PROTECTION OF MINE WASTE TAILING PONDS USING COLD AIR CONVECTION

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ABSTRACT

The reclamation of tailing ponds is an important but very challenging requirement for every mine operation. Due to the fine material in the tailings the consolidation can be slow and the areas covered by the tailings pond are not released back to the public for a long time. By placing a layer of coarse grained, non-toxic mine waste rock on top of the tailings the problem can be diminished. Once the tailings reach its final elevation and a strength level that allows for a safe maneuvering on it, a cover of coarse rock with high air permeability is placed. Numerical simulations show that this layer not only acts as a barrier for animals from grazing on the tailings, but that air convection within the waste rock cover promotes freezing of the tailings underneath, thus accelerating consolidation of the unfrozen sections and strength enhancement. In addition, in permafrost regions, the permafrost table can be maintained on top of the tailings and the system is less sensitive to potentially warming air temperatures in the future. The waste rock cover may also be less expensive than placement of a typical cover of till or esker sand that prevents thaw from reaching the tailings and releasing tailings water to the surface each summer.

INTRODUCTION

During the processing of the ore in mining operations, generally large amount of tailings accumulate that have to be stored during the production phase of a mine and later reclaimed. Depending on the mined ore, these tailings can be toxic. Acid mine drainage (AMD) is a well known environmental problem that results from the exposure of mine waste (e.g. Filion et al. 1990). In a permafrost environment the sub zero ground temperatures can be utilized to slow or eliminate the AMD generation. The cold temperatures may slow chemical and biological processes and freezing can restrict the migration of pollutants. The active layer, that forms during summer, may, however, promote the transport of oxygen gas and release and spread of contaminants to the surrounding areas (e.g. Godwaldt et al. 1999). Encapsulating has been suggested in order to keep the tailings frozen and therefore prevent AMD (Dawson and Morin 1996).

In addition, this freeze back of the tailings in cold regions can accelerate the consolidation and strength enhancement of the surface layers. However, vegetation starts to grow making these areas attractive feeding grounds for caribou or muskoxen. Aboriginal people often expressed their concerns that chemicals from the tailings might enter the food chain once these herbivores start using reclaimed tailing ponds as feeding grounds and therefore solutions to prevent this are needed. Solutions are needed even more desperately when considering the change in air temperature due to global warming where previously frozen tailings may thaw in the future generating increased acid mine drainage.

This paper presents numerical modeling of air convection in a coarse cover to demonstrate the cooling effect this can have on the tailings. Design recommendations are further provided, which can be used as general guidelines or ideas that have to be adopted for a particular situation. The material parameters for this paper are based on the example of the Lupin Gold Mine (Dingwall 1985) where tailings and effluent from underground mining are disposed. Niawchuk (1997), for example, looked at the total time required for the freeze back of a 10 m tailings deposit by thermal numerical modeling. The freeze back time strongly depends on the water content of the material and can last up to 70 weeks. The mean annual air temperature recorded at the site is -12.1 °C. The freeze back of the wet tailings increases exponentially if the temperatures warm, leaving the tailings ponds unfrozen for years or even decades for moderate permafrost conditions.

NATURAL CONVECTION IN POROUS MEDIA

There are two main heat transfer processes in porous media. One is thermal conduction and the other heat convection. The former describes the heat transmission across and through the material and the latter describes the transfer of thermal energy by circulation or movement of the hot particles with a fluid to cooler areas in a particular media. The convection is further divided into natural and forced convection. Natural convection describes the fluid movements as a function of density difference and the forced convection describes forced fluid movements, e.g. winds or seepage.

The very low thermal conductivity of air (2.25 kJ/(day·m·K)) makes it a good thermal insulator. However, the temperature dependent density of the air can provoke natural convection in a porous media. The heat energy transfer associated with air movements, can be the dominating heat transfer mechanism and change the ground temperatures. Air movements start as soon as a thermal gradient is present. Cold air, which is denser than warm air, will move downwards and warm air will rise accordingly. Within porous soil media, such as dry gravel, or blocky layers, these convective air movements have an influence on the temperature of that particular layer, but also on layers below.

Kane et al. (2001) show that the assertion that pure conductive heat transfer always dominates in cold climates is not correct and that non-conductive heat transfer by water and water-vapor are significant, if not dominant under certain conditions. The effect of natural and forced air convection has been demonstrated for many embankments in the laboratory, the field as well as numerically (Goering 2003; Goering and Kumar 1996; Lai et al. 2003a; Lai et al. 2003b; Lai et al. 2004; Lai et al. 2006; Quan et al. 2006; Saboundjian and Goering 2003; Sun et al. 2005a; Sun et al. 2005b; Yu et al. 2006; Zhang et al. 2006). Saboundjian and Goering (2003), for example, demonstrate that the winter-time natural convection occurring in a high-permeability embankment reduces the average annual temperatures of the foundation by approximately 5 °C.

In order for natural convection to occur in a porous media, the moving fluid has to be in a certain ratio to the overall thermal conductivity of the media. The Rayleigh number has been shown to be the key similarity parameter when investigating convective heat transfers in porous media (Goering and Kumar 1996; Kane et al. 2001; Nield and Bejan 1999; Sun et al. 2005a). The Rayleigh number R_a for air flow in a porous media is generally defined as:

$$R_a = \frac{\rho_0 g \beta C_a K H \Delta\theta}{\mu \lambda_e}$$

where ρ_0 is the air density, g is the gravitational constant, β and μ are the coefficient of thermal expansion and the dynamic viscosity of the air, C_a is the volumetric heat capacity of the air, K is the air permeability, H is the height of the porous layer, $\Delta\theta$ is the temperature difference between the lower and the upper boundary of the porous layer, and λ_e is the thermal conductivity of the media.

Many researches have shown that there are critical Rayleigh numbers depending on the geometry, at which natural convection occurs (e.g. Long 1976; Nield and Bejan 1999; Sun et al. 2005a). Only when the fluids, in this case the air, can move at a fast enough rate, will convection dominate conduction. For a two-dimensional rectangular enclosed configuration, the minimum critical Rayleigh number, for example is $4\pi^2$ (e.g. Nield and Bejan 1999). Higher values can trigger different modes that may consist of more than one convective cell within the material.

Because the Rayleigh number is a function of the geometry and temperature difference, the value will not be constant for natural conditions. Accurately defining such a value for a coarse gravel layer in cold regions is difficult because of variable heights and time-dependent temperatures at the upper and lower boundaries (Goering and Kumar 1996). The Rayleigh number therefore changes with time and space and the actual air flow pattern can be very complex. Once the value falls below the critical value, which is generally during summer where the surface temperatures are warmer than the ground temperatures and negative R_a values would be obtained, the heat transfer is reduced to conduction.

In addition to geometry and temperature difference, the air permeability is also an important factor that controls convection. This value might also change with time for a specific soil as a function of water content or possible vegetation. Figure 1 shows air permeability values as a function of the hydraulic conductivity and the intrinsic permeability for air and water temperatures at 0 °C.

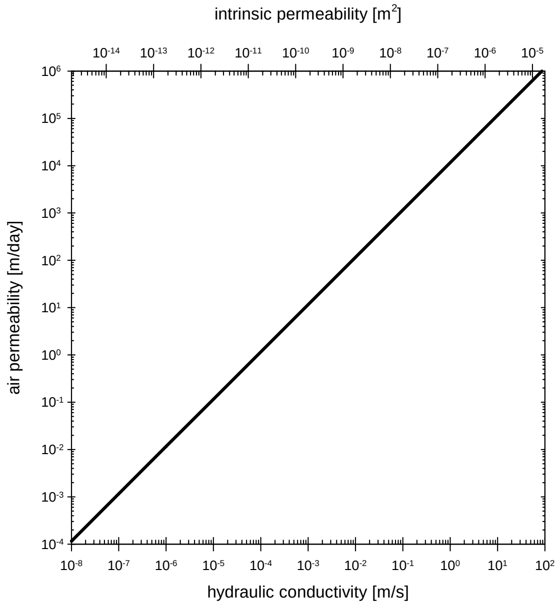

Figure 1. Air permeability versus hydraulic conductivity (@ 0 °C) and intrinsic permeability.

NUMERCIAL MODELING

The ability of modeling convective air flows has been incorporated into the GeoStudio software package (Beta Version of GeoStudio 2007). The program simultaneously solves air and water flow within unsaturated soils. Their SEEP/W module has been modified to solve for density dependent air flow in response to hydraulic, pneumatic and thermal boundary conditions. Information about air movements are then passed onto the TEMP/W module that is used to compute the convective heat transfer associated with moving water and moving air, as well as heat conduction. Details on this numerical implication can be found in Arenson et al. (2006).

Model Parameters

To study the effect of air convection on tailings material, a number of different conditions were modeled. The thermal properties of the tailings and the cover layer, however, were kept unchanged. Thermal parameters for the tailings were chosen according to Niawchuk (1997). For the tailings material with a volumetric water content of 23%, the thermal conductivity changes from 160 kJ/(day·m·K) in the unfrozen state to 236 kJ/(day·m·K) when frozen over a temperature range of approximately 4 °C. A heat capacity of 4380 kJ/m^3 and 4320 kJ/m^3 was chosen for the unfrozen and frozen state, respectively. Initial tailings temperatures were set to 5 °C. The protective rock or gravel layer was assumed to by dry and therefore the thermal parameters were chosen to be similar in the frozen and unfrozen state: 21 kJ/(day·m·K) and 1150 kJ/m^3 for the thermal conductivity and the volumetric heat capacity, respectively.

For all models the tailings were kept uncovered for the first winter allowing winter frost to penetrate. As the surface temperature reached zero degree, the protective coarse cover layer was applied. The surface temperature distribution was a sinusoidal variation with a mean annual surface temperature of 0.75 °C and amplitude of 42.4 °C. In addition, a geothermal gradient of 3 °C/100 m was applied at the base. The numerical model had a total thickness of the 20 meters.

General Behavior

Figure 2 shows a series of temperature isotherms within the protective cover over one year. The changes in air flow pattern between summer and winter can clearly be identified. In summer (positive ground surface temperatures), the isotherms are basically parallel to the surface and convection is observed only at the slopes, where the Rayleigh number are larger than the critical value because of the smaller heights. Because of the large void ratio (~0.4 – 0.6), the thermal conductivity of the cover is relatively low and the tailing material is protected from significant warming. During winter (negative ground surface temperatures), the isotherms show the complex air movements and the formation of convection cells. Cold air sinks to the bottom and warm air rises to the surface. This effect promotes significant cooling of the tailings.

An eight year temperature trend for a point located 2 m below the tailings surface is given in Figure 3 for a 4 m high protection and an air permeability of 50,000 m/day. The temperature variations are significantly smaller below the protection for one year and after the third winter the tailings remain frozen. Without the protective layer, the tailings would thaw completely every summer. The air temperature conditions would not allow for freezing the tailings at depth and reestablishing permafrost conditions. The protection, on the other hand, promotes a slow, but steady cooling and freezing of the tailings. At a depth of 2 meters the cooling is approximately 0.45 °C/year.

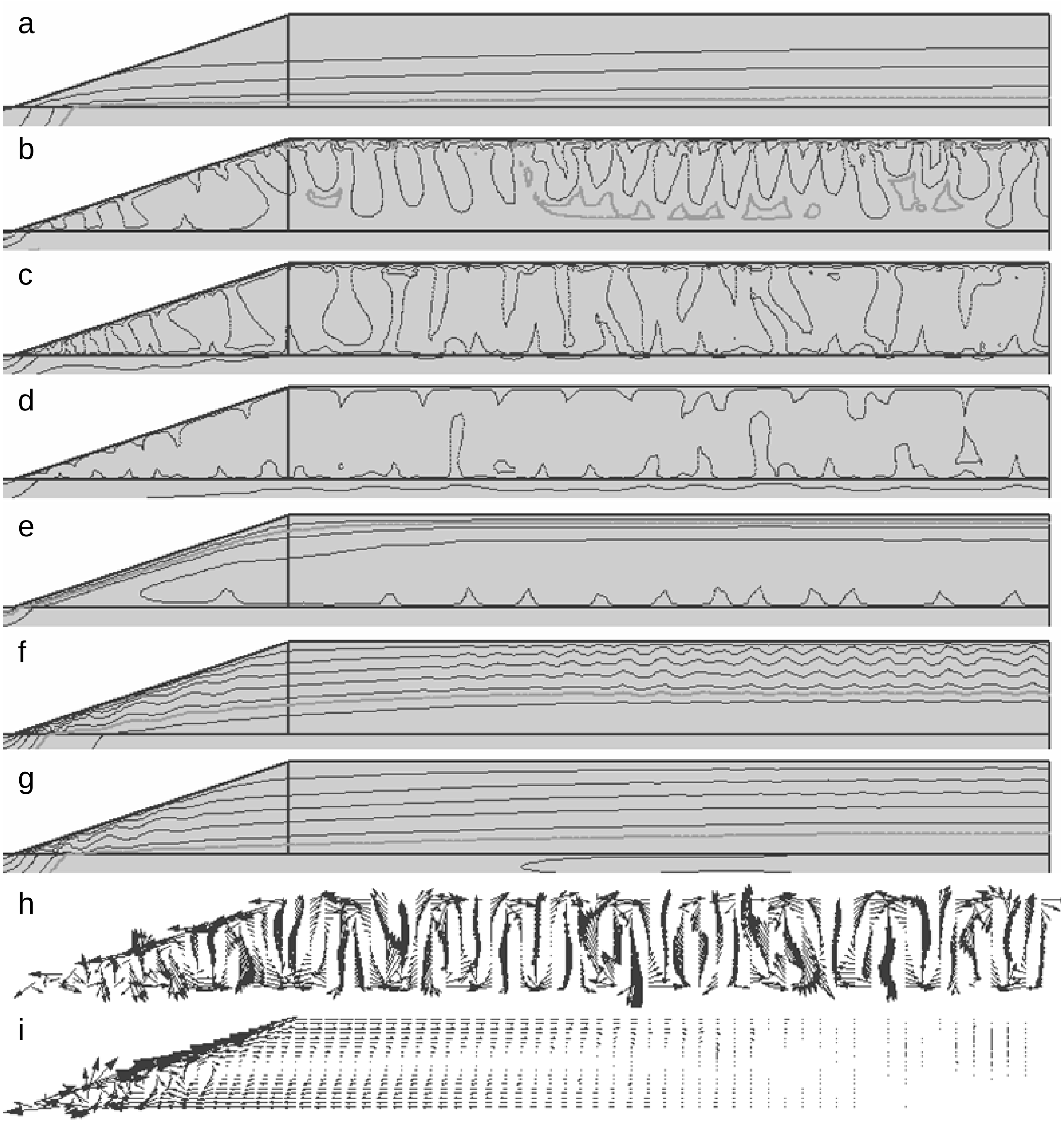

Figure 2. Change in isotherms with time within a 4 m high protection layer. Each picture represents a time step during a one year simulation. The ground surface temperatures at the top boundary are: +12 °C (a), -8 °C (b), -21 °C (c), -11 °C (d), +10 °C (e), +21 °C (f), and +16 °C (g). The air flow vectors in h and i correspond to the isotherms shown in c and g.

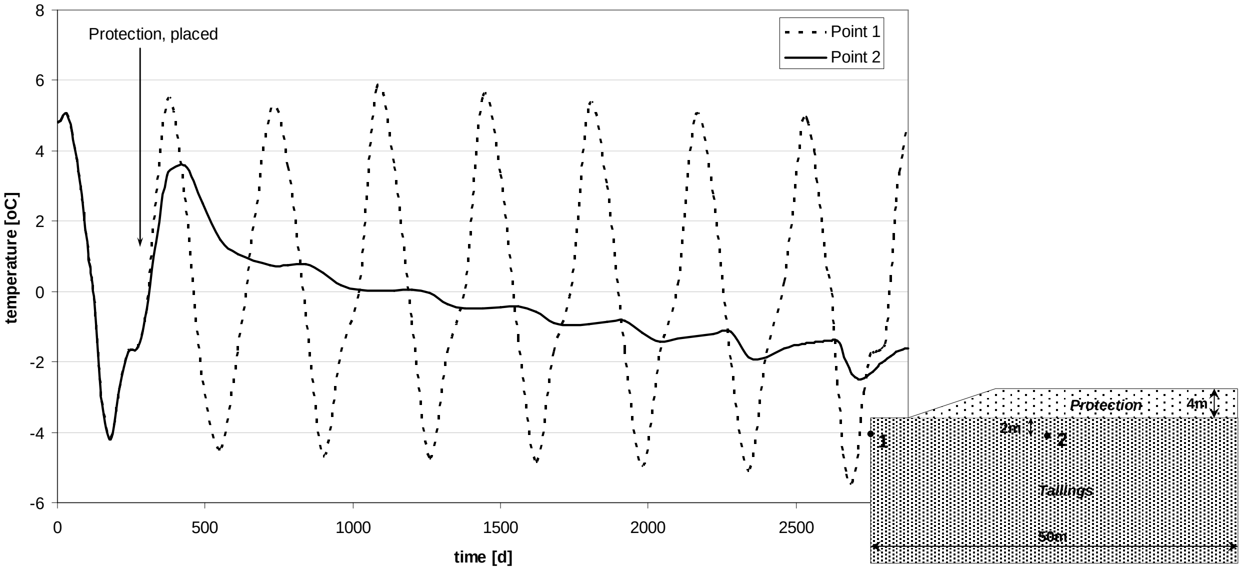

Figure 3. Temperature trend at 2 m depth without (point 1) and with (point 2) protection. The air permeability is 50,000 m/d.

Effect of Air Temperature

The driving factor for air convection to develop is the temperature difference between the top of the protection and its base, at the surface of the tailings. To study this effect the subgrade was eliminated from the model and only the changes at the base of the cover was analyzed. At the base the influence of the tailings are not included, but the same thermal gradient was applied. Hence, latent heat effects in the wet tailings are ignored. However, the comparison of different temperature amplitudes shows how important it is for the development of convective heat flow in the protective cover. The annual temperature changes at the cover base of year seven are presented in Figure 4. The two configurations with the larger amplitudes clearly show the convection effect during winter. The decrease in temperature is much faster because of the sinking air compared to the two conditions with small temperature amplitudes.

Comparisons between the mean, maximum and minimum annual ground temperatures at the base (Fig. 5) also demonstrate the effect of the convection. The two small amplitude cases Temp_3 and Temp_4 are dominated by thermal conduction and therefore the values are close to the input temperatures at the surface shifted by the phase lag for this depth. In fact, the temperatures are warmer because of the thermal gradient applied at the base. Significant cooling, on the other hand, occurs once convection starts. The cooling capacity at the base increases considerably as the temperature amplitude increases. Similarly the minimum and maximum temperatures decrease. For the amplitude of 42 °C, which is the value recorded on the Lupin site, even the maximum temperature at the base is below zero centigrade indicating that the base remains frozen the whole year. The permafrost table remains in the cover layer, whereas for the other cases an active layer is expected to exist in the ground below the cover.

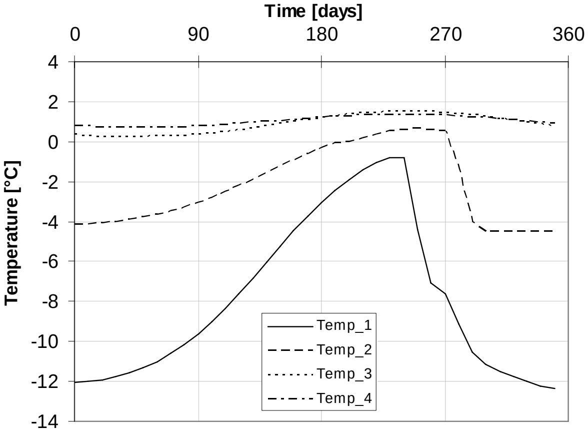

Figure 4. Temperature distribution at the base of the cover layer during one year. Amplitudes: Temp_1 = 42 °C; Temp_2 = 21 °C; Temp_3 = 11 °C; Temp_4 = 5 °C.

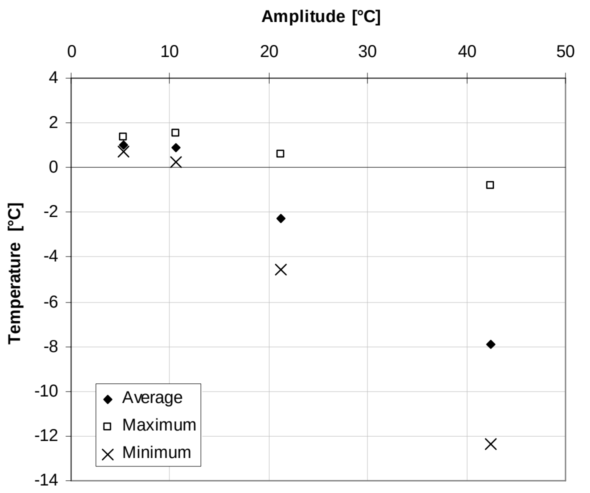

Figure 5. Average, minimum and maximum temperatures at the protection layer base as a function of the surface temperature amplitude.

Effect of Air Permeability

Increased air permeability results in better air convection and therefore the cold air can penetrate faster, cooling the tailings more efficiently.

Figure 6 shows the difference in the mean annual temperature at the surface of the tailings for two different air permeabilities, 50,000 m/day and 200,000 m/day, respectively after eight years. An amplitude of 42 °C was chosen for these simulations, which corresponds to the recorded changes in air temperature at the Lupin Mine site (i.e. Temp_1 in Fig. 4). The temperatures at the initial 5 m on the left represent the temperatures in the tailings without protection, which is above zero degrees centigrade confirming that no permafrost could be established. By placing the high air permeable and low thermal conductive cover, the mean annual temperatures were lowered below the freezing point.

An air permeability that is about four times higher reduces the average temperature at the top of the tailings by approximately 4 °C. The increase in air permeability corresponds to a change from well sorted gravel / pebbles to cobbles / boulders.

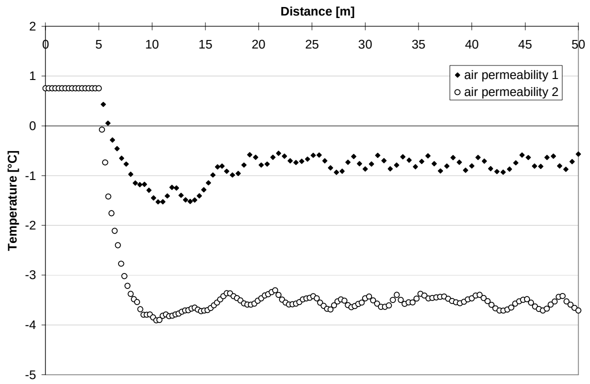

Figure 6. Mean annual ground temperatures at the surface of the tailings for two air permeabilities (50,000 and 200,000 m/day) after eight years. The first 5 m are not covered. The total protection height of 4 m is reached at a distance of 17 m. Temperature amplitude is 42 °C.

Effect of Protection Height

The numerical simulations have shown that the height of the cover layer has only a minor effect on the cooling, in particular for cover thicknesses above 4 meters. Figure 7 shows that the mean temperatures are similar for three cases, 2m, 4m and 6m. Only at the toe, can cooling be improved with higher cover because of the way the convective cells form. The mean annual ground temperatures are similar for all three cover heights with a slightly colder trend for the thinnest cover (2 m). In winter much colder temperatures are recorded at the bottom of the protection because of the faster temperature penetration through the thin cover. The coldest temperatures, for example, in a one year cycle are -2.26 °C and -1.05 °C for the 2 m and 6 m cover, respectively.

The temperature variations during one year can also be reduced in a high cover (Fig. 8) and therefore reducing the active layer depth. The 2 m cover shows positive temperatures for a considerable amount of time, whereas the time for the 4 m and the 6 m cover are very similar. On the other hand colder temperatures are obtained for a thinner cover promoting a more rapid freezing of the tailings if the active layer thaw has no impact on the environment or the design.

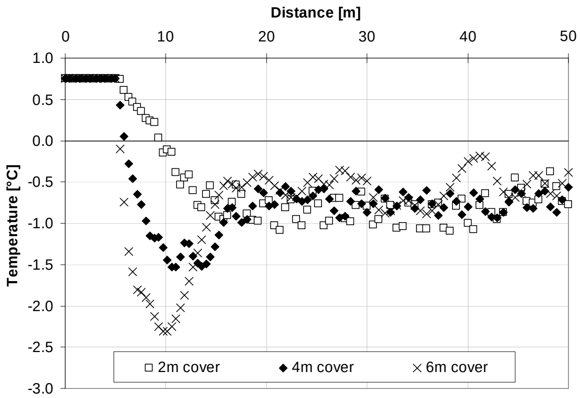

Figure 7. Mean annual ground temperatures below the protection, for different protection heights after eight years. Temperature amplitude is 42 °C.

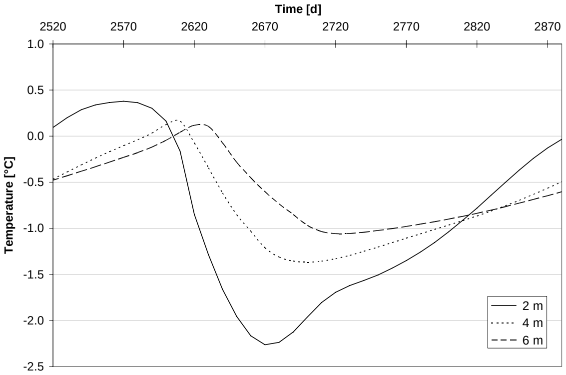

Figure 8. Temperature trends after seven years at tailings surface. A temperature average was taken from the data between 20 m and 40 m (Fig. 7).

Effect of Air Boundary Conditions

Two different air boundary conditions were analyzed during this investigation: (i) air permeable, and (ii) air impermeable to study the effect of possible cover of the tailings due to snow or vegetation. The first boundary condition assumes free entry of air into the cover during the whole modeling period, i.e. it is a free convective boundary. The second boundary condition on the other hand does not allow any air movements into or out of the cover layer. The air is trapped within the cover and the boundary is a conductive temperature boundary condition.

With an open boundary at the top the cooling effect can increase by several degrees. Open side slopes can also increase the cooling, however, during summer strong and warm winds can enter the coarse layer and increase the temperature at the base of the cover (e.g. Quan et al. 2006). Hence, the insulating effect of the dense cold air will diminish. In order to avoid such a scenario it is recommended to cover at least the lower portion of the side slopes with a low air permeability layer so that the wind is redirected from the embankment, e.g. over it, leaving the cold air internally at the bottom of the cover. Even though the cooling effect during winter might be slightly reduced, the overall performance is expected to be improved. In addition, an open side slope only has an effect on the temperatures of the ground in the toe region. By extending the protective cover around the tailings pond, so that the whole pond is covered with the maximum height of the protection, heterogeneities in the tailings ground temperatures can further be reduced.

CONCLUSIONS

Numerical modeling of air convection in a protective cover on top of wet tailings showed the beneficial effect this layer has to the tailings material. Freeze back under permafrost conditions is generally faster, improving the strength of the material. In addition, consolidation can be accelerated due to the formation of ice lenses within the freezing tailings. Even at air temperatures, where no permafrost would form to date, but permafrost exists because of past climate conditions, convective cooling might be the only way to regain the original frozen ground thermal regimes. The method therefore shows promise for regions of discontinuous and sporadic permafrost that are generally sensitive to even small changes in air temperatures. The protection also reduces or may even eliminates the active layer in the tailings, keeping it constantly frozen, i.e. permafrost can be re-established. Not only can the strength be increased, but because the tailings materials remain frozen and protected by a coarse rock cover layer, potential chemicals existing in the tailings are prevented from escaping. The waste rock cover may also be less expensive than placement of a typical cover of till or esker sand required to prevent thaw from reaching the tailings and releasing tailings water to the surface.

The effectiveness of the cover depends on a number of parameters that have to be addressed when designing an air convection cover for mine waste tailings:

- Air permeability: The void ratio governs how much air can actually move within the cover. It is important that this cover does not clog, i.e. the air can freely move during its design life.
- Boundary conditions: The effectiveness of convective cooling also depends on the amount of air that can penetrate into the cover. If the surface layer is sealed, with a snow cover during winter for example, it has to be considered during the modeling since it may reduce the cooling effect significantly. However, even a completely sealed boundary will promote convective heat transfer in the cover layer.
- Cover height and surface temperature: The temperature difference between the top and the base of the cover controls convection, reflected in the Rayleigh number. During winter this number should be large in order to promote the cold air to sink to the bottom. Depending on the local temperature conditions prevailing, in particular the temperature amplitude, the optimum height of the protection layer changes.

During the first summers, thawing of the top layers of the tailings may cause some settlement of the protection. However, initial freezing of this top layer will result in consolidation and therefore the strength increases. Drainage of the water is allowed at the surface and therefore the settlements are expected to be small, not affecting the efficiency of the system. However, the promising results shown by numerical simulations should be confirmed in the field by detailed temperature measurements on tailings protected by an air permeable cover layer.

Design Recommendations

Even though the effectiveness of such a tailings protection has to be proven in the field some recommendations can be made based on the numerical modeling carried out to date.

At cold permafrost conditions the placement of a protective layer would decelerate the freeze back of the tailings because the cover acts as insulation, and the very cold temperatures can not penetrate into the ground. Since active layers will be very small in these regions, the recommended management would be to keep the tailings exposed to winter temperatures during operation of the mines and only cover them with a 1 – 2m thick cover before closure at the end of the winter season. This will guarantee that the tailings will not thaw in summer and they are protected from herbivores grazing on it following closure.

At warmer, discontinuous permafrost conditions it is recommended to place the cover after the tailing surface is exposed to one winter. This will allow deepest penetration of the cold temperatures and the cover layer will act as a thermal insulation during the first summer. Slowly, the cold will penetrate into the tailings and continue to freeze them as well as consolidate them. The thickness of the cover depends on the local temperature conditions. However, 4 m is probably adequate since the effect due to increasing cover thickness is small beyond this thickness.

In an area were cold winters are recorded, but no permafrost exists, the method may be utilized to generate permafrost in the tailings and to accelerate consolidation due to freezing. Detailed numerical modeling and field investigations are recommended for such a situation that considers local soil and climate properties. However, the studies have shown that freezing can be reached at mean annual air temperatures above zero degrees centigrade within typical life time of mine operations. Possible thaw of the tailings during warm summer months has to be considered in the design.

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