MDD) and optimum water content (OMC) of each mixture, 5 specimens were prepared at different moisture contents. For mixtures compacted at their OMC, UCS tests were performed to investigate the effects of SFS content on the strength of CW-SFS mixtures.

Submerged conditions. Other samples were compacted in a 14 L (i.e. 203 mm in diameter and 406 mm in height) split mould using a vibratory hammer. Soil saturated by seawater was poured into the mould in several layers. Each layer was compacted until there was no further change in sample height. The height of each layer was approximately 50 mm. After compaction, these samples were cured in seawater for 7, 14 and 28 days. UCS tests were performed on compacted specimens to investigate the effects of SFS content and curing time in seawater on development of strength of CW-SFS mixtures.

3 TEST RESULTS AND DISCUSSION

3.1 Strength properties of CW-SFS mixtures compacted under relatively dry conditions

Dry density- moisture content relationships obtained by standard Proctor compaction tests for several CW-SFS mixtures are shown in Figure 2. Variations of q_u with varying percentage of SFS, for samples compacted at their OMC, are reported in Figure 3. The values of MDD and corresponding OMC and q_u are listed in Table 2.

Table 2. Compaction and strength properties of various CW-SFS mixtures

Soils	MDD (kN/m^3)	OMC (%)	q_u (kPa)	G_S
CW (100%)	15.0	10.8	91.8	2.13
CW+20%SFS	16.5	9.8	80.0	2.31
CW+50%SFS	19.2	10.2	59.4	2.64
CW+80%SFS	21.0	9.2	26.4	3.09
SFS (100%)	22.3	9.5	4.6 [a]	3.48

[a] Extrapolated by data-plot in Figure 3.

Test results show that as the SFS content increases from 0 to 100%, MDD increases from 15 kN/m^3 to about 22.3 kN/m^3, while the OMC slightly decreases from 10.8 % to 9.5%. The marked increase in MDD is essentially governed by a significant increase in specific gravity (G_S) of mixtures from 2.13 to 3.48 (see Table 2) caused by the high iron content in SFS particles. Note that the MDD of CW+50%SFS, having G_S=2.64, is comparable with that of most compacted natural fills having G_S=2.65-2.70.

Contrary to the increase in MDD, the strength of mixtures drastically decreases from 91.8 kPa to 4.6 kPa as the SFS content increases from 0 to 100%. It is important to note that, for samples containing 100% SFS, USC tests could not be performed due to complete loss of soil cohesion. The expected low strength value, as for cohesion-less soil, is confirmed by data plotted in Figure 3.

In Figure 3, it appears that for mixtures with a SFS content < 50%, q_u decreases by a rate of 0.65 kPa/%, while for mixtures containing > 50% SFS, q_u is reduced by a faster rate of 1.1 kPa/%. This abrupt rate change can be associated to the fact for SFS content up to 50% (i.e. SFS particles in a CW matrix), the overall strength of the mixture is governed by the strength properties (i.e. friction and cohesion) of CW. While exceeding a SFS content of 50% (i.e. CW particles in a SFS matrix) the strength properties of SFS (i.e. cohesion-less material) characterise the mixture strength.

For specimens compacted under OMC conditions, test results suggest that, when the SFS content is <50%, the (favourable) lower density compared to conventional fills and acceptable strength properties enable CW-SFS mixtures to be used as dry port reclamation fill (i.e. above watertable). However, the general belief that an increase in SFS content ensures higher friction properties to the mixtures and thus bearing capacity, may also support the use of mixtures with a SFS amount exceeding 50%. The authors are currently evaluating by triaxial compression tests the effects of SFS on internal friction angle and cohesion of mixtures to support this hypothesis. Moreover, permeability tests are performed to evaluate whenever a mixture has a permeability that guarantee the rapid dissipation of pore water pressure and minimisation of internal erosion.

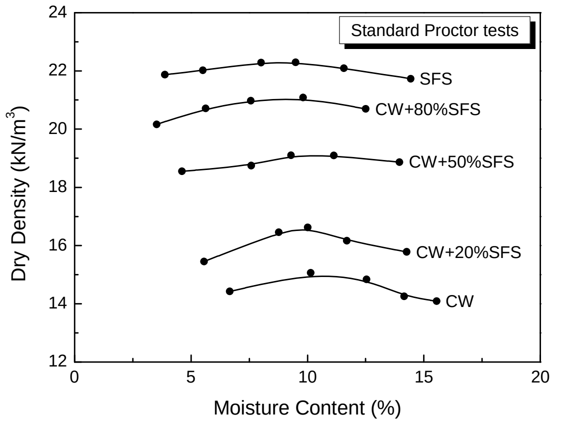

Figure 2. Compaction curves obtained for various CW-SFS mixtures

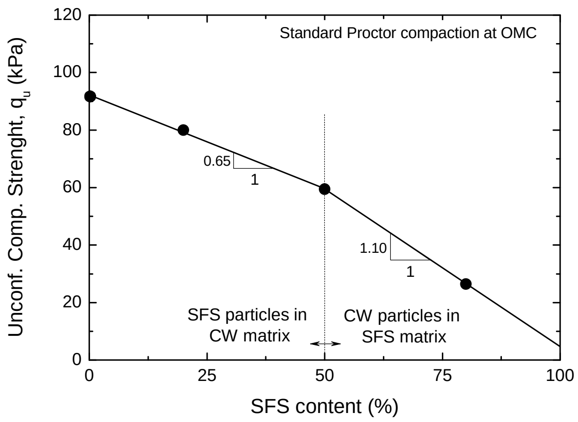

Figure 3. Variation of strength with SFS content for mixtures compacted at their OMC

3.2 Strength and swelling properties of CW-SFS mixtures cured in seawater

Table 3 reports q_u values and percentage of swelling for various CW-SFS mixtures compacted under submergence and cured in seawater for 7, 14 and 28 days. Variations of strength with curing time for tested mixtures are presented in Figure 4. Test results show that q_u increases with the curing time in seawater. However, the extent and the rate of strength development depend on the amount of SFS in the mixtures. After 28 days curing in seawater, the strength measured for a mixture with 10%SFS is almost 1.8 times lower than that measured for a 25%SFS mixture and about 2.3 times lower than that obtained for a 50%SFS mixture.

The presence of free lime (CaO) and free magnesium (MgO), as main chemical constituents, ensures good hydration properties of SFS in the short and long term, respectively. On the other hand, active compounds such as tricalcium silicate (C_3S), dicalcium silicate (C_2S), tetracalcium aluminoferrite (C_3AF) and dicalcium ferrite (C2F) endorse SFS cementitious properties (Wang and Yan, 2010). Therefore, strength development as observed from UCS tests can be attributed to the active compounds in SFS. Through hydration in seawater, these active compounds crystallise and bind together the CW and SFS particles. In other words, SFS acts as a binder and provides the much-desirous hardening and strengthening properties of mixtures with increasing curing time.

Figure 5 reports the swelling behaviour observed for various CW-SFS mixtures which were kept submerged in seawater. A significant swelling behaviour could be observed during the first four-five days. After that, further development of swelling is not observed independently form the amount of SFS in the mixture. However, the maximum value of swelling increases from about 1% to about 3% with increasing the SFS content from 10% to 50%.

The lower values of S_u measured for specimens compacted under submergence compared to those measured for specimens compacted at the OMC imply that, under submerged conditions, the level of soil improvement that can be obtained by compaction is much lower than that obtained under dry conditions. However, the presence of SFS, with its good cementitious properties, ensures a development of strength properties of CW-SFS mixtures with time until hydration process is active. This suggests that CW-SFS mixtures have good potential for use as fill for port reclamation under submerged conditions in seawater. Yet, additional laboratory investigations are required to identify the optimum SFS content in the mixtures for achieving the highest performance.

Table 3. Strength and swelling properties with curing time for various CW-SFS mixtures

Soils	q_u (kPa)			Swelling (%)
	7 days	14 days	28 days	
CW+10%SFS	20.2	21.0	27.6	0.95
CW+25%SFS	28.6	35.4	51.2	1.94
CW+50%SFS	46.0	55.0	63.0	2.81

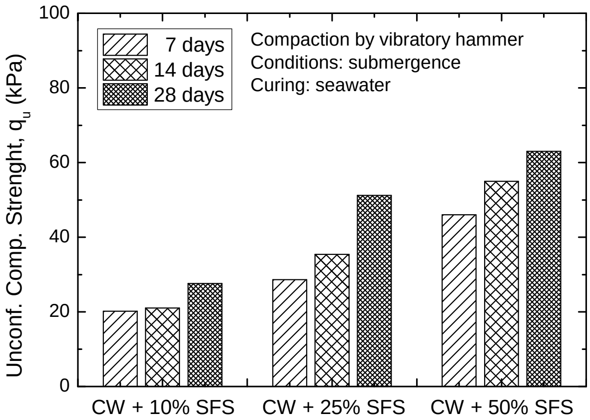

Figure 4. Variation of strength with curing time for various CW-SFS mixtures

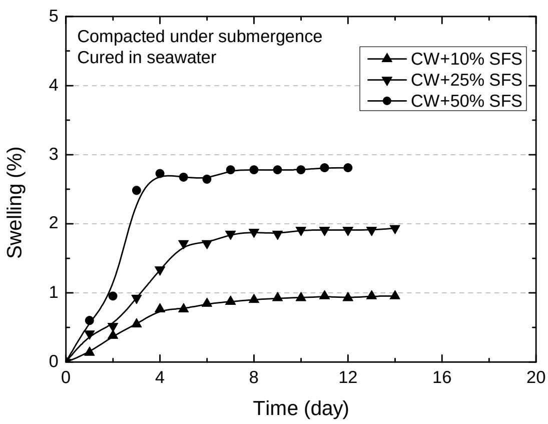

Figure 5. Swelling behaviour of various CW-SFS mixtures cured in seawater

4 CONCLUSION

The evaluation and quantification of the construction potential of CW-SFS mixtures as an effective port reclamation fill offers a significant challenge considering the material heterogeneity and its performance under both relatively dry and submerged loading conditions as shown by this study.

Preliminary findings presented in this paper suggest that CW-SFS mixtures have good potential as fill for port reclamation. However, two different mixtures, in terms of SFS content, should be used for dry and submerged fills:

a) *Dry fills.* When the percentage of SFS is < 50%, the (favourable) lower density compared to conventional fills and acceptable strength properties (60-92 kPa) enable CW-SFS mixtures to be used as dry port reclamation fill.

b) *Submerged fills.* The presence of SFS as a binder ensures a development of strength properties of CW-SFS mixtures with time under submergence in seawater. In addition, compressive strength increases with both SFS content and curing time. For example, after 28 day curing in seawater, the compressive strength measured for a mixture with 50%SFS is almost 2.3 times higher than that measured for a 10%SFS mixtures (i.e. 63 kPa against 27.6 kPa). This suggests that CW-SFS mixtures have good potential for use as fill for port reclamation under submerged conditions in seawater.

The results presented in this paper are only indicative and not applicable to all types of CW-SFS mixtures since the geotechnical properties of CW-SFS blends may vary significantly depending on source and manufacturing process of CW and SFS. In addition, while these laboratory results support the use of CW and SFS as structural fill, additional laboratory and field investigation are necessary to verify the actual performance of these waste materials either when used as dry or submerged fill for port reclamation works.

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