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Life cycle assessment analysis of active and passive acid mine drainage treatment technologies

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ABSTRACT

Acid mine drainage (AMD), resulting from open-cast coal mining, is currently one of the largest environmental challenges facing the mining industry. In this study, a life cycle assessment (LCA) was conducted to evaluate the environmental impacts associated with the construction, operation and maintenance of different AMD treatment options typically employed. LCA is a well-reported tool but is not documented for AMD treatment systems despite their ubiquitous implementation worldwide. This study conducted detailed LCA analysis for various passive and active AMD treatment approaches implemented or considered at a major coal mine in New Zealand using a comparative functional unit of kg acidity removed per day for each treatment option. Eight treatment scenarios were assessed including active limestone and hydrated lime treatments, and compared to passive treatments using limestone and waste materials such as mussel shells. Both midpoint and endpoint LCA impact categories were assessed. Generally, the active treatment scenarios demonstrated greater LCA impacts compared to an equivalent level of treatment for the passive treatment approaches. Lime slaking had the greatest LCA impacts, while passive treatment approaches incurred consistently less impacts except for one passive treatment with a purchased energy scenario. A 50% reduction in transportation distances resulted in the lowest LCA impacts for all scenarios. This study highlights the importance of evaluating the environmental and social impacts of AMD treatment for the mining industry.

1. Introduction

Untreated AMD negatively impacts thousands of kilometers of waterways worldwide, severely affecting the aquatic and neighboring terrestrial environment, so is recognized as the current largest environmental problem facing the mining industry (Hudson-Edwards et al., 2011). Younger et al. (2002), Watzlaf et al. (2004), and McCauley et al. (2006) describe the relevant mineral dissolution kinetics in great detail.

Active AMD treatment typically incurs chemically dosing with lime [applied as calcium oxide (CaO) or as a slurry of hydrated calcium hydroxide ($Ca(OH)_2$)] to neutralize acidity resulting in precipitation of metals (Brown et al., 2002; Waters et al., 2008; Younger et al., 2002). Active treatment options are a proven and reliable AMD mitigation approach, however their high energy and chemical costs result in high net environmental impacts (Younger et al., 2002). Passive treatments are therefore an attractive alternative since they do not require continual pumping of chemical amendments and can operate more sustainably using biogeochemical processes inherent within engineered biosystems (Younger et al., 2002). For these passive designs, mine water is also typically gravity-fed to minimize pumping requirements otherwise needed to convey AMD. Numerous passive AMD-treatment designs have evolved over the past three decades (Johnson and Hallberg, 2005; Wildeman et al., 2006; Younger et al., 2002). The most common design is a sulfate-reducing bioreactor, which relies on the principle of sulfidogenesis to convert sulfates to sulfides through microbial reduction (Chang et al., 2000; Sheoran et al., 2010). Bioreactors have become one of the most proven passive-treatment options for treating acidity (Doshi, 2006; Gusek, 2002) and metals (Gusek, 2004; Neculita et al., 2007; Wildeman et al., 2006) in AMD. Their biogeochemical conditions treat AMD by using an alkalinity source to mitigate the acidity and carbon sources to sustain the microbial community responsible for metal immobilization. Metals are removed via precipitation as hydroxide complexes, sulfides, carbonates, silicates or sulfates or, sorption to organic matter, carbonates, etc. (Gibert et al., 2003; Gusek, 2002; Lo and Yang, 1998; Waybrant et al., 1998; Zagury et al., 2006). Limestone has been the most common alkaline material utilized in AMD bioreactors, primarily because of its effective dissolution rates, and due to its relative abundance near mine sites (Watzlaf et al., 2004; Waybrant et al., 1998; Wildeman et al., 2006; Younger et al., 2002). However,

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alternative substrate media can be employed such as the waste product mussel shells for highly effective acidity mitigation and wood by-products that provide carbon sources for the microbial communities (e.g. McCauley et al., 2009). These waste products can often be sourced cheaply and potentially locally, thus likely affording a lower environmental impact than mining virgin limestone for the same purpose.

It is commonly assumed that in addition to economic savings, passive AMD treatment will incur lower environmental impacts costs compared to an equivalent active treatment approach, primarily due to the lack of chemical and energy requirements. However, a comprehensive analysis of their net environmental impacts evaluated through sustainability assessments such as LCA has not yet been conducted aside from Tuazon and Corder (2008) who assessed red mud as a treatment option for Australian mines by employing LCA tools. This study found that although the alternative material, in their case seawater neutralized red mud, was a very effective and environmentally friendly AMD treatment approach, issues with the transport and treatment efficiency of the red mud introduced some serious potential obstacles for large scale usage. Our results, discussed in Section 5, reflect these issues as they pertain to our study.

LCA provides a 'sustainability audit' through a 'cradle to grave' assessment of all products and processes. LCA modeling has numerous applications in determining the long term, indirect and cumulative impacts of human actions, and has been applied to building design (Ligthart et al., 2010; Mithraratne and Vale, 2004), agricultural production (Beauchemin et al., 2010; Haas et al., 2001; Stone et al., 2010), biofuel production (Cherubini et al., 2009; Davis et al., 2009), and industrial applications (Graedel and Allenby, 2010), metal production (Norgate and Lovel, 2004), and aspects of the mining sector (Norgate and Haque, 2010). Project financial aspects may also be incorporated within an LCA using the Carnegie–Mellon Economic Input–Output Life Cycle Assessment Tool (EIO-LCA, 2008). However, in practice a cost-benefit analysis of the different options would likely be considered in parallel before implementation by the industry.

This research compared the environmental impacts over the life cycles of several implemented and optional AMD treatment methods, incorporating both passive and active approaches employed at Stockton Coal Mine in New Zealand, a site with a wealth of treatment data and knowledge regarding historical AMD challenges (McCauley, 2011; McCauley et al., 2008).

2. Methods

Life cycle assessments were conducted for both active and passive AMD treatment systems using the SimaPro 7.3 LCA modeling software (PRé Consultants, Netherlands) and life cycle inventory EcoInvent (Swiss Centre for Life Cycle Inventories, Switzerland) database (Frischknecht et al., 2007), and the EcoInvent Australasian LCI Database (Australasian-LCI, 2011) following ISO 14040:2006 and ISO 14044:2006 protocols (Finkbeiner et al., 2006). A total of 7 different scenarios were modeled, including five active and two passive treatment systems. A summary of all components and their amounts in each treatment design along with the system abbreviations is provided in Table S1.

2.1. System boundary

A general system boundary for modeling the LCA of each system is shown in Fig. 1, while detailed system boundaries for each treatment scenario are provided in Figs. S1–S6. The system boundaries encompass all substantial components and processes used in each of the treatment scenarios, encompassing raw materials including extraction and processing for mined materials, transportation for all materials, construction including earth excavation and/or substrate emplacement, and process energy required for pumping and processing. For all scenarios, infrastructure processes were not included in the LCA model. These infrastructure processes apply specifically to the infrastructure associated with the production of materials, production of transportation methods, or production of pumping mechanisms. All infrastructure relevant to the treatment approaches was included, such as piping utilized in P-BME or A-LD. Human labor hours associated with operation and maintenance of the systems were also not included, as these pertain more to social issues than environmental issues (Cotton-Incorporated, 2012). For the 'waste products' materials from other industries (i.e. mussel shells), no manufacturing or use process energy was included (since these products did not undergo any modification) and thus their system boundary began with transporting them to the study site.

2.2. Functional unit

The scenarios were all normalized using a functional unit of 1 kg of acidity neutralized per day as the basis of comparison. A 16.9 yr design life was assumed for all passive and active treatment scenarios. This design life was based on laboratory-determined limestone dissolution rates for the AMD at the mine site (700 mg/L acidity fed at 2.29 L/s) determined by McCauley et al. (2009). This acidity loading equated to 85.2 kg acidity as $CaCO_3$ per day neutralized by each passive treatment system with the exception of the mussel shell leaching bed, which only neutralized 11.53 kg acidity as $CaCO_3$ per day, based on an influent flow rate of 0.31 L/s and identical acidity loading parameters to the bioreactors. Acidity loading rates for the active treatment systems were much higher, at 17,808 kg acidity as $CaCO_3$ per day, due to their higher treatment efficiencies.

2.3. Site description

The majority of AMD-impacted streams in New Zealand are located on the West Coast of the South Island within estuarine coal formations. The Stockton Coal Mine on the West coast of the South Island was the basis for this study due to a wealth of data and knowledge regarding historical AMD challenges at this site (McCauley, 2011; McCauley et al., 2008). It is the largest opencast coal mine in New Zealand with an active mining area of ~900 ha and is expected to have AMD treatment issues for the next 100 years. Stockton Mine AMD is characterized by low pH and high concentrations of iron and aluminum, typically accounting for >98.0% of metals (on molar basis) (McCauley et al., 2008). To date, the primary method of treatment has been utilizing ultra-fine limestone (UFL), while more recent studies have investigated lab and field based passive bioreactor and leaching bed systems, which utilize mussel shells as an acidity neutralizing agent instead of limestone (Crombie et al., 2013).

3. Treatment scenarios

A total of seven scenarios were modeled including both passive and active treatment systems (Table 1). The passive systems included a gravity-fed AMD bioreactor utilizing mussel shells as the primary substrate (P-BM); a bioreactor with limestone (P-BL); a bioreactor identical to P-BM, pumping AMD into the system (P-BME); a bioreactor identical to P-BM, but with a 50% reduction in transport distances for all materials (P-BMT); and a mussel shell leaching bed (P-LB). The active treatment systems included ultrafine lime-dosing (A-LD), and lime slaking (A-LS). Inventory summaries of material inputs for the seven treatment scenarios are provided in Tables S1 and S2. Sizing of each system was based