Re-purposing of Acid Generating Fine Coal Waste: An Assessment and Analysis of Opportunities

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Abstract

This paper focuses on opportunities for the re-purposing of separated sulfide-rich coal tailings. The approach used in this study was based on the innovation value chain and included identification and preliminary analysis of alternatives, multi-criteria performance assessment of selected alternatives, and a scenario analysis of the two preferred options to achieve a better understanding of the implications of these applications in the South African context. This analysis indicated that whilst cemented paste backfill and soil amelioration were the preferred options, further developmental work would be required to establish efficacy, particularly in the case of the less promising cemented paste backfill option.

Keywords: sulfidic coal tailings, waste re-purposing alternatives, decision-support analysis

Introduction

The coal industry in South Africa is currently both imperative for South Africa's immediate energy security and a contributor to South Africa's significant acid rock drainage (ARD) problems. ARD in coal mining is generated in the mines themselves, and in deposits of coarse discards and ultra-fine tailings produced in coal washing operations. Researchers at the University of Cape Town's Department of Chemical Engineering have developed a two-stage separation process which separates ultra-fine coal tailings into a recovered coal stream, a sulfide-lean stream which is non-acid generating, and a sulfide-enriched stream (fig. 1). The sulfide-enriched stream, which has a relatively low volume and is acid generating, can potentially be re-allocated as feedstock for other uses. In this way, the long-term pollution risks associated with ARD generation from the coal tailings deposits are effectively eliminated, whilst simultaneously increasing recovery of mined resources.

The selection and implementation of the preferred options for the re-purposing or utilisation of wastes, such as the separated sulfide-rich coal tailings fractions, is, however, not a trivial exercise and needs to be based on a comprehensive understanding of the alternatives available and the consequences of these alternatives (Zeleny 1982; Cano-Ruiz and McRae 1998). In this regard, an approach for the identification and analysis of opportunities for the re-purposing of mine wastes has

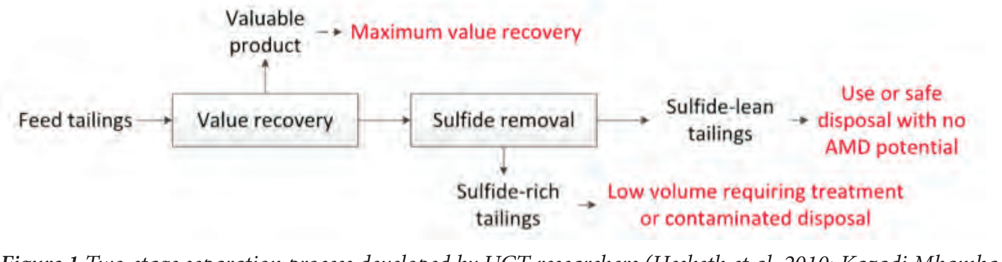

Figure 1 *Two-stage separation process developed by UCT researchers (Hesketh et al. 2010; Kazadi Mbamba et al. 2012).*

Figure 2 *The innovation value chain (Dervitsiotis 2010).*

been developed, which is based on the innovation value chain (fig. 2). This is an iterative process, with increasing articulation of detail on progressing from the early to later project development stages.

The focus of this paper is on the identification, selection and pre-feasibility assessment of potential re-purposing opportunities for the specific case of sulfide-enriched coal tailings fraction, consistent with the early project stage application of the first three steps of the innovation chain. The methodological approach and key outcomes are summarised in the sections below.

Stage 1: Alternative identification

The innovation value chain (fig. 2) starts with idea generation. The set of identification activities are both creative and systematic (Douglas 1985; Cano-Ruiz and McRae 1998; Sinnott 2005). These solutions are represented using block flow diagrams and mass balances and, if information permits, energy balances to ensure technical rigor (Cano-Ruiz and McRae 1998). In the case of our sulfide-enriched coal waste the application alternatives (box 1) were identified through a combination of literature survey and first principles, based on a preliminary characterisation of the stream. It comprised of residual coal, ash and a significant sulfur component in the form of pyrite (Kazadi Mbamba et al. 2012). A sulfur content of up to 16% has been achieved experimentally (Howlett and Marsden 2013).

Stage 2: Alternative selection

Alternative selection requires a clear indication of what constitutes a superior outcome. A conception of this 'superior outcome' is usually defined using several different, and often conflicting, criteria. Alternative selection therefore normally entails the trade-off between different processes based on relative performance in accordance with multiple project criteria. In this study, analysis and selection of alternative options for the sulfidic coal tailings was carried out in two stages: screening and multiple criteria decision analysis.

Step 1: screening analysis

The first step entailed preliminary screening of the 14 identified alternatives (box 1), to make the process of multiple criteria analysis less onerous. In the case of the sulfide-enriched coal waste, the screening criterion was whether the application alternative would be effective when it was only 20% enriched in pyrite. On this basis seven alternatives were identified for further analysis: sulfuric acid production, ferric sulfate production, ferrous sulfate production, Cr(VI) reduction, soil ameliorant, facilitating heap leaching, and cemented paste backfill production.

Step 2: multiple criteria decision analysis

Multiple criteria decision support tools are commonly used to evaluate the trade-offs between, and facilitate the selection of, alternative process or product options (Cano-Ruiz

Box 1 *Potential application alternatives for the sulfide-enriched stream, where sulfide is mainly in the form of pyrite.*

Sulfuric acid production	Iron production	Facilitating heap leaching
Sulfuric acid & paint pigment	Secondary lead refining	Cemented paste backfill
Glass pigment production	Copper smelting	Photovoltaics production
Ferric sulfate coagulant	Chrome(VI) reduction	Use in nano- and micro-linear actuators
Ferrous sulfate heptahydrate	Soil ameliorant	

Box 2 *Steps used in Value Function Decision Analysis (Von Winterfeldt and Edwards 1986).*

1. "Define alternatives and value-relevant attributes"
2. "Evaluate each alternative separately on each attribute"
3. "Assign relative weights to the attributes"
4. "Aggregate the weights of attributes and the single-attribute evaluations of alternatives to obtain an overall evaluation of alternatives"
5. "Perform sensitivity analyses and make recommendations"

and McRae 1998). In this study multiple-criteria analysis of the 7 potentially viable alternatives was conducted using the Value Function Decision Analysis framework (box 2) and tools, as these are relatively easy to understand and can be used effectively by non-experts in the field (Edwards and Barron 1994).

In line with the first stage of the value-based decision analysis framework, several criteria were developed for the technical, social, economic and environmental categories (tab. 3) to make sure that the application alternatives perform well over a range of important considerations, and not just techno-economics.

The alternatives were subsequently scored by design professionals based on the identified criteria (stage 2 of the framework outlined in box 2). To make the scoring process consistent between design professionals, a scoring scale was developed for each criterion. This allowed the design professionals to score an application alternative from 0 to 4 based on descriptions for each score. The semi-quantitative nature of the scoring scale was consistent with the early design stage requirements in terms of uncertainty. The design experts also rated their level of certainty in the score they assigned, to reflect their experience and knowledge of the specific application alternative.

The scores were then aggregated to arrive at a single, comparable number for each application alternative, which would indicate a level of preference. The aggregation process was conducted in two steps. Scores for each criterion were first aggregated across the different design experts, using the levels of certainty to weight their scores. This achieved a single score per criterion per alternative. Then the criterion scores were aggregated using a weighted average. Some criteria are more important than others to decision makers, taking into account the ranges in which they are found and the variability between the alternatives, and should therefore be assigned heavier 'weights' when aggregating the scores (Von Winterfeldt and Edwards 1986; Belton and Stewart 2002). Decision makers are required to indicate their preferences by assigning criteria weights. In our case the academics choosing which application alternative to invest research in were the decision makers and weighted the criteria. As outlined by Belton and Stewart (2002), there are several different ways to do this. In this study three different weighting methods were used: Indifference Weighting, Swing Weighting and a modified version of the Analytical Hierarchy Process.

Whilst the different weighting methods did give rise to slightly different aggregated score, in all cases soil amelioration and cement paste backfill were ranked as the pre-

Table 1 *The criteria used to assess the suitability of the application alternatives for sulfide-enriched coal waste.*

Technical	Social	Economic	Environmental
• System complexity • Simplicity of process control • Technical maturity • Conversion efficiency	• Job creation • Operating health & safety • Community health & safety • Skills development potential • Entrepreneurship	• Expected profitability • Availability on the local market • Local deficit • Scale of use	• Waste generation • Mineral recovery • Energy consumption • Water consumption

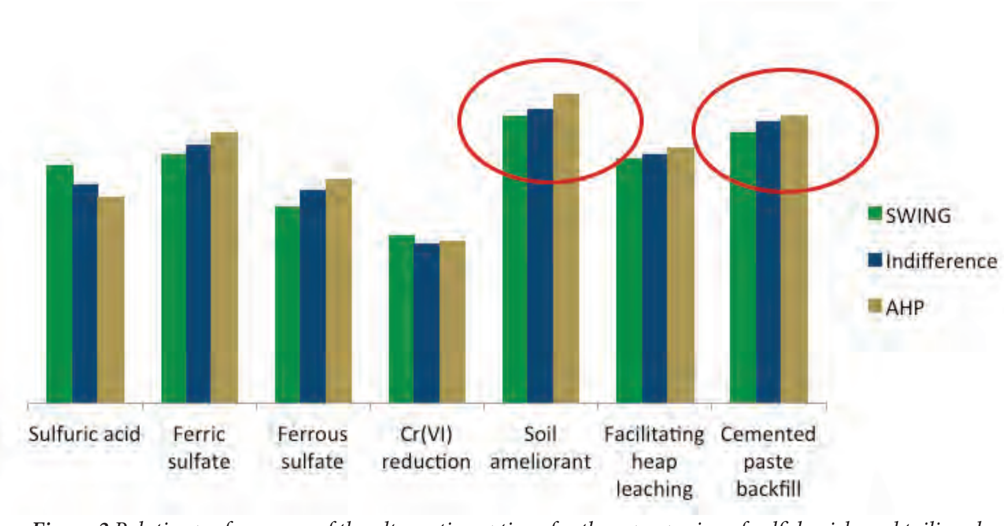

Figure 3 *Relative performance of the alternative options for the repurposing of sulfide-rich coal tailings based on Value Function Decision Analysis using three different weighting methods. (Since the alternatives are ranked relative to each other, a y-axis scale is not necessary. The abbreviation AHP stands for Analytical Hierarchy Process.)*

ferred options for the repurposing of sulfide-rich coal tailings (fig. 3).

Stage 3: Pre-feasibility assessment

For early stage development, a scenario study is done to understand some of the context-specific issues associated with the preferred options that will need to be addressed if a solution is to be developed further and ultimately implemented. This enhances understanding of the implications of implementing an alternative within a specific context, in this case the South African coal industry. In the case of the sulfide-enriched coal waste, soil amelioration and cemented paste backfill were considered. The assessment included an in-depth literature survey on the alternative and the science and technology that enables it. This was followed by an assessment of the economic, environmental, social and technical feasibility of the application in the South African context. Issues such as market location, application efficacy compared to competitor products and pollution potential were considered. As such, information sources such as local agricultural co-ops, government-published regional agricultural production reports, as well as company annual reports were consulted.

Cemented paste backfill, a mixture of tailings, water and binder, is used to fill underground mine workings and in so doing enhance the stability of underground mines (Belem and Benzaazoua 2004; Kesimal et al. 2005). This improves the stability of operating mines, reduces surface waste disposal of tailings and prevents problems like ground subsidence in derelict mines (IIED 2002; Jung and Biswas 2002; Lu and Cai 2012). The preliminary assessment of the cemented paste backfill option showed that sufficient sulfide-enriched material is unlikely to be produced in South Africa for this alternative to be considered viable. The material is also potentially reactive and long-term stability has not been proven. Therefore, it is uncertain whether this approach will be environmentally beneficial over the course of many years.

Soil amelioration is the improvement of the physical and chemical characteristics of soil through the application of an ameliorating substance (Bradshaw 1997; Liebenberg-Weyers 2010). In the case of the sulfide-enriched stream this means application to alkaline soil to reduce the soil's pH (Castelo-Branco et al. 1999). This improves the soil's chemical and physical characteristics by precipitating sodium, reducing the availability of boron ions and increasing the availability of nitrogen, phosphorus, iron and manganese

(Vlek and Lindsay 1978; Somani 1986; Foth and Ellis 1996; Castelo-Branco et al. 1999). Sulfide-enriched coal waste will also improve sulfur availability in soils. Preliminary assessment indicated that this application shows some promise, since it should be effective in improving alkaline soil conditions in arid regions in South Africa and there is enough alkaline farmland to absorb the material stream. The solution may not be profitable, though, since the material will have to travel large distances from coal mines to regions with alkaline soil. For example, the distance between Upington, where table grapes are grown, and the Emalahleni (Witbank) coal fields is around 930km (Google and AfriGIS (Pty) Ltd 2016). The suitability of this solution will also be impacted by the safety of the material for agricultural applications. This will depend on the coal content as well as the trace element content of the material.

Concluding remarks

This study showed that there are several potential applications for sulfidic coal tailings, with cemented paste backfill and soil amelioration being the preferred options. However, a more detailed scenario analysis showed that cemented paste backfill is unlikely to be viable in the South African context, whilst further developmental work would be required to establish economic feasibility of the soil amelioration option.

The approach presented here for the identification, selection and preliminary assessment of options for the downstream application or re-purposing of sulfidic materials can be applied to a diverse range of mine wastes and supports waste management approaches which remove the ARD generating risk and long-term liability associated with land disposal of these materials. Such waste management approaches are also consistent with the principles of sustainable development and the circular economy and have the potential to contribute to local social and economic development, by stimulating additional business opportunities.

It is, furthermore, recognised that technology transfer is an important activity in the development of environmental technologies for the mining industry, since improving the industry's tangible environmental footprint is the objective. Obtaining commitment and buy-in from potential industrial partners is an important part of the innovation chain and should be undertaken in the early-stages of project development.

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