Proceedings Tailings and Mine Waste 2015
Vancouver, BC, October 26 to 28, 2015

Combined tailings and mine waste

Bryan Ulrich
Jeff Coffin
Knight Piésold and Co., Denver, USA

ABSTRACT

The benefits of combining tailings and mine waste in a relatively homogenous manner, in which tailings just fill the voids between the waste rock particles while the waste rock maintains particle-to-particle contact, has been the subject of study over the course of several years. Such a combination of materials could be used for a closure cover or as a singular large-scale facility to store both mine waste products. The possible benefits of this combination of materials include the creation of a deposit with the footprint smaller than two dedicated facilities, the shear strength of waste rock, the permeability of tailings, low oxygen diffusion rates, and theoretically a decreased potential to develop and emit acid rock drainage. If properly combined and placed, such a landform may be constructible with steep stacking angles, and it may exhibit a low potential for liquefaction. The authors briefly discuss previous work by others and provide information regarding some recently completed advances in this methodology.

1 INTRODUCTION

There are many challenges in typical mining operations, mine waste management being one such challenge. Mine waste storage facilities require stable long-term physical and geochemical containment in a manner that is acceptable based on appropriate regulatory requirements and that demonstrates good stewardship practices.

As current and planned mining operations are becoming larger and larger, alternative methods of mine waste management need to evolve to keep stride with increasingly demanding mine plans. Several mine waste management practices are currently successfully employed, including conventional tailings storage facilities that receive conventional slurried tailings. Such facilities, if designed, constructed and operated correctly, will serve the industry well into the future in the appropriate environments. The same can be said for the storage of waste rock in dedicated facilities, or when allocated to form portions of the impounding embankments for a conventional tailings storage facility (TSF). If acid rock drainage (ARD) is anticipated either from the tailings or the waste rock, there can be additional challenges, especially when developing closure plans that must function into perpetuity. One way ARD can be mitigated is to prevent oxygen from coming into contact with the ARD-prone mine waste reducing oxidation potential. One example that can be used to achieve this goal is a “wet cover” either for waste rock (i.e., placed in a pit lake) or tailings (i.e., a water cover). In certain environments those applications can be very successfully designed and constructed. Another potential application that can prevent oxygen from entering into waste rock is to combine tailings and waste rock, where the voids between waste rock particles are just filled with tailings thereby effectively saturating the combined mass and reducing air-infiltration potential.

The potential advantages offered by a well-blended mixture of tailings and waste rock, where the tailings just fills the voids between waste rock particles, includes:

- Reduced footprint
- Shear strength like waste rock
- Permeability like tailings
- Low oxygen diffusion rates
- Reduced ARD potential
- Improved permitting timeline

- Better public acceptance
- Improved closure opportunities
- Improved Access to Tailings Surface: Reduced Perpetual Liability of Tailings Impoundment

1.1 Background: Unsolved Problems in Mine Waste Management

Most recent studies of tailings and waste rock mixtures justify their research as part of the ongoing search for practical solutions to the environmental challenges caused by tailings and waste rock disposal. The problem is significant, given that the "global cost for environmental liability associated with ARD is estimated to be in the order of $100 billion" (Wilson, 2008). Ideally, waste rock and tailings could be placed so that they weather into perpetuity with a release of potentially harmful constituents into the environmental at a rate no greater than they would have if they had not been excavated. While this seemingly utopian goal may be quite challenging to reach, if not altogether infeasible, there are no demonstrated designs for "dry" closure of mine waste that provide perpetual environmental stabilization of metal and ARD release without perpetual management and/or treatment of captured effluent.

1.1.1 General Discussion of Waste Rock

The term "waste rock" is often applied to a broad range of materials and can have a broad range of characteristics. For example, waste rock from a coal mining operation may consist predominately of shale. Hard rock mining may produce hard, durable waste rock. Mine overburden is often also termed waste rock. The characteristics of waste rock are quite important to the design of combined tailings and waste rock; however for brevity their behavior will not be expounded upon to any great detail herein.

1.1.2 Tailings

Tailings can exhibit a wide range of characteristics depending on the nature of the host rock from which it was derived, and the process it is subjected to during minerals recovery. Tailings can be sandy or clayey, coarse or fine-grained, dilute, thickened or prepared into a filter cake. For example, tailings from kimberlite operations are vastly different than tailings from phosphatic clay operations. The behavior of tailings is quite important to the study of combined tailings and waste rock. However, such characteristics are commonly presented by others and will not be repeated herein for the sake of brevity.

Environmental risks from tailings fall into two broad categories: Structural failure of impoundments, which may include short-term catastrophic impoundment failures and the associated risks to life and property but also the long-term erosional loss from dams; and chemical releases, where constituents present in the original pore water, with or without solutes added by the oxidation of sulfide minerals, leaching from the tailings by meteoric water percolation and degrading receiving waters. As the comments below indicate, the physical and chemical characteristics are tightly interrelated, and the recurring themes are reclamation, impoundment stability, and the dilemma of long-term management.

1.1.3 Chemical Stabilization of Mine Waste

Chemical stability in tailings with residual sulfide minerals is best managed by maintaining near saturation. Because oxygen has very low mobility in water (i.e., in water, oxygen has ~1/30th the volumetric concentration and 1/10,000th the diffusivity relative to air), there is essentially no sulfide mineral oxidation in water-saturated tailings. As a result, "in many cases a water cover must be maintained over tailings to ensure they do not 'turn acid'" (Wickland and Wilson, 2005). Unfortunately, the design options for chemical and physical stability in tailings can be in direct opposition: "Geotechnical stability competes directly with geochemical stability in that the prevention and control of sulphide oxidation requires full saturation while maximizing shear strength requires full drainage" (Wilson 2008). Challenges the closure of ARD-prone tailings exhibit includes:

a. "In humid climates with positive water balances, ensuring an adequate supply of water to maintain a sufficient depth of water is not a concern, but the risk of overtopping during severe storm events is a very serious threat. Water covers that have been used in semi-arid such as Portugal and Spain are proving to be unsustainable following closure since an excessively large water sheds must be available to replenish water losses due to high evaporation." (Wilson et al., 2010)

b. "Waste rock facilities created by end dumping develop an internal structure associated with segregation producing coarse and fine layers with a high permeability rubble layer at the base (Wilson, 1995; Herasymiuk, 1996; Wilson et al, 2000; Fala et al, 2003)". "The combination of unsaturated soil conditions and the interbedded structure [in waste rock] creates ideal conditions for weathering of the waste rock through geochemical and biological pathways. Sulphide oxidation and acid generation often begins during the construction of waste rock dumps and results in long-term acid drainage."

In response, environmental management options for sulfide bearing waste rock often focus on reducing oxygen, water, or both.

Closure covers have been shown to reduce, but not eliminate, water and oxygen transport into waste rock. Excavated rock begins oxidizing as soon as it is exposed to the environment, and after that oxidation, products are either stored in the waste rock matrix or flushed out by precipitation infiltration. Covers that reduce percolation rates produce an approximately proportional reduction in discharge load. Examples would include low conductivity layers or store-and-release vegetated caps. A limitation is that covers of natural material, such as vegetated store and release surface layers, typically achieve only a slight reduction in oxygen transport, so that pollutants accumulate in the pile and are leached out over a longer period of time. This experience led Ward Wilson to conclude that "in general, cover systems have been shown to be most successful for the reclamation of tailings and least successful for the closure of waste rock dumps" (Wilson 2008).

2 CONCEPTUAL OVERVIEW OF BLENDING TAILINGS AND WASTE ROCK

The goal of blending tailings and waste rock is to create a material that has the high strength of waste rock and the hydraulic characteristics of tailings. In this mixture, tailings in the void space between rock particles is considered to reduce the opportunity for oxygen flow (and ARD), while the coarse waste rock skeleton is relied upon to provide shear strength for mechanical stability (Khalili et al., 2010).

Effective oxygen diffusivity in porous media decreases steeply with increasing moisture content, so that media with greater than ~85 percent saturation is a very effective barrier to oxygen diffusion (refer to Figure 1 below from the GARD Guide, [INAP 2009]). Thus the desired hydraulic characteristics of well-blended tailings and waste rock include low hydraulic conductivity, reducing flushing rates of solutes due to meteoric infiltration or long-term draindown; and high values for moisture retention and high air entry pressure, both of which encourage high water saturation long-term (Wickland et al., 2006; Khalili et al., 2010; Wilson 2008). These are conditions typical of fine tailings.

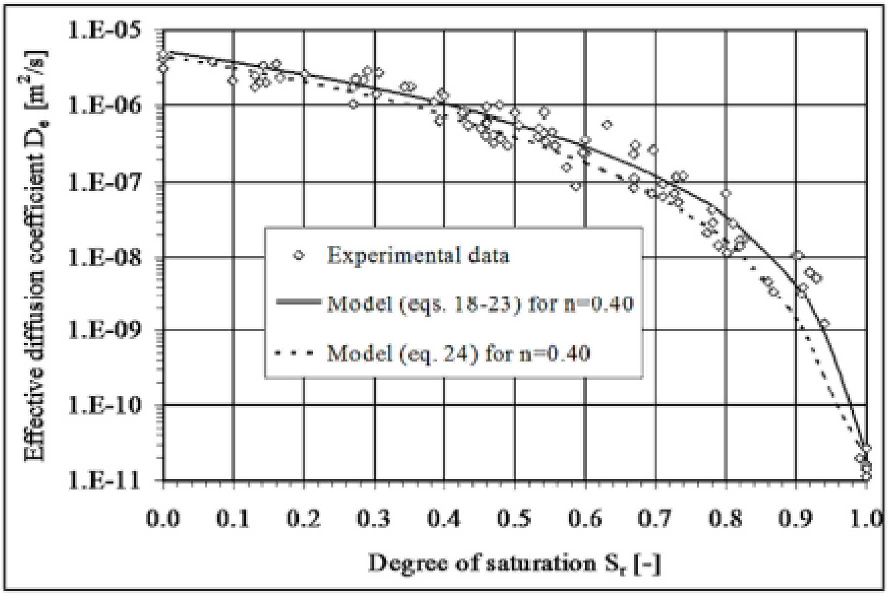

Figure 1. Relationship Between Degree of Saturation and Oxygen Diffusion for Porous Media, (INAP, 2009, Used With Permission)

Ideally, the blended tailings and waste rock philosophy is based on an optimal ratio of coarse waste rock to fine tailings, which is the ratio where tailings just fill the voids of the waste rock, that the blended material has compressibility and shear strength similar to waste rock, hydraulic conductivity and moisture retention characteristics of tailings, and higher density (and lower voids ratio) than either end member. (Wickland et al. 2005; Longo and Wilson, 2007).

A more recent study was conducted to assess, more specifically, the cyclic failure of blended tailings and waste rock materials by measuring cyclic shear response in undrained conditions for waste rock blended with tailings to just fill the rock voids (see Wijewickreme et al., 2010). Results indicate no strain-softening or loss of shear strength, suggesting that the material is unlikely to experience flow failure under undrained cyclic loading. Thus, in this particular case, a blended tailings and waste rock mixture would be much less prone to structural failure during and after earthquake loading than tailings alone.

Wickland et al. (2006) developed approximate mixing guidance indicating that blends of materials with mixing ratios greater than approximately 5:1 (waste rock:tailings mass) will contain air because the volume of tailings slurry is less than the volume of voids in the waste rock. This 5:1 mixture that just fills the waste rock void space also corresponds to the point of maximum density in these tests.

Table 1. Typical Values of Porosity

Parameter	Conv. Slurried Tailings	Compacted/ Filtered Tailings	Waste Rock
Particle SG	2.65	2.65	2.65
Dry Density (t/m^3)	1.0 – 1.4	1.4 – 1.8	1.4 – 2.0
Void Ratio	0.8 – 1.5	0.5 – 0.8	0.5 – 0.8
Porosity, pct	50 – 60	35 – 45	35 – 50

Porosity: ratio of volume of voids to total volume (times 100%)
Void ratio: ratio of volume of voids to volume of solids

An example of the effects of the varying the mixing ratio is provided in Figure 2.

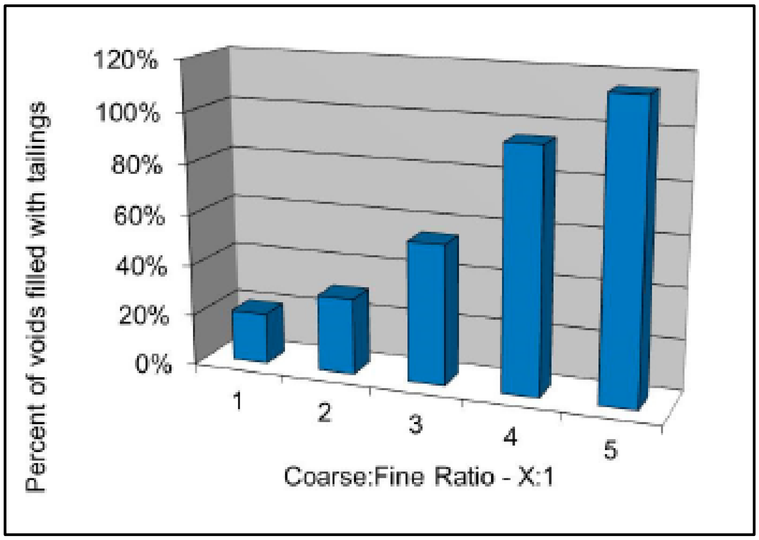

Figure 2. Example of the Effects of Varying the Coarse-to-Fine Ratio

3 LABORATORY TESTS OF BLENDED MATERIALS

There are several types of geotechnical and geochemical tests that should be carried out when assessing the properties and parameters associated with blended tailings and waste rock, depending on the stage of design being completed. For geotechnical design, such tests may include procedures to quantify hydraulic continuity (permeability), compaction, compressibility, shear strength and liquefaction susceptibility.

For a recently completed project, demonstration tests were carried out using mine tailings and a temporary “stand-in” material to represent waste rock. In this case, the waste rock was represented by decorative marble landscaping gravel, which is commonly available in many lawn and garden stores. This type of marble is fairly uniformly graded, whereas waste rock is more typically broadly graded. For these tests, the marble gravel was subject to crushing in an LA abrasion machine (which is similar to a small ball mill) until a fairly broadly-graded material resulted. The tailings and “waste rock” were subject to a series of tests, including compaction testing using both the standard and modified Proctor tests. The results of those tests are shown in Figure 3 and 4.

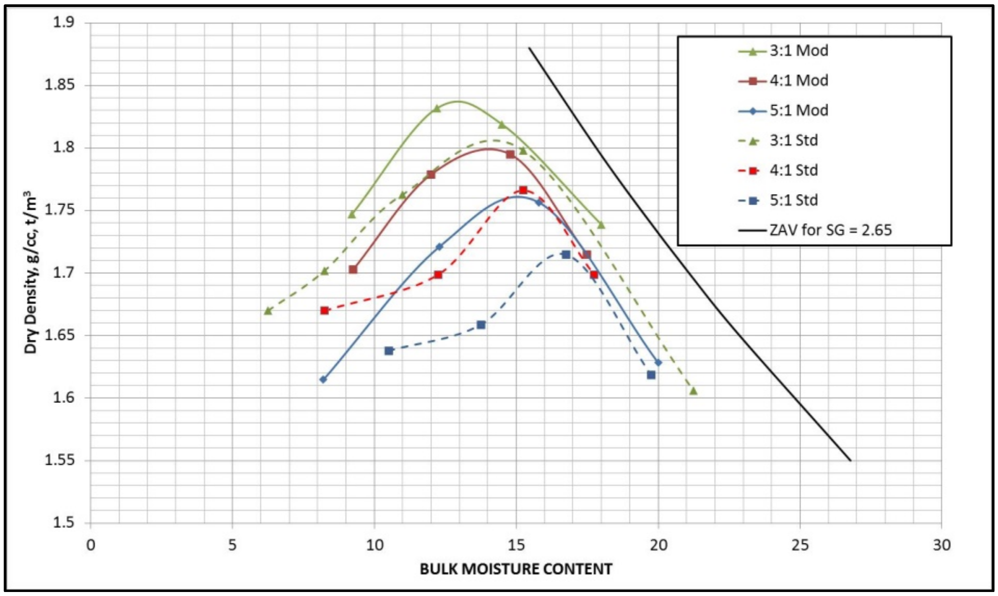

Figure 3. Results of Compaction Tests Using Standard and Modified Proctor Methods

The same test results may by reconfigured to relate tailings solids content to saturation, as shown in Figure 4.

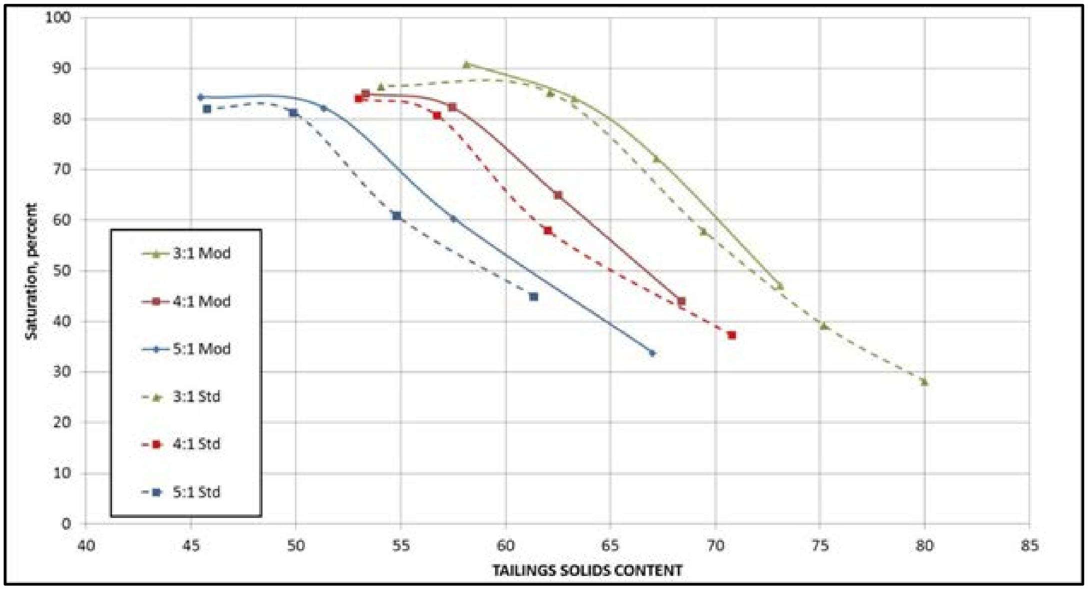

Figure 4. Comparison of Tailings Solids Content to Saturation from Standard and Modified Proctor Tests

For the sake of brevity, the remaining test results are not provided in this paper.

4 PRACTICAL BLENDING CONSIDERATIONS

A review of co-disposal options (see Leduc et al. 2004, as cited in Wickland et al., 2006) identifies the following options for blending:

- Injection of tailings into a waste rock pile,
- Placing tailings in trenches within a waste rock pile,
- Combined tipping at the dump faces,
- Dumping waste rock along with tailings in an impoundment,
- Placing waste rock and tailings in the same depression,
- Pumped slurry of comingled waste (mainly used in coal applications), and
- Active mixing of waste rock and tailings immediately prior to disposal.

Only the last two of these appear to be viable technologies for producing blended tailings and waste rock mixtures that are homogeneous enough to consistently meet the design requirements for moisture retention and strength.

Pumped co-disposal was identified early as a means of creating an ideal ratio of rock to tailings so that during hydraulic deposition the coarse particles settle out in a “just-touching” configuration and that fine particles “just fill” the void space between the larger coarse particles (Williams, 1998; Morris and Williams, 2000b). In practice, these examples above (e.g., for coal mine waste) are limited, and “typically use mixture designs with lower than ideal mixture ratios [i.e., less coarse rock] at low solids contents to prevent plugging and wear on piping and pumps” (Williams, 1998). Also, “the largest size that can be pumped is... typically around 10 cm diameter” (Wickland et al., 2006). In contrast, a more optimistic paper on blended tailings and mine waste alleviates the concern over particle segregation, noting that the use of tailings thickened to the consistency of paste moves through a pipeline as a plug flow (Longo and Wilson, 2007).

In the Active Mixing approach the two constituents are mechanically blended at the point of deposition to produce a design mixture, as is done in design of concrete. A small-scale example of this is the blending of waste rock and tailings using a concrete mixer truck for the 5.5 m tall column test study (Wickland and Wilson, 2005). An important comment from that work is that there is a lack of means of making mixtures of this type in a large-scale. Wickland et al. (2006) conclude that although active mixing has been proven to produce mixtures with beneficial properties, it is expected that the effort required would make this method cost-prohibitive in a mining context. Thus a means of mixing these materials at the rates they are produced at a mine is needed in order to advance this application.

5 STATIC MIXING DEVICE

As part of a recently completed project, blended tailings and waste rock was studied as a waste management option. If such a blend could be achieved, challenges brought on by steep terrain could potentially be overcome, as the available terrain was too steep to reasonably construct a conventional TSF, and tailings production throughput was thought to be too great for the use of filtering technology. As others have found, conventional mixing apparatuses (such as agglomerators, flow-through ball mills, pug mills, continuous cement mixers) do not exist in a scale large enough to accommodate the mine waste produced at most large-scale mining operations. Given this challenge, the use of a non-mechanized, static mixing device was investigated. In general, there are two types of static mixers: Channel mixers and pipeline mixers. Both types of mixing devices include element that disrupt the flow of materials as they flow through the mixer. For the current assessment, the channel-type static mixing device is being pursued.

Paterson and Cooke of Golden, Colorado was approached to help develop a laboratory-scale device. The device was constructed in order to conduct proof-of-principle testing. The device is shown in Figure 5.

Figure 5. Photograph of Laboratory-Scale Static Mixing Device

Shown in Figure 5 is the static mixing device. The materials being tested in the first tests are concrete sand and pea gravel. Initially the materials were placed into the device at a ratio of about 1:1 (pea gravel to sand), but later at a ratio of about 4:1 to better mimic mixing ratios desired in blends of waste rock and tailings. The tests offered encouraging results, which may be observed in Figure 6.

Figure 6: Static Mixing Device Showing Mixing of Materials

The results of the tests using pea gravel and concrete sand were considered successful to homogenously blend two different materials, and a second series of tests was conducted using tailings slurry and pea gravel, the results of which can be seen in Figure 7.

Figure 7. Results of Tests Using Tailings Slurry and Pea Gravel

The results shown in Figure 7 were achieved using a more continuous feed of tailings and pea gravel, the means of which are shown in Figure 8.

Figure 8. Static Mixing Device with Continuous Feed

The demonstrations of the static mixing device offer encouragement. The device repeatedly demonstrated that dissimilar materials could be blended into a relatively homogeneous mixture, indicating that this application may offer a solution for mixing materials on a larger scale. Knight Piésold is now perusing projects where a field-scale device could be developed to further provide a proof-of-principle, but at larger scales.

6 ACKNOWLEDGMENTS

Knight Piésold would like to thank Mr. Robert Cooke and other contributors of Paterson and Cooke in Golden Colorado for developing and demonstrating the static mixing device.

7 REFERENCES

The International Network for Acid Prevention (INAP), 2009. Global Acid Rock Drainage (GARD) Guide, www.gardguide.com (viewed September 7, 2015).

Khalili, A., Wijewickreme, D., Wilson, G. W. 2010. Mechanical response of highly gap-graded mixtures of waste rock and tailings. Part I: Monotonic shear response, *Canadian Geotechnical Journal, Volume 47(5), pp. 552-565.*

Longo, S. and Wilson, W. 2007. Paste Rock: Part of the Future for Mine Waste Management? *Canadian Mining Journal, Oct. 2007, 128 (8), Pg. s4-s25.*

US EPA. Guidance for Conducting Remedial Investigations and Feasibility Studies under CERCLA, Interim Final, *EPA/540/ G89/004. U.S. Environmental Protection Agency, 1988*. http://www.epa.gov/superfund/action/guidance/remedy/rifs/overview.htm

Wickland, B.E., Wilson, G W., Wijewickreme, D., Klein, B. (2006). Design and evaluation of mixtures of mine waste rock and tailings. *Canadian Geotechnical Journal, Volume 43 (9), pp. 928-945.*

Wickland, B. E., and Wilson, G.W. (2005). Self-weight consolidation of mixtures of mine waste rock and tailings. *Canadian Geotechnical Journal, V 42 (2), pp. 327-339.*

Wijewickreme, Dharma; Khalili, Ali; Wilson, G. W. 2010. Mechanical response of highly gap-graded mixtures of waste rock and tailings. Part II: Undrained cyclic and post-cyclic shear response. *Canadian Geotechnical Journal, Volume 47(5), pp 566-582, doi: 10.1139/T09-122.*

Williams, D.J. 1998. Depositional behaviour of coal tailings, co-disposed coal washery wastes, and loose-dumped coal reject. In: Proceedings of Minefill '98, the 6th International Symposium on Mining with Backfill, 14-16 April 1998, Brisbane, QLD. The Australasia Institute of Ming and Metallurgy (AusIMM), Carlton Victoria 3053, Australia, pp. 341-346.

Wilson, W., 2008. Why Are We Still Struggling Acid Rock Drainage? *Geotechnical News, June 2008*. pp. 51 - 56: http://www.infomine.com/publications/docs/Wilson2008.pdf

Wilson, G.W., Miskolczi, J., Dagenais, A.M., Levesque, I., Smith, Q. Lanteigne, L, Hulett, L., and Landriault, D. 2006. The application of blended waste rock and tailings for cover systems in minewaste management. In: 7th International Conference on Acid Rock Drainage, March 26 – 30, 2006, St. Louis Mo. Published by Am. Soc. Of Mining and Reclamation.