Development of Co-Disposal Methods for Fine Coal Waste and Coal Waste Rock to Facilitate the Prevention of Acid Mine Drainage

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Abstract

Co-disposal of coal waste rock (WR) and fine coal waste (FW) offers the potential to mitigate the generation of acid mine drainage. ARD is generated when sulfide minerals in WR are exposed to aqueous oxidants. In this study, geochemical and geotechnical characterisation of mixtures of coal WR and FW in dry mass ratios of 3:2 and 2:3 (WR: FW) was conducted. Results indicated that FW dominated samples are effective in delaying the generation of acidity when co-disposed with coal WR whereas WR dominated samples result in incompressible and impermeable beds. This provides insight to developing detailed ARD prevention strategies.

Keywords: packing methods, drainage, compressibility, acid mine drainage, mitigation

Introduction

With increasing mining and processing of coal in South Africa, large volumes of coal waste rock and fine waste are generated (Pujado, 2006). The accumulation of these coal wastes creates an environmental burden as metals in high concentrations are released and acidic sulfur-rich waste waters are formed (Johnson and Hallberg, 2005). Sulfidic minerals, which may predominate as pyrite, react with natural elements to initiate these acid producing reactions and are accelerated by the presence of acidophilic microorganisms (Hesketh et al., 2010). This leads to the proliferation of acid rock drainage (ARD) which is a major pollutant of the limited underground and surface water sources and poses a threat to the survival of surrounding flora and fauna.

Preventing the occurrence of ARD from its source is critical. Success has been demonstrated in the coating of sulfidic waste rocks (Shu et al., 2013). These coatings, that include phosphate and silica compounds, limit the access of oxygen and water to sulfide mineral surfaces (Descostes et al., 2002; Johnson and Hallberg, 2005; Kollias et al., 2014). The efficacy of these synthetic coatings in long term ARD prevention can, however, be compromised by excessive degradation over time (Shu et al., 2013). ARD remedial options have also been developed. Addition of phosphates such as apatite can lead to the formation of ferric phosphate precipitates that limit the amount of ferric ion available for oxidation. However, this approach can be resource intensive, especially at large scale (Johnson and Hallberg, 2005).

In prevention studies, the repurposing of fine desulfurised coal waste from a two-step flotation process has been investigated, with various methods being developed to dispose of the fine environmentally benign component effectively (Kotsiopoulos and Harrison, 2018; Mbamba et al., 2012). The co-disposal of sulfidic waste rock and fine benign waste provides an alternative solution to sustaining neutral conditions over long periods (Kotsiopoulos and Harrison, 2015, 2017). Acid consuming components that contain relatively high bicarbonate concentrations, such as sand and clay, offset the net acidity of the mixture thereby delaying the acidification of the waste water. Covers with capillary barrier effects have shown effectiveness in preventing ARD by forming impermeable layers that restrict acidic runoffs (Bussière et al., 2003; Kotsiopoulos and Harrison, 2017).

Co-disposal of coarse coal waste rock and fine-grained coal wastes offers potential environmental benefits over conventional disposal operations, particularly in the prevention of ARD. However, to gain an informed perspective of the geochemistry and geotechnical properties of the waste, it is essential that the ARD potential (Alakangas et al., 2013) and packing behaviour (Li et al., 2017; Shokouhi and Williams, 2017; Wickland et al., 2006) of the samples are determined prior to codisposal application. The geochemical characterisation of individual waste rock and fine waste samples has been previously investigated with success (Hesketh et al., 2010; Kotsiopoulos and Harrison, 2017; Mbamba et al., 2012). However, the use of geochemical indicators to determine the acid producing potential of mixtures of sulfidic waste rock and benign fine waste has rarely been practised. Further, an integrated geochemical and geotechnical approach when developing packing procedures of coal mine waste is essential for successful co-disposal practices.

In this study, blended samples of coal waste rock and fine coal waste were analysed for their ARD generating potential over time, their packing behaviour and consistency. Bench-scale coal waste handling approaches were developed to impede the flow of oxidants in packed beds. Geotechnical properties such as void ratio, packing density, compressibility and slump, were investigated when developing packing procedures. This work demonstrates opportunities for the sustainable management of mine wastes and ARD mitigation through mechanisms that are applicable in the field.

Materials and methods

Acid base accounting tests and biokinetic tests

Two coal waste samples were used in this study. These included coal waste rock (WR) and fine coal waste (FW) samples from mines in the eMalahleni region in Mpumalanga, South Africa. LECO sulfur analyses of the individual WR and FW samples and blended ratios of 3WR:2FW and 2WR:3FW of the waste samples indicated sulfur contents of 1.32%, 0.50% ,0.97% and 0.81 %, respectively. To characterise the ARD potential of the two coal waste samples, static acid-base accounting (ABA) tests were conducted according to methods presented elsewhere (Miller et al., 1997; Skousen et al., 1997; Stewart et al., 2006) . The biokinetic test developed by Hesketh et al., (2010) was used to analyse the blends of coal waste rock and fine coal waste with respect to their relative acid producing and acid neutralising potentials over time. In these tests, 7.5 g of the blended waste samples (particle size < 150 μm) were introduced into 150 mL autotrophic basal salts solution at pH 2 in a 250 mL Erlenmeyer flask. Test samples were inoculated with equal proportions of *Leptospirillum ferriphilum* and *Acidthiobacillus caldus* dominant cultures (10^9 cells/mL) while control samples were similarly prepared but were not inoculated. The flasks were continuously agitated and incubated at 37 °C at 150 rpm for 90 days. The pH, redox potential, ferrous iron, total iron and sulphate concentrations of the sample solutions were monitored daily. Sample volumes were corrected for evaporation gravimetrically by adding distilled water as required over the test time frame.

Packing density and slump tests

Packing protocols, as stipulated in the American standard test method ASTM:C29/C29M-09 (2009), were applied when performing both dry and wet packing density tests. In the dry packing tests, the blended sample was introduced into a polyvinyl chloride (PVC) (H/D=1; H=0.19 m) mould in three equal portions using both assisted and un-assisted packing protocols. In the assisted packing approach, rodding and levelling was performed on each portion prior to the introduction of the following fraction. Wet packing tests were conducted according to procedures developed by Wong and Kwan (2008). The weight of the packed sample was measured to compute the packing density (ø) as the ratio of the solid volume (V_S) to the bulk volume (V). The unconfined flow potential of the mixed coal samples WR and FW was evaluated in terms of flow spread using a modified standard testing method (ASTM Committee C09.47, 2009) by using a cylindrical mould instead of the conventional Abrams cone (Clayton et al., 2003). For these tests, assisted and un-assisted packings were evaluated in which the PVC mould (H/D = 1), open at both ends, was placed vertically on a flat surface and loaded with the well-mixed samples. After loading the test sample, the PVC mould was slowly and steadily lifted vertically to ensure minimal disturbance of the packed contents upon release. The flow spread, an indication of lateral flow of the sample during deposition, was then determined by measuring and averaging the liberated diameters of the formed heap.

Results and discussion

Acid base accounting test results for blended samples of waste rock (WR) and fine waste (FW)

The WR sample was found to be potentially acid forming (PAF) with a NAPP of 10.88 kg_{H2SO4}/t and a pre-boil NAGpH of 1.98 while the FW sample was non-acid forming (NAF) with an ANC of 56,55 kg_{H2SO4}/t, a NAPP of -41.21 kg_{H2SO4}/t and a pre-boil NAGpH of 6.04 (Table 1). The 3WR:2FW sample demonstrated acid producing tendencies (pre-boil NAGpH of 2.85), with an ANC of 32.04 kg_{H2SO4}/t comparable to the MPA of 29.76 kg_{H2SO4}/t. In contrast, the 2WR:3FW sample had an ANC of 45.86 kg_{H2SO4}/t that was significantly greater than the MPA of 24.82 kg_{H2SO4}/t indicating that it was not acid forming. This suggested that the higher fine waste fraction in the 2WR:3FW samples was responsible for the observed low acid producing characteristics with a pre-boil $NAGpH_{2WR:3FW}$ = 5.37. Comparison of these blended samples showed similar acid producing behaviour with after-boil $NAGpH_{3WR:2FW}$ = 2.61 and $NAGpH_{2WR:3FW}$ = 2.73 over time.

Effect of coal waste rock (WR) and fine coal waste (FW) mixture ratios on ARD prevention: reactivity analysis

Two sets of three shake flasks containing WR and FW in dry mass ratios of 3:2 and 2:3 (WR: FW) were investigated for combined acid producing and neutralising potential. With a maximum pH of 2.8 and 3.0 from a pH 2.0 at initiation of the tests, coupled with a decrease in redox potential from 500 mV to *ca*. 420 mV and from 473 mV to 395 mV recorded for the 3WR:2FW inoculated and uninoculated samples respectively, dissolution of acid neutralisers such as carbonates was evident in the first 3 days of the biokinetic test (Figure 1 a & b).

Thereafter, the pH gradually decreased to 2.4 as acid producing reactions dominated in both the inoculated and uninoculated samples. In the uninoculated 2WR:3FW sample, an increase in the pH from pH 3.0 to pH 4.9 with corresponding drop in the redox potential from 305 mV to 280 mV in the first 6 days was noted indicating a significant buffering effect of the fine waste component. By day 40, some acidification was observed in all samples, with the increased redox potential of *ca*. 700 mV indicating the facilitated regeneration of ferric ions by the microorganisms, whether added by inoculation or occurring naturally on the coal samples. However, acidification was not sustained in the uninoculated 2WR:3FW sample, with pH returning to pH 3.5 by day 55 (Figure 1a).

These results indicate the limitation of the benign low sulphur component in sustaining near neutral conditions when mixed with the acid producing waste rock component. Given

***Table 1** Acid base accounting test results showing the total sulphur (S), maximum potential acidity (MPA), acid neutralising capacity (ANC), net acid producing potential (NAPP), and the pre-boil, after-boil and extended boil net acid generating pH (NAGpH) of the WR, FW, 3WR:2FW and 2FW:3WR samples.*

Sample name	Total S	MPA	ANC	NAPP	Pre-boil	After-boil	Ext - boil	ARD classification
	%		kg H_2SO_4/t		NAGpH	NAGpH	NAGpH	
WR	1,32	40,39	29,51	10,88	1,98	2,54	2,57	PAF
FW	0,50	15,34	56,55	-41,21	6,04	5,18	5,21	NAF
3WR:2FW	0,97	29,76	32,04	-2,28	2,85	2,61	5,14	NAF
2FW:3WR	0,81	24,82	45,86	-21,04	5,37	2,73	5,45	NAF

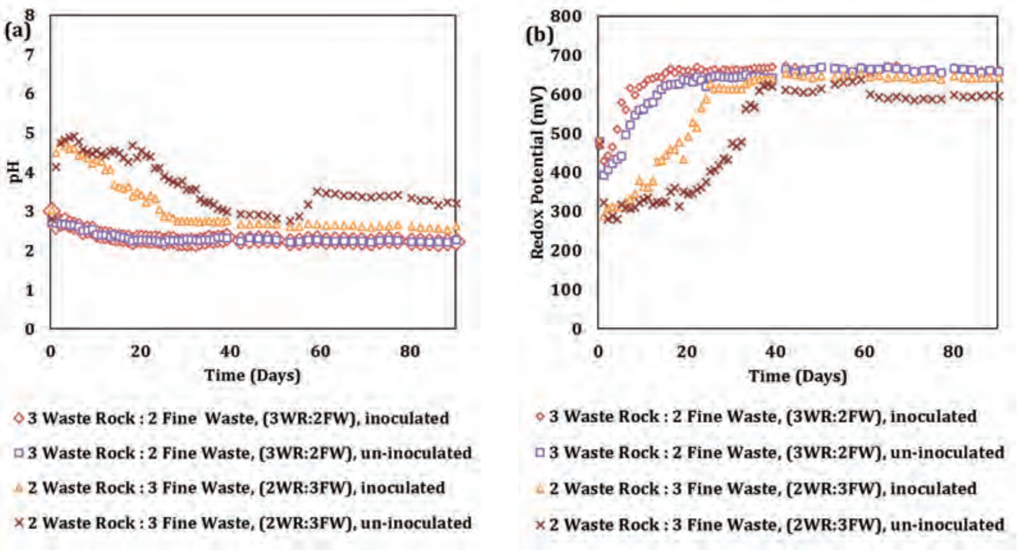

Figure 1 *Biokinetic pH and redox potential profiles for tests performed on waste rock (WR) and fine waste (FW) blends*

that these experiments were conducted in a batch system where acid neutralisers are sustained in the reaction environments, highly acidic environments are more rapidly likely to ensue in flow-through systems with the continual dilution and washout of generated neutralisers. The proliferation of preferential flow paths and unrestricted access of oxidants to the acid generating fraction would further worsen this phenomenon. Developing improved packing protocols to minimise voids within ore beds and reducing the permeability thereof therefore is an important limiting factor in ARD post dissipation of the neutralising components. To achieve this, the homogeneity of co-disposed blends is investigated to improve deposition techniques that increase the packing density and bed stability of mine waste sites.

Effect of packing methods on packing density and flow spread

The packing density is influenced by the water/solid (W/S) ratio (Figure 2a). Under dry conditions (W/S = 0), the packing density is equal to the solids concentration. The increase in W/S ratio beyond 0.08 (v/v) in both the 3WR:2FW and 2WR:3FW blended samples resulted in an increase in the packing density suggesting a reduction in voids. The maximum packing density was reached at the W/S ratio of 0.089 with a corresponding spread of 0.330 m as shown in Figure 2b for the 3WR:2FW sample whereas in the 2WR:3FW sample, the maximum packing density was reached at W/S = 0.170 with a corresponding spread of 0.351 m. This suggests a relationship between blend proportion and the W/S ratio needed to achieve maximum packing density and the associated unconfined flow potential of the sample during deposition. At a specific WR to FW ratio, typically 3WR:2FW, the fine waste just fills the voids of the waste rock skeleton promoting effective occupation of the bulk volume by the solid particles, and enhancing particle-particle interaction between the coarse and fine grains hence the lower spread (Wickland et al., 2006).

The addition of fine coal waste to fill the voids between waste rock particles improves the packing density of the bed. The void content ϵ, defined as the ratio of the volume of voids ($V - V_s$) to the bulk volume V of the granular material, decreased with an increase in solid content (Figure 3). The void content is higher in the fine waste dominated sample (2WR:3FW) than in the waste rock dominated sample (3WR:2FW). This indicates that voidage is reduced as the blend approaches

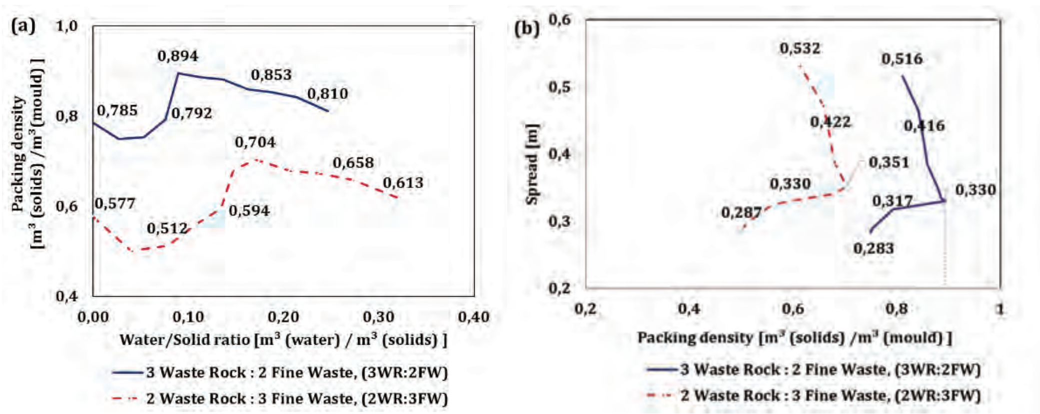

Figure 2 *(a) The effect of water/solid (W/S) ratio on the solid concentration and (b) the relationship between packing density and spread*

the 'just filled in' state (*viz*. 3WR:2FW in Figure 2 & 3a). Comparatively, the 3WR:2FW packing results in a more compact structure.

Compact beds are less susceptible to volume change under the action of compressive loads, particularly in coarse particle dominated samples (Li et al., 2017; Shokouhi and Williams, 2017). The load-bearing waste rock skeleton limits the total axial strain and increases the stability of the bed (Wickland et al., 2006). Such stress-strain behaviour shows the significance of mix proportions in developing packing protocols for ARD prevention.

Conclusions

The suitability and packing behaviour of co-disposed coal waste rock (WR) and fine coal waste (FW) in preventing the generation of ARD was demonstrated. ABA and biokinetic tests were used to evaluate the ARD potential of the coal WR, FW and the co-mingled blends of these samples (3WR:2FW and 2WR:3FW). The packing behaviour of these mixtures was analysed using packing density tests and slump tests.

The FW dominated blended sample (2WR:3FW) showed higher neutralisation characteristics than the WR dominated blends (3WR:2FW). Consistent with ABA tests, FW samples showed potential in delaying the generation of acidity when blended with sulfidic coal WR. The limited neutralising effect of FW over time calls for the development of packing methods that would enhance the prevention of ARD by restricting access of aqueous oxidants to acid generating coal waste fractions. The WR dominated sam-

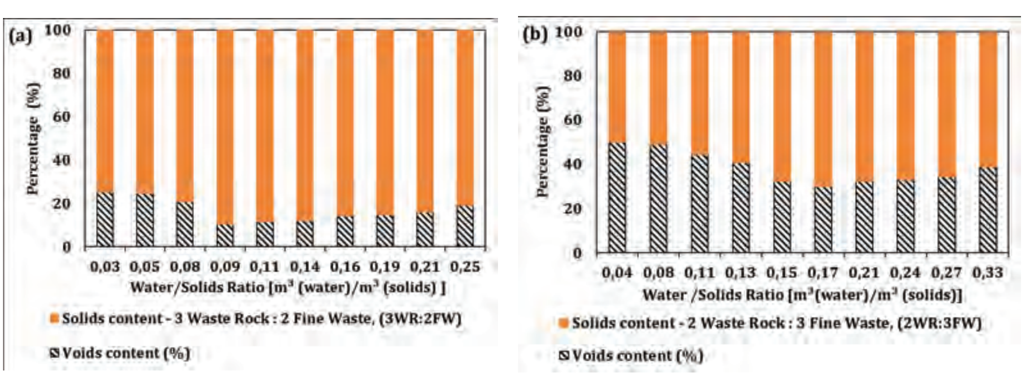

Figure 3 *Relationship between solids and voids content for blends in dry mass ratio (a) 2WR:3FW (b) 3WR:2FW*

ple (3WR:2FW) displayed favourable packing densities (0.89 m^3_{solids}/m^3_{mould}) with low void content (10.6%) relative to the FW dominated blends. Compressibility tests are expected to validate that with decreasing void content, minimum axial strain will be observed under constant rate loads; thereby providing insight into the engineered design of geochemically and geotechnically stable packed beds.

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