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A practical testing approach to predict the geochemical hazards of in-pit coal mine tailings and rejects

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ABSTRACT

Coal mining operations produce a large amount of coal spoil and tailing wastes that may cause environmental problems. Coal mine wastes can be returned to the mine by in-pit disposal of tailings, thereby reducing the environmental risk caused by the failure of tailing dam constructions. Geochemical characterization of coal mine wastes is important prior to in-pit disposal of the wastes because such disposal may result in the release of acid mine drainage, saline water, and heavy metals. The objectives of this study were to identify the major characteristics required to determine the feasibility of in-pit disposal of coal tailings and rejects and to provide simple experimental methods to better define the potential release, reactivity, and mobility of contaminants from tailings. Statistical analyses of data can alleviate the need for extensive sampling and chemical analyses of tailings to perform risk assessment on contaminant release. For this purpose a principal component analysis was used in this study and showed significant (greater than 0.7) loadings on the first component of selected ions, i.e. for Fe, Mn, S, pH, EC, acidity, and SO_4^{2-}, which accounted for 26.3% of the total variance. Therefore, because the first component explains mainly acidity and related salts, the parameters of this component can be used as a proxy to compare different samples or different sites for potential acidity and salinity without the need to measure the remaining parameters. Repeated leaching tests on tailing samples of various chemical and physical properties have been performed and the electrical conductivities measured fitted well into a new variant of the shrink core model, which is suggested as a simple test method to predict the potential salinity generated by tailings. The results acquired from the statistical analysis and sequential leaching showed good agreement, and the procedures suggested will help better characterize and classify coal mine tailings and rejects for in-pit disposal.

1. Introduction

Coal mining operations generate significant amounts of waste in the form of spoils, rejects, and tailings. Spoils summarize the overburden and waste rocks generated to gain access to coal seams, whereas coal rejects are washery wastes resulting from the processing of coal. Coal tailings are fine particle waste generated in the production of the coal product by crushing, screening, washing, sedimentation, and dewatering (Parton, 1947). Coal tailings commonly consist of 50% coal and 50% inorganic material (Williams and Morris, 1988), and the quantity of tailings produced is generally about 7–10% of the final coal product (Radloff et al., 1995). This type of mine tailings and rejects can be classified as a Technosol according to FAO World Reference Base for Soil Resources (WRB, 2014). A Technosol is a soil dominated by technical origin and contains materials exposed by human activity.

Most coal wastes are transferred to impoundments, dumped on the surface, or backfilled into open-pit or underground mines. Traditionally, tailing dams, or surface containments of tailings, have been used for disposal of tailings. Tailings are pumped as slurry containing in general about 30% solids (Radloff et al., 1995). In the tailing dam, tailings can be dried through surface evaporation and drainage from the dam walls and base. The initial surface drying process may result in the consolidation of a surface crust, which limits further evaporative drying of tailings because of poor hydraulic conductivity (Radloff et al., 1995). Tailing dams also may fail or produce chronic environmental impacts through seepage or movement of dust. Because tailing dams produce problems such as the release of acid mine drainage, and salts, and because they may fail, demand for alternative disposal facilities is increasing. Recently, there has been a trend toward a more sustainable environment. As a result, there has been an effort worldwide to minimize waste and increase waste recycling. Tailings can be returned to the mine by in-pit disposal or backfilling and also can be mixed with coarse mine waste such as rejects and spoils (Mendez and Maier, 2008).

In-pit disposal of tailings refers simply to the process of backfilling an open pit with tailings, which is very attractive to mine operators because of its cost benefit and structural stability. Whereas in-pit disposal of tailings has considerable potential benefits, such as placing the tailings below the natural ground surface, filling final voids, minimizing air pollution, minimizing the surface area to be capped and

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vegetated, and reducing the risk of failure, it may have environmental disadvantages. In-pit disposal of coal tailings and rejects can potentially result in the release of salts and other contaminants from the pit to aquifers surrounding and underlying the voids. The major problems caused by tailings are generation of acid mine drainage, release of saline water, and mobilization of heavy metals and metalloids. Weathering of tailings may result in the release of salts and a change in the acidity of underlying or nearby substrates, with the potential to impact the receiving environment, if these materials remain exposed at the surface (Mulligan, 2003; Schüring et al., 1997).

Coal tailings may potentially contain a range of coal-related trace elements and heavy metals associated with sulfides (mainly pyrite), which can also be mobilized during exposure and/or leaching (Doka, 2009). Therefore, a careful characterization of the tailings should be conducted when tailings are disposed in pit and the characterization process should be simple and easy to be tested on site. Dang et al. (2002) evaluated the mobility of heavy metals in coal mine spoils through mineralogical analysis and sequential extractions to predict the environmental impact of natural weathering of coal mine spoils. Geographical information system tools were employed to evaluate pollution levels at an abandoned coal mine site (Yenilmez et al., 2011). Geochemistry in pit lakes was predicted through water–rock reactions and adsorption reactions (Castendyk and Webster-Brown, 2007). Although there have been some studies to assess environmental risk of coal tailings to surrounding environments, information about characterization of coal tailings and rejects for in-pit disposal is limited. Therefore, the overall objective of this study is to suggest the characterization process of coal tailings and rejects to address potential environmental issues arising from the in-pit disposal of coal wastes. The detailed objectives of this study are to identify the major geochemical parameters representing the properties of coal tailings, provide simple experimental methods to characterize those, and predict the environmental impacts of the tailings. A practical approach for characterization, evaluating leaching, and modeling is introduced based on the testing of in-pit tailing samples from selected coal mines in eastern Australia.

2. Methods

2.1. Geochemical characterization of coal mine tailings

Samples were collected from selected coal mines in the Bowen Basin (Site 1) and Hunter Valley (Sites 2 and 3), eastern Australia, because these sites showed a wide range of particle size, pyrite content, clay mineral content, and degree of weathering. Coal-tailings and reject samples were collected randomly from tailing ponds at depths of 0–20 cm, dried at 40 °C, and then sieved to less than 2 mm. Particle size distributions were measured using a particle size analyzer (Malvern Mastersizer 3000). The scattering pattern of a He–Ne laser caused by a sample of particles was recorded and a size distribution was calculated. pH and electrical conductivity (EC) were measured after extracting 5 g of air-dried sample with 25 mL of Milli-Q water. Acidity was measured using a Metrohm 902 Titrando autotitrator. To measure acidity, 5 g of each sample was extracted with 25 mL of boiled Milli-Q water after shaking for 1 h in an end-over-end shaker. After centrifugation for 10 min at 4000 rpm, supernatant was transferred to a 50-mL beaker and the solution was titrated with 0.1 N NaOH solution at a rate of 1 mL/min. Acidity was reported as mg/L $CaCO_3$ equivalent by titrating to pH 8.3. The titration curves showed three distinct stages with increasing pH. Three inflection points were determined by first-derivative plotting at approximately pH 3.7, pH 5.5, and pH 7.5, which reflect the relative contributions of H^+, Al^{3+}, and Cu^{2+}/Fe^{2+}/Zn^{2+}/Mn^{2+}, respectively. Samples were digested using a Milestone Ethos 1 with a 5:2:1 mixture of nitric, hydrochloric, and hydrofluoric acid, respectively, to determine total element concentrations. Digested solutions were analyzed using inductively coupled plasma-optical emission spectrometry (ICP-OES, Varian). Anions were analyzed using ion chromatography (Dionex) after extracting samples with Milli-Q water.

Table 1
Particle size of coal tailings and rejects.

Source	Sample name	Clay (%) <0.002 mm	Silt (%) 0.002–0.02 mm	Fine sand (%) 0.02–0.20 mm	Coarse sand (%) 0.20–2.0 mm
Site 1	BT1	21.1	35.7	32.5	10.7
	BT2	22.7	48.8	27.7	0.810
	BT3	25.3	43.6	29.4	1.72
	BR1	9.63	22.1	35.6	32.6
	BR2	8.71	16.7	38.7	35.9
Site 2	MAT1	35.5	46.4	18.0	0.178
	MAT2	23.6	34.5	35.4	6.39
	MAT3	20.7	36.8	36.3	6.27
	MAT4	17.3	39.6	40.2	2.88
	MAT5	21.2	37.0	35.6	6.21
Site 3	WT1	23.4	34.3	38.8	3.50
	WT2	23.6	33.3	36.8	6.27

2.2. Repeated leaching of tailings and rejects with milli-Q water

To suggest a simple and easily applicable field test method, repeated leaching tests were developed and compared with characterization results of coal tailings and rejects. Air-dried samples were extracted with deionized water (solid:solution = 1:5) for 2 h at 150 rpm in an orbital shaker and centrifuged for 10 min at 4000 rpm. The supernatant then was analyzed for pH and EC. The same amount of deionized water was then added to the remaining samples, tubes were shaken as described above, and the pH and EC of supernatant were measured. This leaching procedure was repeated 8 times.

2.3. Statistical analysis

Data were collected throughout a range of experiments. The collected data were analyzed statistically using Statistica 12 to show correlations between different variables and to reveal major components that best represented the characteristics of the coal tailings and rejects. A correlation matrix of variables was then produced to determine relationships among the different variables. Principal component analysis, which transforms an original number of variables to a smaller number of uncorrelated components, was used. The principal components were simplified by varimax rotation to increase the participation of the variables with higher contribution and reduce the participation of the other variables. The principal component score was presented to provide a geochemical hazard index of samples for the case of in-pit disposal of tailings. In total, 25 variables including total element concentrations, pH, EC, total acidity, particle size of the 50th percentile, and Cl^- and SO_4^{2-} concentrations were used for the statistical analysis. Cluster analysis with Euclidian distance as the criterion for forming clusters of elements was performed to classify samples of different characteristics.

Table 2
pH and EC of coal mine tailings and rejects (data are the means ± standard deviation of three replicates.)

Source	Samples	pH	EC (μS/cm)
Site 1	BT1	6.58 ± 0.01	1281 ± 80
	BT2	3.87 ± 0.16	1569 ± 58
	BT3	6.12 ± 0.03	743 ± 2.4
	BR1	6.26 ± 0.02	548 ± 1.9
	BR2	3.35 ± 0.04	2609 ± 46
Site 2	MAT1	3.22 ± 0.03	2361 ± 6
	MAT2	3.38 ± 0.03	1917 ± 22
	MAT3	7.00 ± 0.04	938 ± 43
	MAT4	2.91 ± 0.01	4435 ± 134
	MAT5	7.39 ± 0.01	1026 ± 15
Site 3	WT1	9.76 ± 0.03	1703 ± 16
	WT2	9.82 ± 0.01	974 ± 54