Rock Dumps 2008 — A. Fourie (ed)
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https://papers.acg.uwa.edu.au/p/802_9_Wilson/

Design and Performance of Paste Rock Systems for Improved Mine Waste Management

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Abstract

Waste rock and tailings can be blended to produce an engineered material with superior physical and hydraulic properties for the construction of post mining landforms. The new material, termed paste rock has a low hydraulic conductivity, high water retention capacity (air entry value), high strength and low compressibility. These properties can be used to restrict oxygen entry and water seepage into mine waste deposits for minimising oxidation and metal leaching within sulphide bearing materials. The new material also has a density much higher than either conventional tailings or waste rock deposits, thereby reducing the total volume of waste and creating opportunities to reduce surface area requirements for impoundment design and construction.

Laboratory testing, meso-scale experiments and field scale trials using selected blends of waste rock and tailings were constructed between 2000 and 2007 at the Porgera mine, PNG and the Copper Cliff mine, Canada. Results show that hydraulic conductivity values for paste rock mixtures comparable to consolidated paste tailings (i.e. 10^{-7} m/sec to 10^{-8} m/sec) with volume change characteristics similar to waste rock can be achieved. In addition, field scale lysimeter measurements demonstrate infiltration and drainage rates are reduced by almost 2 orders of magnitude when paste rock is used to construct cover systems on tailings. The present paper summarises the key findings for the seven year study and describes implementation of the new technology into mine waste practice.

1 Introduction

Paste rock is a new method for the disposal of tailings and waste rock that involves full blending of the two materials to a specified mix design followed by deposition of the material in a single repository. Conventional mine waste management systems produce both wet and dry waste steams. The wet tailings stream is commonly discharged as slurry that produces a segregated deposit with problematic drainage and seepage conditions, low shear strength and slow consolidation properties. Impoundment design for slurry tailings is generally controlled by physical issues. The primary design philosophy is capacity, stability, containment and safety. However, numerous failures in tailings impoundments, such as Merriespruit, Omai, and Los Frailes to name a few, have occurred in recent times and it can be broadly stated that the primary concerns with tailings impoundments remain rooted in physical instability. In contrast, the dry waste rock stream offers high shear strength with excellent physical stability characteristics and thus the material is routinely disposed of in large waste rock dumps constructed above the natural ground surface. While run-out failures in high, over-steepened dumps may occur, waste rock dumps typically form steep topographies with high stability.

The hydraulic properties of waste rock together with surface hydrology, internal structure and topography result in unsaturated conditions within waste rock dumps. Waste rock dumps constructed with tip faces greater than 4 to 6 m develop an internal structure associated with segregation producing coarse and fine layers with a high permeability rubble layer at the base (Herasymuik, 1996; Wilson et al., 2000) as shown in Figure 1. The combination of unsaturated soil conditions together with the interbedded structure 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 the rock dumps and results in long-term acid drainage and metal leaching, or other problems associated with neutral drainage and salinity.

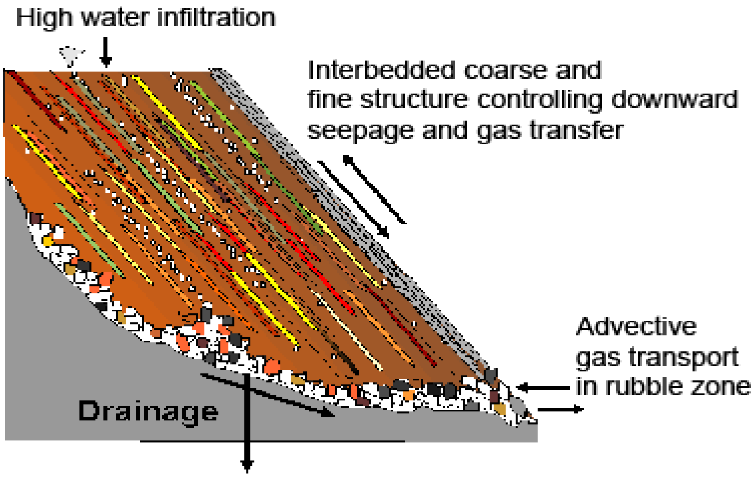

Figure 1 Primary transport mechanisms for reactive rock dumps

Oxygen entry is dramatically reduced for tailings since the fine grained texture of tailings offers hydraulic properties that maintain high water saturation and blocks gaseous oxygen diffusion. Fine grained tailings also offer low hydraulic conductivity values that reduce seepage rates. The purpose of the studies described herein were to investigate the hypothesis that the integration or blending of tailings with waste rock could produce deposits that are self-sealing, thus minimising infiltration, gas transport, oxidation and associated drainage problems.

2 Field investigations

Two extensive field investigations, beginning in 2000, have recently been completed to investigate the properties of mixtures of tailings and waste rock to form the new material now referred to as “paste rock”. The first field study was carried out at the Porgera mine, PNG with the second study completed at the Copper Cliff mine in Sudbury, Canada. The Porgera study, which has been described in detail by Wickland (2006) involved the construction of meso-scale columns with selected mixtures of carbon in pulp (CIP) gold tailings and waste rock. Five large field scale lysimeters were constructed for the Copper Cliff experiment to test the sealing characteristics of blended waste rock, slag and tailings to form cover material, and is described by Miskolczi (2007). A summary of the field and laboratory testing for each research project is presented in the following sections.

2.1 Porgera meso-column experiment

The meso-scale column experiment conducted at the Porgera mine consisted of filling of four 1 m diameter x 6 m high columns, as shown in Figure 2, with various mixtures of CIP tailings and waste rock. One column contained unmixed waste rock while the remaining three columns had average mixture ratios of 5:1, 6:1, and 7:1 based on dry weight of rock to tailings. The CIP tailings were thickened to a solids content of approximately 42% and blended with the waste rock using a transit mixer. All waste rock was hand scalped to minus 150 mm to ensure oversize particles did not influence measurements obtained within the 1 m diameter specimens. Figure 2 includes inserts (clockwise from bottom left): the waste rock used for blending, the skip used to load to columns, the 5:1 blended paste rock at the time of placement, and finally a dissection of the 5:1 blend after approximately 18 months at the conclusion of the experiment.

Instrumentation including electric and pneumatic piezometers to measure porewater pressures, tensiometers to measure matric suction, and magnetic sensors to measure settlement were used to observe performance. A free drain with a constant water table was established at the base of each column and flow rates were monitored with respect to time. Precipitation at the Porgera mine is approximately 3000 mm annually and the unmixed waste rock specimen was left open to infiltration to monitor drainage water quality (not reported here). A zero flux boundary condition was established in the three remaining columns to observe consolidation, drainage and saturation profiles under increasing suction induced by long-term drainage.

Figure 2 Construction of the meso-scale column experiment at Porgera mine

2.1.1 Meso column results

A critical question with respect to the deposition of paste rock relates to the development of strength, so that it can be used to construct self supporting earth structures with similar configurations to rock dumps, while at the same time providing the ability to maintain high saturation and minimise oxygen entry. The primary purpose of the meso-scale column experiment was to observe the consolidation and drainage characteristics of the paste saturated rock matrix following deposition, as well as the capacity to maintain saturated conditions under negative water pressures above a water table.

Figure 3 presents a summary of the measured porewater pressures following deposition of a 5:1 paste rock mixture within the 6 m profile of the column. It can be seen that the initial excess porewater pressure distribution measured 1 hr (i.e. 0.05 days) after deposition decreases by more than 50% within 8 days and continued to drain to relatively small values after 4 weeks of drainage. Negative porewater pressures can be seen to develop after 125 days of continuous drainage with the water table fixed 5.5 m below the surface the profile. It should be kept in mind that while free downward drainage was maintained at the base of the column, a lid was placed on the top of the column to prevent evaporation as well as infiltration during precipitation events.

The meso-scale column experiments conducted in the field were support by a laboratory test programme completed at the University of British Columbia. Figure 4 presents the particle size distribution for an idea mixture of waste rock and tailings computed on the basis of particle packing theory (Wickland, 2006). The idea mix ratio was determined to be 4.3:1 (slightly less than that achieved during mixing in the field) in order to create a just filled condition for tailings within the voids of the waste rock. Figure 4 compares the particle size distribution for the waste rock, with less than 2% passing the 75 um sieve, and the CIP tailings having 100% passing the 75 um sieve. It can be seen in Figure 4 that the particle size distribution for the 4.3:1 mixture of rock and tailings is shifted to a finer material with approximately 20% passing the 75 um sieve. This increase in the fines content for the paste rock produces a dramatic reduction in hydraulic conductivity as well as an increase in the water retention capacity of the material, while at the same time maintaining the strength and compressibility characteristics of the waste rock since more than 2/3rd of the particles are gravel size and coarser.

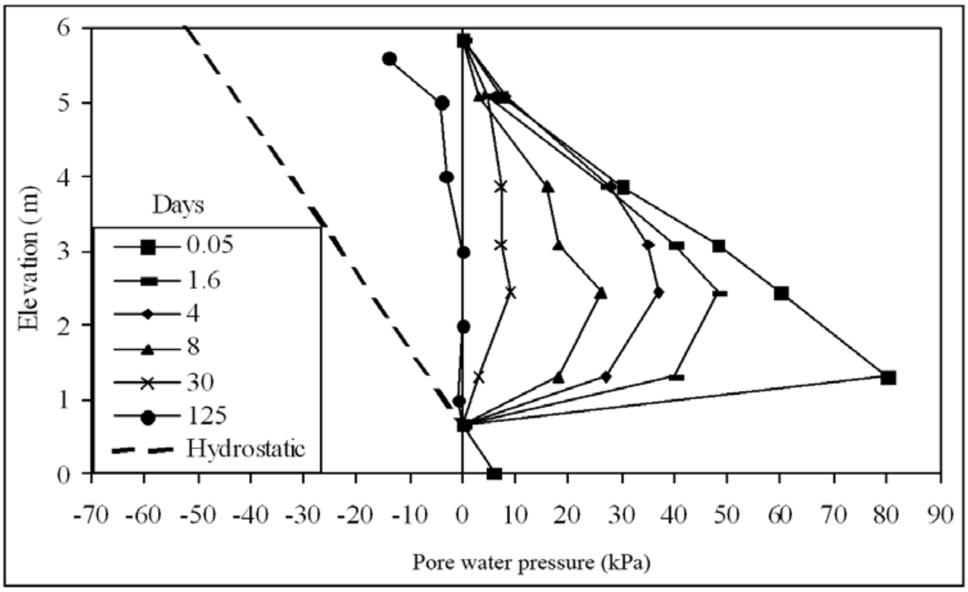

Figure 3 Pore water pressure measurements in the meso-scale column for the 5:1 mixture

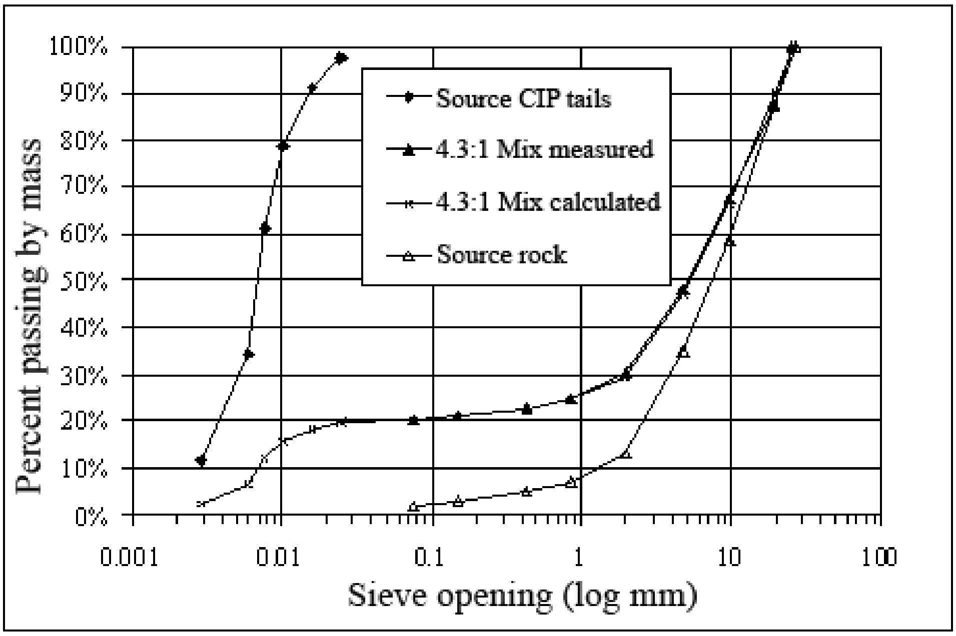

Figure 4 Typical particle size distributions for laboratory paste rock mixtures

Figure 5 presents the soil water characteristic curves (SWCC) for the waste rock, the tailings and a typical paste rock mixture. It is difficult to determine the air entry value (AEV) for tailings since the material under goes large volume change due to consolidation, but it generally can be considered to be greater than 200 kPa. Alternatively, a very low and distinct AEV of about 0.02 kPa can be seen for the waste rock and that the material is virtually fully drained at values of matric suction exceeding 1 kPa. The AEV shown for the black sedimentary waste rock used for all testing is typical of most waste rock materials and helps illustrate the mechanism that causes waste rock dumps to maintain low saturation and high air permeability for oxygen entry.

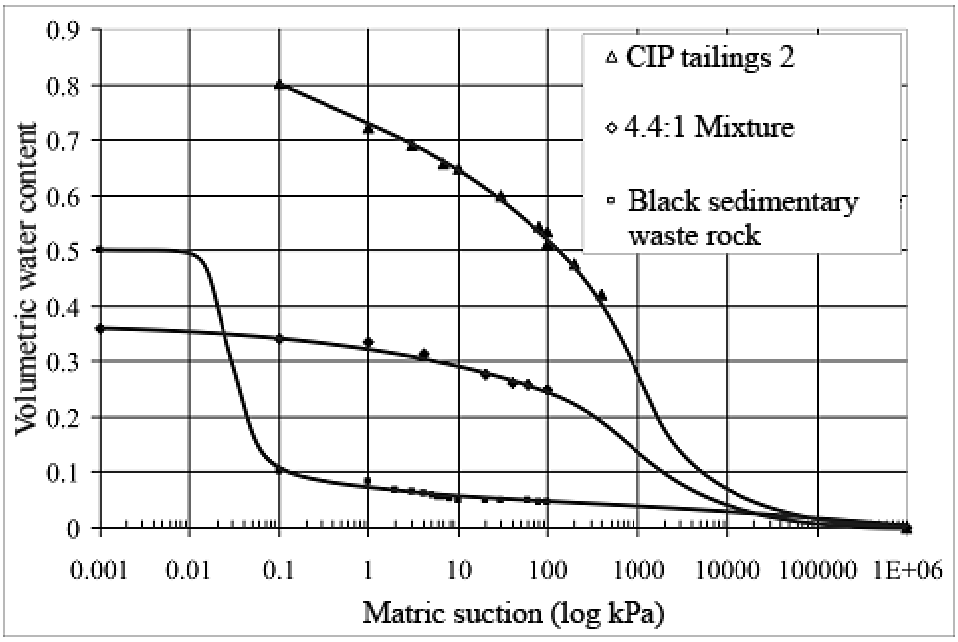

Figure 5 **Soil water characteristic curves for waste rock, tailings and a paste rock mixture**

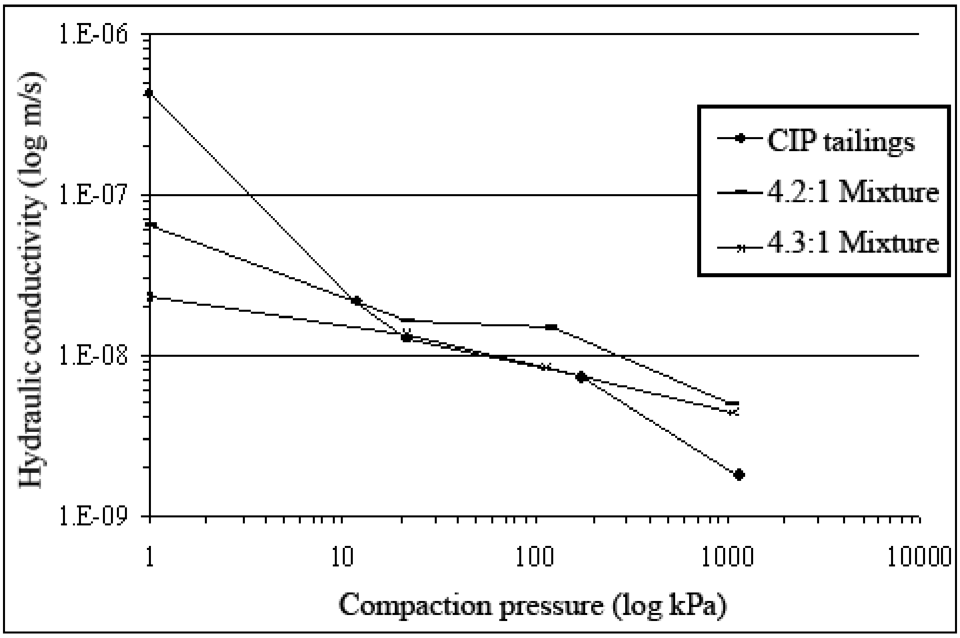

Figure 6 **Hydraulic conductivity verses confining pressure for CIP tailings and paste rock mixtures**

Figure 5 also shows the SWCC for a 4.4:1 paste rock mixture. It can be seen the AEV for the paste rock is dramatically increased to a value in the order of 100 kPa, compared to 0.02 kPa for the unmixed waste rock. Figure 6 shows the hydraulic conductivity measured for the paste rock mixtures versus confining or compaction pressure. The hydraulic conductivity of the paste rock is typically in the range of 1 x 10^{-8} m/sec at low to intermediate pressures, which is similar to the CIP tailings. Falling head hydraulic conductivity tests were also conducted over the entire length of the specimens within meso-scale columns, and a value of 1 x 10^{-8} m/sec was also measured for the 5:1 paste rock mixture, which is seven orders of magnitude less than the hydraulic conductivity for the unmixed waste rock that was determine to be 2 x 10^{-1} m/sec.

The results for the meso-scale column field experiments and laboratory test programme show that the mixtures of tailing and waste rock produce a paste rock material with hydraulic conductivity and air entry values similar to consolidated tailings. In other words, the blended material takes on the hydraulic properties of tailings, thus forming a low permeable material with a high moisture retaining capacity. The 5:1 paste rock profile in the meso-scale column maintained full saturation, even after 125 days of free drainage, since the maximum value of suction did not exceed 20 kPa (see Figure 3) which is much less than the AEV of approximately 100 kPa (see Figure 5). The paste rock material was also observed to have a compressibility value similar to the unmixed waste rock with total settlements of about 1% over the 6 m height of the column. The average total density of the paste rock mixtures was also measured to be very high, ranging between 2100 and 2300 kg/m^3. In summary, the paste rock material was observed to retain the physical characteristics of waste rock while adopting the hydraulic sealing properties of consolidated tailings.

2.2 INCO lysimeter experiment

A field and laboratory study was carried out to investigate the potential for blending tailings, waste rock and slag at the Copper Cliff mine in order to produce a suitable material for the construction of a barrier cover system. A laboratory test programme was conducted that indicated it should be possible to produce a high quality cover material as reported by Fines et al. (2002). Field samples of tailings, waste rock and slag were obtained for blending trials. Waste rock was collected from fresh production rock produced by the underground operation for the South mine. Slag samples were collected from a stockpile of fine-screened material (approximately 25 mm and finer). Tailings samples were obtained from the Tailings Area R3. The blending ratios of waste rock, slag, and tailings were designated with numbers such as 1:1:2, which indicated 1 unit of waste rock, 1 unit of slag, and 2 units of tailings on a dry weight basis. Blend 1:1:2 produced a well graded material with a particle size distribution similar to Equity till as shown in Figure 7. Equity till has proven to be an excellent cover material at the Equity Silver mine in British Columbia.

The hydraulic conductivity of the blended tailings, waste rock, and slag were measured in a 150 mm diameter permeameter using the falling head test method. The blended samples were mixed at a gravimetric water content of approximately 10 to 12 percent to produce a paste consistency with slumps of 100 mm to 200 mm. Additional samples were also compacted at a lower water content (i.e. approximately 8 percent) using a Standard Proctor effort in order to determine the reduction in hydraulic conductivity associated with increased density. The influence of the addition of a small percentage of bentonite (equal to 1.5 percent based on the dry weight of waste rock, slag and tailings) for non-compacted and compacted samples was also evaluated.

A blend ratio of 1:1:2 for R3 tailings produced a material with a hydraulic conductivity of 2×10^{-7} m/s without compaction (i.e. loose, semi-fluid state). The value of hydraulic conductivity was found to decrease to 4×10^{-8} m/s (i.e. approximately one order of magnitude) after compaction with Standard Proctor effort. Furthermore, the hydraulic conductivity was found to decrease to 3×10^{-8} m/s with the addition of 1.5% bentonite. A more striking and significant benefit was found with 1.5% bentonite and compaction to produce a material with a hydraulic conductivity of 5×10^{-9} m/s. It was also found that the AEV for paste rock Blend 112 was approximately 30 to 50 kPa as shown in Figure 8. The AEV or air entry value corresponds to the negative water pressure or soil suction at which the material will begin to desaturate. In summary, the results of the hydraulic conductivity testing together with the soil water characteristic curves show that the hydraulic properties of the paste rock materials are similar to those for the tailings used for blending.

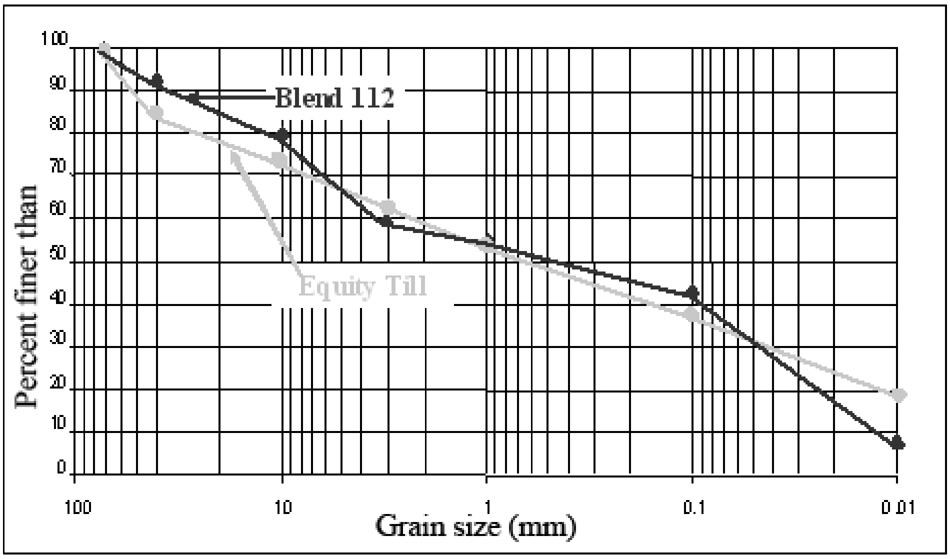

Figure 7 Particle size distribution of paste rock blend 112 compared to Equity Till

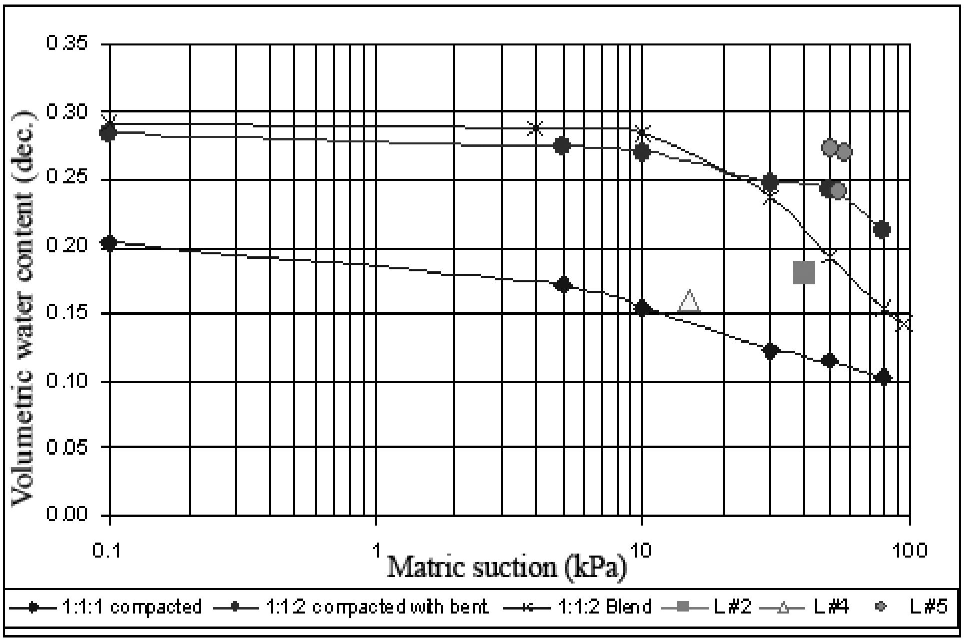

Figure 8 Soil water characteristic curves for paste rock materials used in the INCO Lysimeter experiments

Five large field lysimeters were constructed in October 2004 to test the performance of the paste rock materials for the construction of barrier type cover systems. The surface of each lysimeter measured 15 m x 15 m with a total depth of 2500 mm. The lysimeters were lined with HDPE and the bases were graded to a central collection sump for the measurement of vertical seepage due to infiltration. Approximately 1000 mm of coarse sand tailings was placed into the base of each lysimeter. The purpose of the field lysimeters were to measure net infiltration and drainage rates for each tailings profile with different cover systems constructed using various paste rock materials and layer thickness. Furthermore, the ability of each cover profile to maintain high saturation for minimising oxygen diffusion was also evaluated. The construction of lysimeters is illustrated in Figure 9.

Figure 9 Sequence showing the construction of the INCO lysimeter experiment

The five test pads were constructed including one control section 'L1' with the lysimeter filled to full depth with coarse sand tailings (i.e. no cover). The first paste rock cover for Lysimeter L2 was constructed with a thickness of 1000 mm using minus 200 mm minus ROM waste rock and a blend ratio of 2:1:1 (tailings: slag :waste rock). Lysimeter L3 was also constructed with 1000 mm thick paste rock cover but a blend ratio of 2:1:1, using 50 mm minus waste rock. The primary difference between L2 and L3 was that the cover material placed in L2 was at low slump (i.e. 50 mm), while L3 was placed at high slump (i.e. 150 mm) to simulate a mixture that may be pumped. Lysimeter L4 was constructed using the same paste rock blend as L2 but with the cover thickness reduced to 600 mm and the density of the cover increased by compaction to 95% Standard Proctor density. Likewise, Lysimeter L5 was also constructed similar to L4 with a reduced cover thickness of 600 mm and compaction, but in addition, the high slump paste rock blend was modified with the addition of 1.5% bentonite. A final grade of approximately 4% was created for each cover to ensure all run-off flowed to the perimeter ditches.

Thermal conductivity sensors were installed at various locations to measure in situ values of matric suction and samples for gravimetric water content measure were obtained at specific time intervals. All drainages from each lysimeter were collected within basal sumps and drained by PVC pipes to tipping bucket gauges for continuous measurement of outflows. Following construction, a layer of top soil was put in place on top of the paste rock surfaces. The topsoil was a locally acquired loam from a borrow source and consisted of more than 80% finer than 75 microns. The thickness of the topsoil layer varied according to the level of compaction and settling observed in each lysimeter. The hydraulic conductivity of the topsoil is about 5 x 10^{-6} m/sec. The aim was to construct the topsoil cover thick enough to provide a growth media as well as to provide proper topography such that surface run off is directed to the perimeter ditch around each lysimeter. The protective layer of topsoil was hydroseeded with a mixture of grass seeds normally used for reclamation works. Finally, perimeters drains were also installed on the surface of each completed lysimeter to collect and measure surface runoff.

2.2.1 INCO lysimeter results

The constructed lysimeters have provided two years of field observation and measurement. Year 1 (2005) allowed direct observation with respect to material behaviour and volume change under extreme climate conditions, while Year 2 (2006) provided extensive data for hydraulic performance of each paste rock cover system. Figure 10 shows the measured outflow rates from each of the lysimeters for the period April 2 through November 13, 2006. The total precipitation for the 7 month period including snow melt from the spring melt was approximately 900 mm.

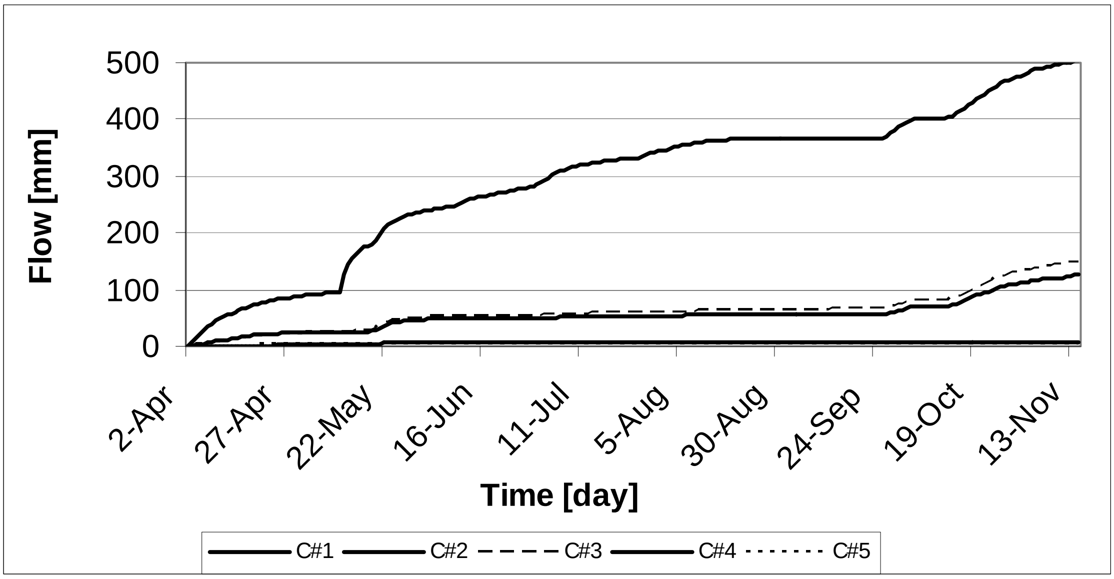

Figure 10 Measured outflow from the INCO Lysimeter

The measured out flow values from the lysimeters clearly demonstrate the paste rock covers dramatically reduce the quantity of infiltration draining through the profiles. The uncovered tailings profile produced 500 mm in infiltration, which corresponds to approximately 55% of total precipitation. The quantity of infiltration was reduced to 140 and 120 mm or 16% and 13%, respectively, of precipitation for lysimeters 2 and 3 with 1000 mm uncompacted paste rock covers. Furthermore, lysimeters 4 and 5 with the 600 mm of compacted paste rock covers showed extremely low values of infiltration of 8 mm and 5 mm, respectively or values less than 1% of total precipitation. Further in situ sampling and tensiometer measurements showed the paste rock covers remained highly saturated at all times since measured in situ values of suction generally remained less than 30 kPa.

The paste rock covers proved to be resistant to volume change and cracking. This characteristic can be attributed to the high total density, typically in the range of 2000 to 2200 kg/m^3, and low compressibility established by the rock dominated matrix of the material. The resistance to volume change and cracking helps the paste rock material be less susceptable to freeze/thaw and wet/dry cycles, hence the cover systems appeared to provide excellent performance after a complete cycle of winter freeze and summer drying. However, on going monitoring will be required over several years to establish long term performance. In summary, the results of the laboratory testing programme and measure field lysimeter results show that it is possible to construct high quality barrier covers using mixtures of waste rock, tailings, and slag to form a paste rock cover.

3 Conclusions

Laboratory testing, meso-scale experiments and field lysimeter trials using selected blends of waste rock and tailings were constructed at the Porgera mine, PNG and the Copper Cliff mine, Canada. Results show hydraulic conductivity values for paste rock mixtures comparable to consolidated paste tailings (i.e. 10^{-7} m/sec to 10^{-8} m/sec) with volume change characteristics similar to waste rock can be achieved. The results from the meso-scale column experiment show that low values of hydraulic conductivity in the order of 1 x 10^{-8} m/sec with an AEV in the range of 100 kPa is achieved for the paste rock. The paste rock material was found to consolidate relatively quickly after deposition with low volume change and settlement characteristics similar to unmixed waste rock.

These findings suggest it should be possible to construct paste rock structures with similar topographic features as conventional reclaimed rock piles. Long-term drainage testing demonstrated the capacity of the paste rock material to maintain saturation under negative water pressures 5.5 m above a fixed water after 125 days of continuous drainage. This is a critical issue since it demonstrates that the material will be highly resistant to oxygen entry and thus potential oxidation and weathering reactions. The high capacity of the paste rock material to maintain high saturation combined with the low hydraulic conductivity of the material suggests the material will be highly resistant to weathering and leaching following deposition.

The measured results for the field scale lysimeter measurements demonstrate infiltration and drainage rates are reduced by almost 2 orders of magnitude when paste rock is used to construct cover systems on tailings. This result supports the conclusions drawn from the meso-scale experiment conducted at Porgera mine. In summary, waste rock and tailings can be blended to produce an engineered material, termed paste rock, with superior physical and hydraulic properties for the construction of post mining landforms. The new material also has a density much higher than either conventional tailings or waste rock deposits; thereby reducing the total volume of waste and creating opportunities to reduce surface area requirements for impoundment design and construction.

Acknowledgements

The writers would like to gratefully acknowledge the support given by Placer Dome (Barrick), the Porgera Gold mine, INCO Ltd Copper Cliff mine and the National Sciences and Engineering Research Council of Canada for the financial and in kind mine-site support to complete this research programme.

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