Potential use of bentonite-paste tailings mixtures as engineering barrier material for hazardous waste containment facilities: Experimental results

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ABSTRACT
This study investigates the feasibility of using bentonite-paste tailings (BPT) as a barrier (liner, cover) material for hazardous waste containment facilities. Improvements of the hydraulic properties are realized by using compaction to densify the paste tailings in the first stage and mixing an additive- like natural bentonite to paste tailings to further reduce the voids that control hydraulic conductivity in the second stage. A significant decrease in hydraulic conductivity is observed with these transformations. Additional investigations are conducted to evaluate the freeze-thaw and wet-drying performance of BPT. The results show that negligible to acceptable changes in hydraulic conductivity occur. The results place this recycled BPT material as a promising candidate for barrier design while reducing the amount of waste to be managed and the cost of surface tailings management.

1 INTRODUCTION

The mining industry produces a huge amount of tailings. The tailings have been traditionally stored in tailings disposal facilities (e.g. dams, ponds and other types of surface impoundments) located at the mine surface in a variety of different methods (Fall and Merkel 2001, Yillmaz et al. 2003, Fall et al. 2004, 2008). However, the degradation and/or failure of the aforementioned tailings disposal facilities can result in serious environmental and geotechnical problems with severe social and economical ramifications. These risks and consequences associated with the conventional tailing impoundments, the immense operation and maintenance cost of these impoundments as well as public perception and stricter regulations regarding the disposal of such waste have made the mining industry and engineering community consider alternate usage of the tailings, and develop new strategies of tailings management which should be environmentally sound and cost effective. Therefore, finding alternative approaches for tailings management and usage of tailings as construction materials have become a great challenge for the mining and civil engineering community.

Over the last few years, new and modified surface tailings disposal methods have been introduced to reduce the geotechnical and environmental hazards associated with conventional tailings impoundments. These new methods include densified tailings (thickened, surface paste, and filtered tailings which are also called dry stack tailings), co-disposal of tailings and waste-rock. In summary, these densified tailings have been significantly dewatered to a point where they form a dense material with a solid content, usually between 50% and 70% (for thickened tailings), 70% and 80% (for paste tailings) and over 85% (for filtered tailings). The main advantages of the technology of densified tailings include, but are not limited to, reducing seepage from stored tailings and minimizing the requirement for retaining dams due the self-supporting ability of the densified tailings (reduction of capital cost). However, it should be mentioned that the densified tailings do not fully eliminate the AMD and seepage problem. Furthermore, the relatively low degree of saturation of the filtered tailings can be very favourable for AMD development. Finally, mine co-disposal involves the mixing and disposal of tailings together with coarse mine waste. This further improves drainage properties and increases the rate of consolidation, resulting in a greater final strength and geotechnical stability (Struthers 1999). In addition, the co-mixing of waste rock and tailings reduces the air and water permeability of the co-disposal mass, thereby resulting in the improvement of resistance to AMD development.

The above summarizes the emerging methods of surface tailings management. Although they have improved geotechnical performance and reduced environmental risks (e.g., AMD, seepage) of tailings disposal facilities, they are still based on the permanent surface storage of tailings and the containment concept, and are also relatively unproven. These new methods (densified tailings) also require larger surfaces of land compared to the conventional tailings impoundments. Hence, if space is a constraint, this will immediately exclude densified tailings. Moreover, none of them can fully eliminate the AMD and seepage problems. Lastly, the mining companies are still reluctant to switch from conventional tailings impoundments to these new tailings management approaches although wet deposition is more problematic.

Considering the facts mentioned above, it can be concluded that the environmental risks related to conventional and modern tailings surface disposal facilities will still remain a pressing issue and concern in the coming years or decades. Therefore, the development or improvement of new technology to eliminate or limit AMD and seepage associated with tailings disposal facilities as well as the constructive recycling of tailings in mining and/or civil engineering construction is needed. One of the most cost-effective techniques used in surface mine waste management to eliminate or limit AMD development and seepage (i.e. control acid and/or pollutants migration) into underlying aquifers is a barrier (liner, cover), which can also be a cost-effective means of recycling tailings as explained below.

One of the most desirable properties in liner design is low hydraulic conductivity that prevents migration of hazardous fluids to underlying areas where wastes are deposited. In the case of compacted clay, the Environmental Protection Agency (EPA) requires a hydraulic conductivity less than 10^{-7} cm/s (Daniel, 1993) of the compacted clay. Previous studies performed on paste tailings (PT) materials revealed that its saturated hydraulic conductivity is in the range of 10^{-5} to 10^{-6} cm/s, i.e. close to the minimum saturated hydraulic conductivity required for liner design according to the EPA. This means as soil permeability is governed by the proportion and nature of the finer fraction (Shafiee 2008), PT mixed with other fine or swelling materials, such as bentonite, can be potentially used as liner for tailings disposal facilities or municipal waste disposal facilities, in regions where preferred materials, such as natural clay, are not available for the design. This will result in reduction in the cost of the liner design as well as a good opportunity to recycle tailings into mining and civil constructions that can promote environment sustainability. However, the recycling of PT materials has not yet been proposed as liner materials. This may be due to the fact that PT materials can contain (but not always) a high quantity of sulphide minerals that can generate AMD. However, the use of environmental desulphurization (e.g. Leppinen et al. 1997) can allow the separation of the sulphide (acid generating) and non-sulphide minerals, thereby producing non-acid generating PT materials. The latter can be used as liner materials while the acid generating tailings will be used in the CPT preparation. The technical and economical feasibility of environmental desulphurization have been proven by several studies (e.g. McLaughlin and Stuparyk 1994, Yalcin et al. 2004). Furthermore, non-reactive natural tailings (i.e. tailings with very low sulphide content and do not generate AMD) are largely available in many mining areas, such as eastern Canadian mining sites. Thus, there is a need to study the suitability of the mixture of non-acid generating PT and bentonite as liner for tailings disposal facilities.

However, in practice, the liner alone is not enough to control AMD and its impact on the groundwater, since in the long term, infiltration water can enter into the tailings impoundment and become acid. When the infiltration water cannot escape via seepage, it will accumulate until the available storage is filled and then discharge over the lip of the liner (Robertson et al., 1998). Thus, an effective means to control water infiltration as well as oxygen supply to the tailings impoundment is the construction of a cover. One of the approaches used in mining operations is the soil cover. The details about the various types of soil covers and their characteristics are given in Nicholson et al. (1989), Yanful (1993), Yanful et al. (2006), etc. Covering tailings with a soil layer that has a low hydraulic conductivity limits accessibility of water to the tailings (Yanful et al. 2006). In addition, when the soil cover is placed close to saturation and maintained at this high water content, oxygen accessibility is also restricted (Yanful et al. 2006). Thus, a fine-grained soil cover with minimum hydraulic conductivity, but maximum degree of saturation can drastically reduce the accessibility of water and oxygen to the tailings (Yanful et al. 2006). Hence, non-reactive PT materials blended with small amount of bentonite can be an adequate soil cover. However, our knowledge about the hydraulic properties of bentonite-paste tailings (BPT) mixture is limited.

In consideration of the facts that are mentioned above, a research program has been conducted at the University of Ottawa to study the suitability of the mixtures of non-acid generating PT and bentonite as the liner and cover for waste containment facilities. If PT can be recycled in engineering barrier constructions, then significant amount of tailings can be reutilized in the mining or municipal waste management which helps to reduce environmental problems as well as costs associated with surface tailings and municipal management. A part of the obtained results, i.e. those related to one of the key parameters (saturated hydraulic conductivity) used to judge the suitability of BPT mixtures as a liner or cover will be presented in this paper. The main objectives of this paper are:

- To present the results of the experimental evaluation of the saturated hydraulic conductivity of compacted PT;
- To present the results of the experimental evaluation of the saturated hydraulic conductivity of compacted BPT mixtures ;

2 EXPERIMENTAL PROGRAM

2.1 Materials used

Tailings: In this study, artificial tailings prepared industrially from ground silica (available commercially) and natural tailings are used. The ground silica has similar physical properties as natural tailings from the milling process. The artificial tailings have an advantage where they are exempt of chemicals that can interfere with the test results. The principal mineral component of this material is quartz whose percentage is listed as 99%. Natural tailings were used to prepare some PT samples for comparison with respect to the compaction behaviour of tailings. The natural tailings have a grain size curve close to that of the ground silica. The natural tailings originate from hard magmatic rocks and are characterised by the dominance of sulphide minerals (pyrite), quartz and paragonite.

Bentonite: Bentonite was obtained from a commercial distributor. The sodium mineral type of sodium bentonite was chosen as it presents good swelling potential, absorbing almost 5 times its weight and occupying a volume up to 15 times its bulk dry volume at full saturation

(Kashir and Yanful 2001). The bentonite has a percentage of 92% clay. The results of the diffractogram conducted on the Bentonite and presented in Fall et al. (2009) show that the dominant clay mineral present is smectite (sodium montmorillonite).

Mixing water: Deionised water was used to ensure that no chemical parameter was involved during this series of tests.

2.2 Preparation of the specimens

For the plain tailings and BPT mix, the anhydrous material was first homogenized in the dry state. Once mixing was completed, the amount of deionised water was gradually added until there was a uniform hydration of blend. After compaction in a proctor mould, a cutting cylinder of 5 cm in diameter was used for sampling undisturbed cores for hydraulic conductivity testing. Thereafter, specimens were removed from the cylindrical sampling tube using a mechanical press and stored in a polyethylene packaging for 24 hours prior to conducting the hydraulic conductivity test. Hydrated samples were trimmed and installed in a triaxial cell where the hydraulic conductivity measurement took place.

2.3 Testing and procedures

The tests conducted include compaction and hydraulic conductivity tests. The compaction tests were conducted on plain paste tailings and BPT following ASTM D 698-00a for Standard Proctor. Hydraulic conductivity tests were carried out on BTP samples and BTP subjected to various cycles of freeze-thaw or wetting and drying.

The flexible wall permeameter principle was used following ASTM D 5084-00 to perform hydraulic conductivity tests. The effective stress maintained in the cell was an average of 130 kPa, which is a value that can be produced by overlying waste (Kashir and Yanful 2001) or found in the majority of tailings management facilities (Qui and Sego 2001). The constant hydraulic gradient of 600 was applied during tests using controlled air pressure from the control panel.

To evaluate the performance of the proposed barrier materials to freeze-thaw conditions, compacted BPT samples were subjected to cyclic freeze-thaw. Hydraulic conductivity tests were carried out over samples submitted to 1 and up to 5 cycles of freeze-thaw. ASTM D 6035-96 was followed during freeze-thaw stress application by ascertaining that all ice lenses melted and moisture in samples became at equilibrium.

To evaluate the hydraulic response of BPT to freeze-thaw cycles, the following procedure was adopted. Samples were first prepared at a water content corresponding to the minimum hydraulic conductivity which was determined during previous compaction accompanied with hydraulic conductivity tests at 20 ºC. After measuring the initial hydraulic conductivity, the samples were removed from the permeameter and dried in an oven at 45℃ for 24 h. The 45℃ drying temperature was selected to approximate hot summer temperatures and minimize the possible impact of high temperature on the bentonite clay mineral. After completion of the first drying, the specimens were cooled to room temperature prior to submerging them in distilled water and their hydraulic conductivities were determined again. This completed the first cycle of testing and measurement. Wetting and drying cycles were repeated a number of times.

3 RESULTS AND DISCUSSIONS

3.1 Compaction test results

Figure 1 presents the compaction curve for plain tailings using an effort of 592.7 kJ/m^3 as prescribed by ASTM D 698-00a. Similarly, the results of compaction tests conducted on samples made of natural tailings are presented for the objective of comparison only. The maximum dry density of 1580 kg/m^3 was obtained for a water content of around 19%. This point corresponds to the one where minimum voids are achieved. This point eventually provides the range for best hydraulic conductivity of the material itself and mixes to be enhanced or improved with additives. The information gathered from this curve is used as guidance for the approximate location of the optimum water content for subsequent mixes of PT with bentonite as additives.

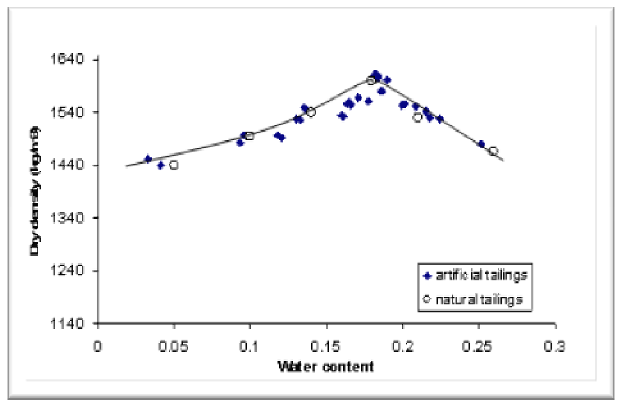

Figure 1. Compaction curve of plain paste tailings

As the optimal water content was determined to lie in the 19% range, further tests were conducted on BPT mixes containing bentonite in proportions of 2%, 4% and 8% by weight to determine the effect of the bentonite on the dry density. The results of the standard proctor curves obtained by varying the water content with the compaction tests are plotted and presented in Figure 2. From this figure, it can be observed that the best improvement of the dry density (or packing ddensity) of the BPT is realized with the addition of 4% of bentonite which gives a dry density of 1640 kg/m^3. Up to this proportion, however, further increasing the bentonite content does not lead to a proportional increase of the dry density. This behaviour and shape in the curve observed is merely due to the fact that after the presence of bentonite have contributed to densify the tailings by supplying appropriate fines to fill the voids and build the best packing density, the relatively high proportion of fines supplied by the bentonite has a detrimental effect on the mix.

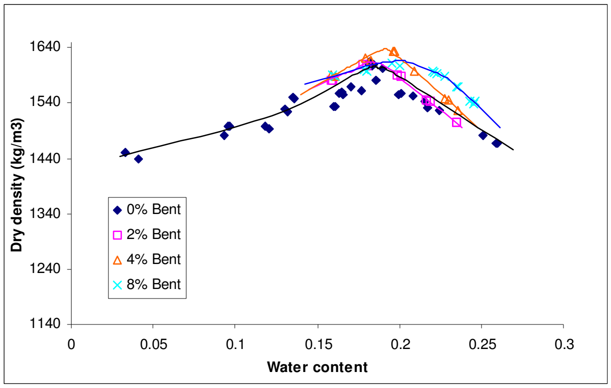

Figure 2. Effect of bentonite proportion on the compaction curves of BPT.

3.2 Hydraulic conductivity test results

Figure 3 shows the evolution of the hydraulic conductivity of compacted plain tailings with the water content. A continuous narrow pattern of hydraulic conductivity values was difficult to draw. However, a certain decreasing trend was recognized in the scatter of permeabilities ranging from 1.3 10^{-5} to 4.1 10^{-6} cm/s in the testing interval of water contents that were considered.

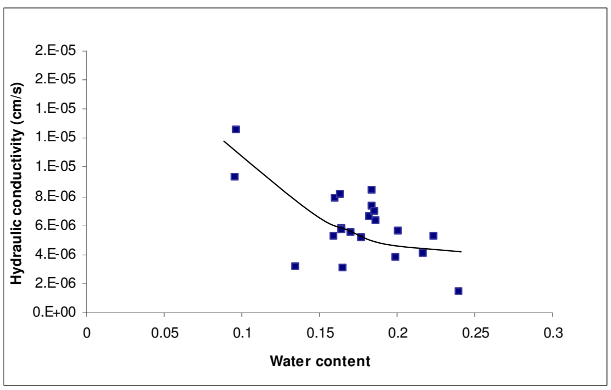

Figure 3. Hydraulic conductivity scatter pattern of plain paste tailing compacted in the range of 10% to 24% water content

Based on hydraulic conductivity values determined from samples of raw compacted PT at various water contents, further improvement was investigated by mixing bentonite in proportions of 2%, 4% and 8% to tailings by total weight. Referring to results presented in Figure 4, it can be noticed that the hydraulic conductivity decreases in all samples as the water content is increased.

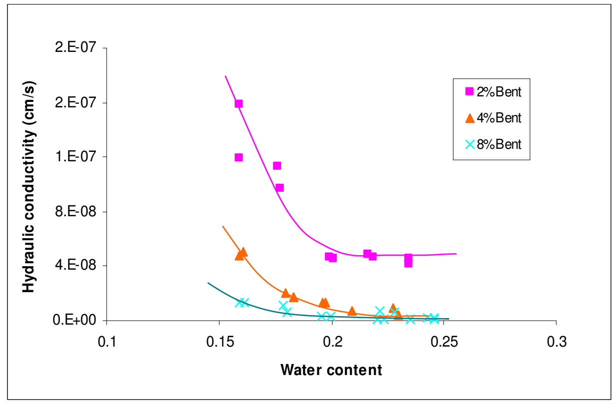

Figure 4. Effect of different bentonite proportions and water content on hydraulic conductivity of BPT.

3.3 Effect of freeze-thaw cycles on hydraulic conductivity of BPT

Typical results of the effects of cyclic freeze-thaw on the hydraulic conductivity of BPT are presented in Figure 5. In Figure 5, the measured stabilized permeabilities for BPT with different bentonite contents are plotted versus the number of freeze-thaw cycles. This figure shows that, the changes of hydraulic conductivity of BPT observed with freeze-thaw cycles are relatively low (less than one order of magnitude in hydraulic conductivity) compared to the more substantial changes reported on materials such as compacted clay (Kim and Daniel 1992, Othman and Benson 1993). It can be observed that for 8% bentonite, the permeability values fluctuate between 4.8 10^{-10} and 1.2 10^{-9} cm/s which represents a 153% increase of the hydraulic conductivity, or an increase factor of 2.5. In another way, the increase is less than one order of magnitude. For the 4% bentonite mixes presented in Figure 5, minor fluctuations in hydraulic conductivity occur in the range of 2.8$10^{-9}$ to 1.3 10^{-8} cm/s within the 5 freeze-thaw cycles which represents an increase of 355% or an increase factor of 4.6. This increase is also less than one order of magnitude. The values for the 2% bentonite appear to decrease slightly from 4.69 10^{-8} to 2.14 10^{-8} cm/s with the number of cycles. It represents a decrease factor of only 0.46. In terms of percentage, it represents a decrease of 54% in the hydraulic conductivity. The increase in permeability observed for 8% and 4% bentonite-BPT and after 3 freeze-thaw cycles may be attributed to the formation of a network of micro-cracks (not visible to the naked eye) and larger pores during freezing. However, from Figure 5, it can be noted that after 3 freeze-thaw cycles, the permeability of the 8% and 4% bentonite decreases until reaching its initial value. This observed decrease can be attributed to the self-healing ability of the BPT.

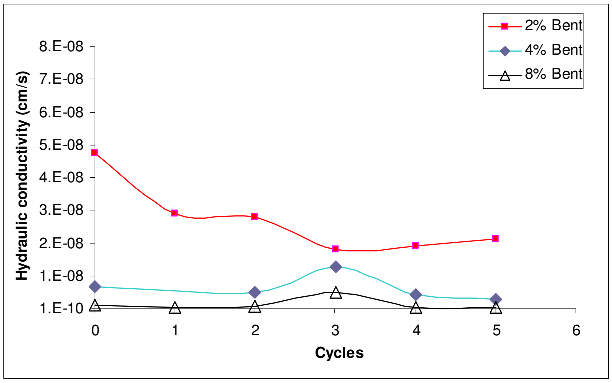

Figure 5. Evolution of the hydraulic conductivity of BPT with freeze-thaw cycles

3.4 Effect of wet-drying cycles on hydraulic conductivity of BPT

The obtained results show that the hydraulic conductivity of BPT samples compacted wet of optimum increases within one to two drying cycles. However, this increase is less than one order of magnitude. For illustration purposes, an example of the typical results from the impact of wet-drying cycles on the hydraulic conductivity and relative (normalized) hydraulic (k_N/k_0) of BPT containing 4% bentonite compacted wet optimum is presented in Figure 6. From this figure, it can be observed that after two wet-drying cycles, the permeability values increase from 5.8 10^{-9} (initial value of hydraulic conductivity) to 2.0 10^{-9} cm/s which represents only an increase factor of 3.5 (Figure 9). In other words, the increase is less than one order of magnitude. This increase in hydraulic conductivity can be attributed to the desiccation cracks formed in the BPT. However from Figure 9, it can be noted that the hydraulic conductivity decreases after two wet-drying cycles. It is believed that this decrease of hydraulic conductivity is associated with self-healing processes that affect the various soil types by different degrees (Eigenbrod 2003).

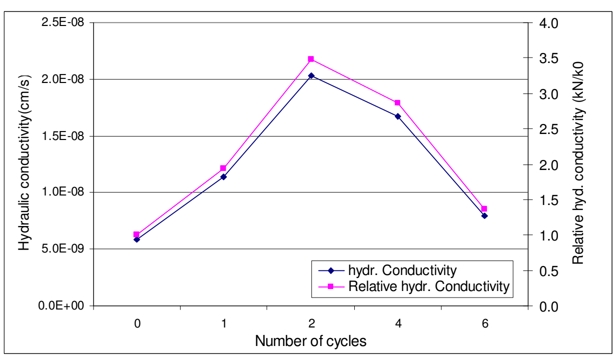

Figure 6. Evolution of hydraulic conductivity and normalized hydraulic conductivity (k_N/k_0) of BPT with wetting-drying cycles

3.5 Cost effectiveness of BPT engineer barrier

For the proposed barrier material to be of interest, it should be capable of adding value in comparison to existing alternatives available in the construction practices aside from recycling capacity. Based on the EPA minimum requirement for hydraulic conductivity and relatively good behaviour under freeze-thaw and wet-drying conditions, a cost analysis was conducted on the BPT mixes. It is obvious that the additive materials mainly control the prices in such mixtures. The investigation was conducted taking into account, variable additive proportion. A balance can be established between saving costs and an acceptable level of permeability. To appreciate such, costs were compared to reference barriers made of sand and clay mixed with 12% bentonite. At a unit kilogram price of \$3.96 for bentonite, for any determined mass M of barrier, the cost for 12% bentonite is estimated at \$0.47 while the costs for 8%, 4% and 2% of bentonite are estimated at \$0.32, \$0.16, and \$0.08, respectively. Still using the 12% bentonite cost as a reference, the benefit realized can be estimated at 33%, 66% and 83% when using BPT barriers containing 8%, 4% and 2% of bentonite, respectively. The benefit is presented graphically for ease of comparison in Fall et al. (2009).

4 CONCLUSION

This study has produced valuable data and information. The compacted BPT mixtures exhibit low hydraulic conductivities. Values that are as low as $6.27.10^{-10}$ cm/s and 4.10-9 cm/s are obtained in 8% and 4% bentonite, respectively. The study has also shown that the proposed BPT barrier resists environmental stresses (freeze-thaw and wet-drying cycles) relatively well. The freeze-thaw cycles only have a light adverse effect on the hydraulic conductivity of BPT. Cost assessment of the material in reference to 12% bentonite (usually used in sand mixtures) shows that economical gains as high as 83%, 67% and 33% can be achieved when using 2%, 4% and 8% of bentonite, respectively. However, one has to evaluate the ratio hydraulic conductivity versus economical returns.

From the promising results obtained, it can be concluded that the BPT mixture has the potential to be used for liner or cover materials for mine and municipal waste containment facilities. However, further research is needed to provide an understanding of the mechanical behaviour, water retention ability and durability of BPT. Research in this area has not been done for the project in this paper, but currently being implemented in a new project.

5 ACKNOWLEDGEMENTS

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