Convective heat transfer in waste rock piles under permafrost environment

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ABSTRACT
Reaching and maintaining sub-freezing temperatures within waste rock piles is of significant interest for the mining industry in the North as a method of limiting or eliminating acid rock drainage. Some of the rock mined to gain access to the valuable ore contains sulfides, which become a source of sulfuric acid when exposed to the atmosphere. Temperature data from a small scale test waste rock pile that was constructed at the Diavik Diamond Mine site will be presented and were used to calibrate other measured parameters (thermal conductivity and air permeability) and predict future temperature developments. The effects of impeded-impervious layer show clearly the reduction of inward flux of oxygen and also heat in summer. Without the existing of low permeable layer the field temperature clearly indicates the convection of air with air moves inward from side slopes and outward on the top in winter and oppositely in summer. Initial modelling results show that the convective cooling can lower the temperature the core of waste rocks about 5^{o}C after nine winter season but the active layer will be deeper.

RÉSUMÉ
L'atteinte et le maintien des températures congelée dans les piles de roche est d'intérêt significatif pour l'industrie minière dans le nord comme méthode de limiter ou d'éliminer le drainage acide de la roche. Une partie de la roche extraite pour accéder au minerai valable contient les sulfures, qui deviennent une source d'acide sulfurique dès que exposés à l'atmosphère. Les données initiales de la température d'une pile de roche à échelle réduite qui a été construite à l'emplacement de Diavik Diamond Mine sera présantée. Ils ont été employées pour calibrer des paramètres mesurés (convection thermique et perméabilité d'air) et pour prévoir de futurs développements de la température. Les effets d'un banc internes imperméable montrent clairement la réduction de flux de l'oxygène vers l'interieur et la chaleur thermique en été. Sans banc internes la température dans les piles de roche indique clairement la convection d'air avec des mouvements d'air vers l'intérieur des côtés du talus et l'extérieur par le bord supérieur en hiver et inversement en été. Les résultats modelants préliminaires prouvent que le refroidissement convecteur peut abaisser la température dans le centre de les piles de roche de 5°C après neuf hivers, mais la couche active du pergélisol sera plus creuse

1 INTRODUCTION

Acid drainage from mine waste rock piles or chemicals from tailing ponds entering the food chain have severe impacts on the environment and aboriginal communities in northern regions. Cold winter temperature conditions at most mine sites have the potential to reduce these problems (e.g. Kyhn and Elberling 2001). Numerical studies showed that in a permafrost environment natural air convection can be utilized to freeze and to keep coarse waste rock piles frozen (Klassen et al. 2007). This may prevent acid generation in mine waste rock piles or by placing a coarse rock cover on top of a tailing pond, it can induce freezing more quickly and keep them frozen (Arenson and Sego 2007). In winter, the cold air cools down the rock pile because of a gravity driven flow of cold air. In summer, when the surface temperatures are warmer than the temperatures in the pile, the low thermal conductivity of the air protects the rock pile from warming because heat transfer is reduced to conduction, and only limited air flow is recorded.

The movement of air due to air convection also forces oxygen from one location to the other location inside the piles or from outside the piles depending on boundary conditions such as cover layers. The presence of oxygen promotes oxidation of sulphide minerals

Since 2004, three 14m (test pile 1&2) and 16m (test pile 3) high, large scale test waste rock piles have been constructed (Figure 1 & 3) solely for research purposes at the Diavik Diamond Mine site. using three different waste rock materials (Blowes et al. 2006). Amongst other parameters, temperatures are recorded inside the waste rock piles to investigate the phenomenon of natural convection and oxidation of pyritic materials.

The paper presents results from ongoing field data and numerical modelling of convective heat transfer in porous waste rock piles. Temperature data from the Diavik waste rock piles are available for approximately two years that are used as reference and model calibration, respectively.

Figure 2. Location of Diavik Diamond Mine Ltd

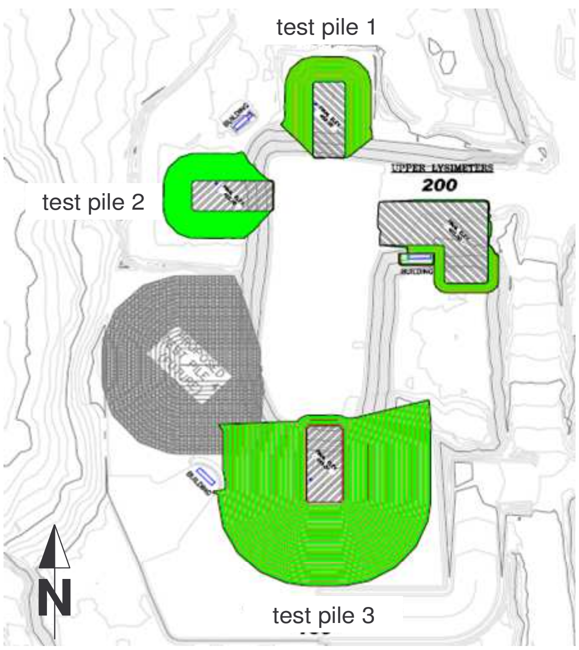

Figure 1. Location of the three test piles at the Diavik Diamond Mine site.

2 SITTE LOCATION AND FIELD DATA

2.1 Site location and configuration of test piles

The Diavik Diamond Mine is located on a 20 square kilometre island (Figure 2), informally called East Island, in Lac de Gras, approximately 300 kilometres northeast of Yellowknife. The Arctic Circle is located 220 kilometres north of the mine. The mean annual air temperature (MAAT) is estimated about -10^{o}C with an active layer of 4m (Mend report 1.61.4).

Figure 3. View on the front of test pile 2 during construction and placement of instruments in 2006 (Photo: Michael Gupton).

There are 3 test piles with different shape and configurations (Fig. 2 & 3). Test pile 1 and test pile 2 are small having the same angle but different materials with different pyritic contents (Figure 4 & 5). Test pile 3, or covered pile, is the biggest and containing combined materials with an impermeable layer (till) to separate them and to prevent the penetration of heat during summer and to eliminate the amount of oxygen by diffusion into the active mine waste.

Thermistor strings and other instruments such as gas line and TDR were installed at the faces where they were installed 5m from central line and also along the batter lines.

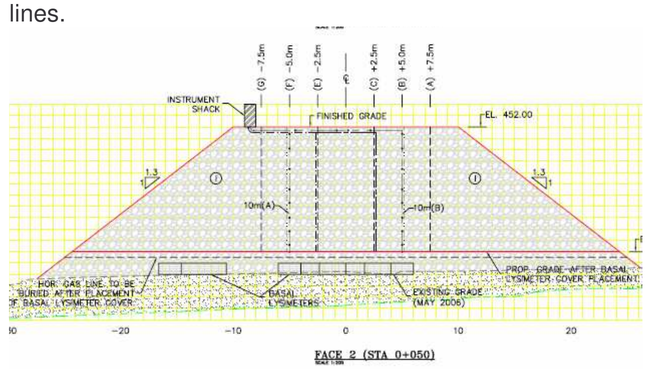

Figure 4. Typical cross section (Face 2) of Type 1 and Type 2 piles

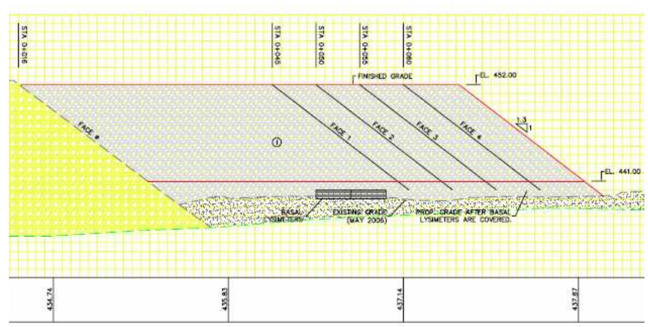

Figure 5. Longitudinal section of type 1 and 2 piles

2.2 Field data

In order to examine the impact of convective heat transfer on the temperatures of waste rock piles, the active layer can be utilized since it only formed by conduction. By comparing of the depth of the active layer, one can qualify the amount of heat transferred by convection and conduction.

The test site has an active layer of 4 meters (Figure 7) and show that the maximum and minimum recorded surface temperatures are 16.5°C and -27.1°C respectively from 2004 to 2008 where bedrock expose to surface.

Temperature data inside test piles 1 and 2 has been collected since Oct 4, 2006 up to March 18, 2008 and test piles 1 and 2 were constructed in June 2006. Figure 8 - 10 show maximum and minimum temperatures at face 2 of test pile 1. It was below 0°C during winter and above 0°C during summer. In addition, the irregular shape of the trumpet in Figure 9 and 10 compared with Figure 8, which temperatures gradually decrease and increase with depth during summer and winter respectively.

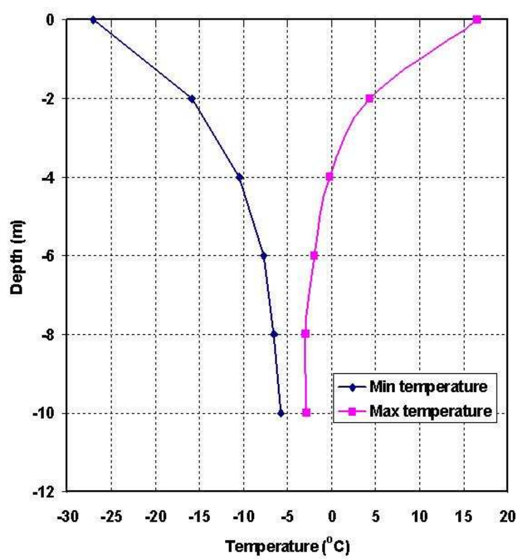

Figure 7. Trumpet curve of ground temperature at Diavik mine site.

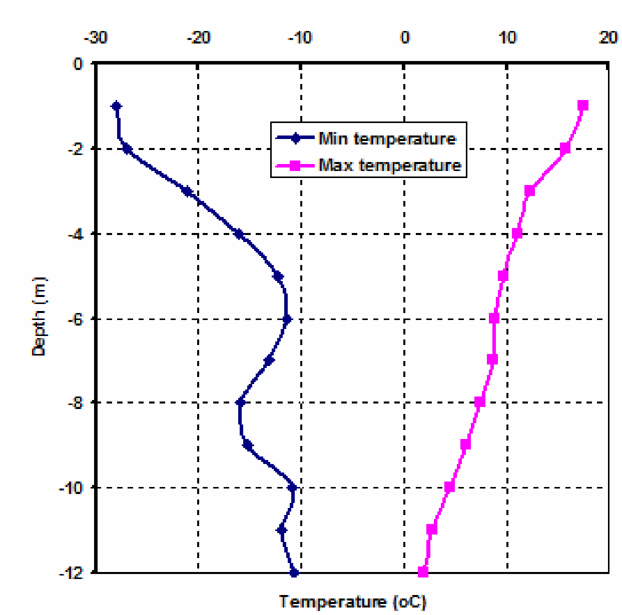

Figure 8. Trumpet curve of temperature of one vertical (2m-5m (2)) string at Face 1 of test pile 1 from the surface of test pile and shifted 5m to the left from centre line.

All of these indicate that other phenomena are happening along with conduction such as convection in which heat is removed by the moving air or oxidation of pyrite releasing heat about 1440 kJ/mol (O'Kane, 1995).

Figures 11 and 12 show similar temperatures of test pile 2 as shown in Figure 8 - 10 for test pile 1 the active layer of test pile 1 and 2 reaches to the base of the test piles.

During winter test pile 1 is colder than test pile 2 (compare Figures 11&12 to 9&10). This could be an effect of the greater permeability of test pile 1or the concentration in test pile 1 is less. In summer the maximum temperature is about the same due to the fact that in summer only conduction occurs in the waste rock piles, which have similar thermal conductivities.

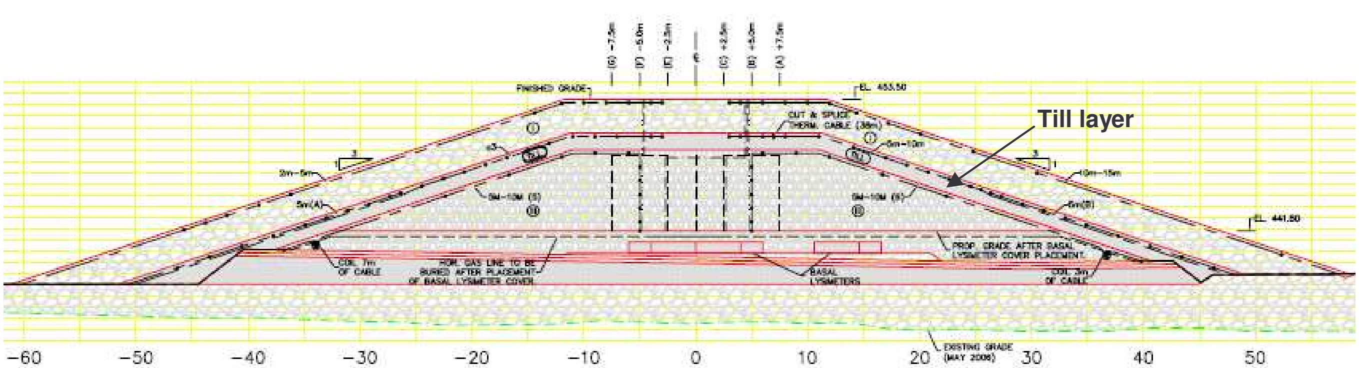

Figure 6. Typical cross section (Face 3) of Type 3 (covered pile) with locations of thermistors and other instruments

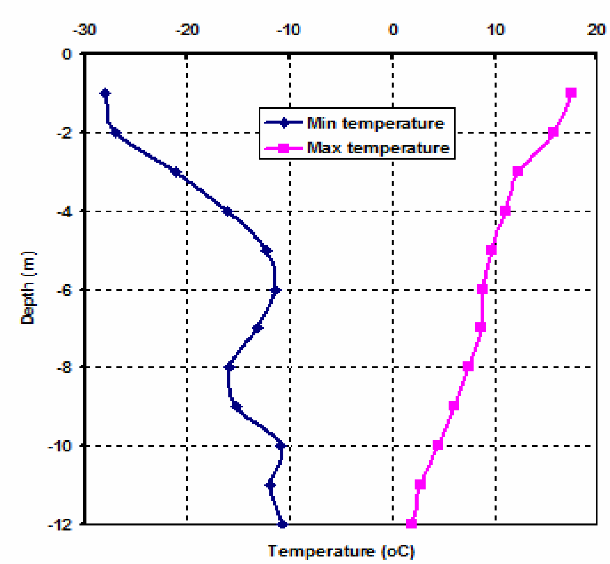

Figure 9. Trumpet curve of temperature of one vertical (2m-5m (2)) string at Face 1 of test pile 1 from the surface of test pile and shifted 5m to the left from centre line.

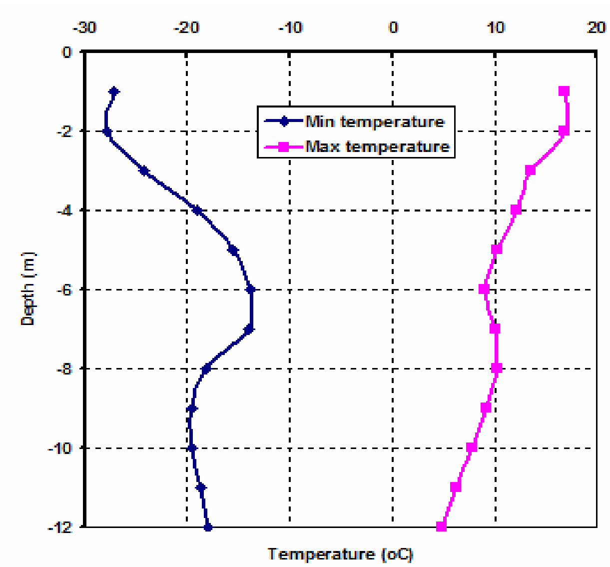

Figure 10. Trumpet curve of temperature of one vertical (2m-5m (3)) string at Face 1 of test pile 1 from the surface of test pile and shifted 5m to the right from centre line.

Temperature contours of test pile 1 & 2 (Figure 13 & 14) on March 18, 2008 conform what is shown in Figure 9 – 12. Temperatures are all below zero and hottest in the middle and coldest at the top. The shape of the contour alone is different from one due to conduction proves that convection or oxidation is occurring along with conduction. Based on the temperature contour (Figures 13 & 14) test pile 1 seems to be colder than test pile 2.

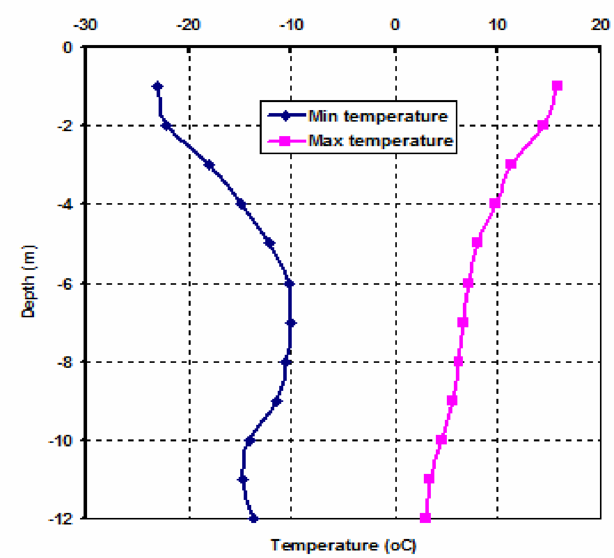

Figure 11. Trumpet of temperature of 5m-10m (6)) string at Face 1 of test pile 2 from the surface of test pile

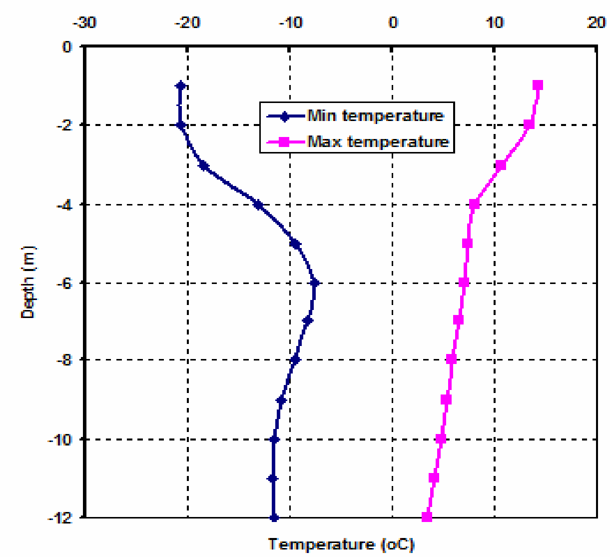

Figure 12. Trumpet of temperature of 5m-10m (3)) string at Face 1 of test pile 2 from the surface of test pile

Test pile 3 (covered pile) is recording temperature data since July 2007 and it is not in steady state condition yet. As a result, the temperature trumpet will shift over time but not like in test pile 1 and 3. The temperatures below the till layer (impermeable) are not susceptible to surface temperatures due to that fact that till layer is preventing the penetration of cold air by convection. Heat transfer to the space below the till layer is limited to conduction, which is slow. In addition, the till layer prevents acid mine drainage (AMD) by slowing the influx of oxygen (Nicholson et al. 1989).

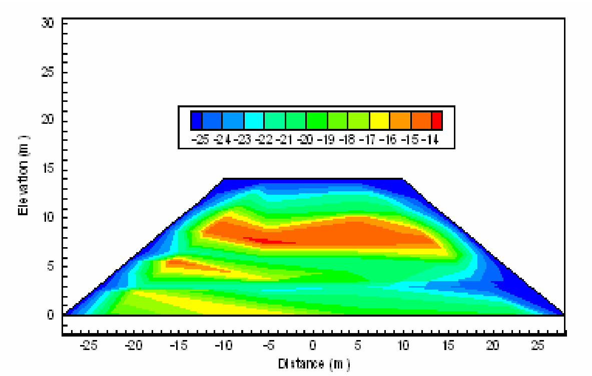

Figure 13. Temperature contour of test pile 1 at face 4 on March 18th 2008.

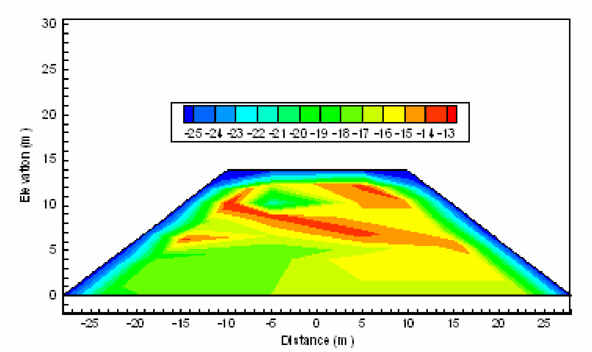

Figure 14. Temperature contour of test pile 2 at face 4 on March 18th 2008.

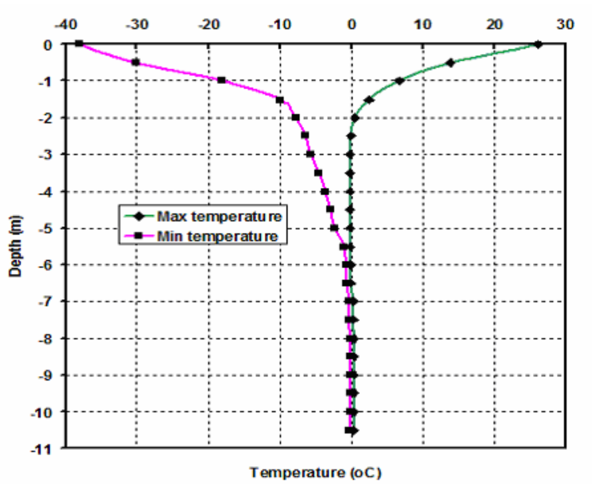

Figure 15. Trumpet of test pile 3 (covered pile) at center cross section

The temperature contour (Figure 16) shows that the highest temperature area of the internal layer is right below the till layer. This can be explained as follows: The rate of oxidation of pyritic material within the test pile 3 depends on the supply of oxygen. The transport of oxygen within the waste rock piles can occur by diffusion, convection, and advection. Because of the till layer barrier, it can reduce inward transport of oxygen from the atmosphere by convection, diffusion and advection (the infiltration of water carrying dissolved oxygen).

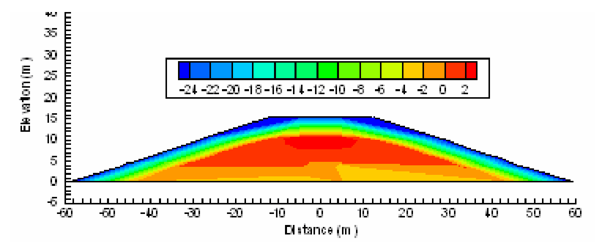

Figure16. Contour temperature of test pile 3 (covered pile) at face 2 March 18, 2008

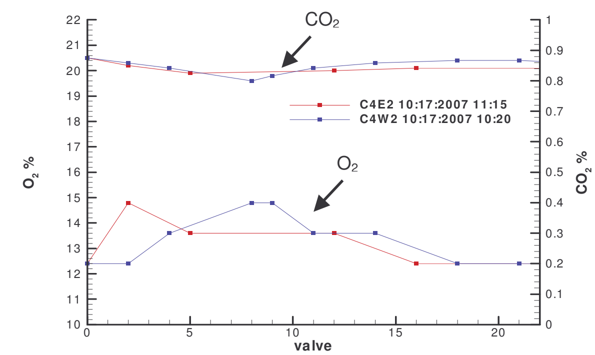

Figure 17. Concentration of O_2 and CO_2 at Face 4 of test pile 3 (Rich Amos, 2008)

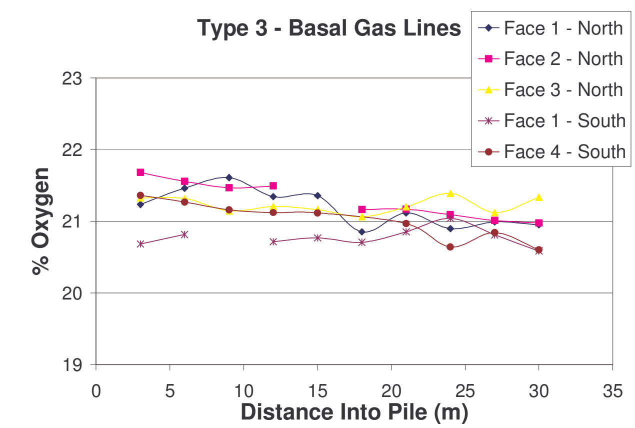

Figure 18. Concentration of O_2 and of test pile 2 (Rich Amos, 2007)

The concentration in oxygen in test pile 3 (Figure 17) is about 7% lower than that in test pile 2. Therefore, the rate of oxidation is low and also the heat release. As a result, the temperatures inside test pile 3 are low.

The concentration in oxygen in test pile 2 (Figure 18) is much closed to that of the atmosphere and thus the oxygen supply is high. In consequence, the rate of oxidation is high and also heat productive. In addition, the rate of oxidation also depends on temperature. The optimal growth temperature for iron-oxidizing bacteria is between 20-35^{o}C. The activity of bacteria generally decreases to zero when temperature is lower than 4^{O}C (Guo, 1993) and at -10^{O}C all oxidation is ceased (Mend report 1.61.4). As a result, temperature is high during summer in test pile 1 & 2 (Figure 9 - 12).

3. NUMERICAL MODELING

3.1 Waste rock pile material properties

All parameters for test piles 1, 2 and 3 were collected during summer 2007. The results for the intrinsic permeability of the waste rock at Diavik show higher values than for other mine sites; however the variation is smaller (Table 1). The values for the thermal conductivity are lower than at the Kelian and Rum Jungle mines

Table 1. Intrinsic permeability of test piles at Diavik and other mines (Rich Amos, 2008).

Minesite	Range (m^2)
Diavik – Type 1	**5.0×10^{-10} – 3×10^{-9}**
Diavik – Type 3	**2.0×10^{-10} – 3×10^{-9}**
Aitik Mine, Sweden	2.6×10^{-11} – 1.4×10^{-9}
Heath Steele, Canada	1.6×10^{-10} – 4.7×10^{-9}
Kelian, Kalimantan	3.9×10^{-13} – 9.3×10^{-10}
Rum Jungle, Australia	8.89×10^{-13} - 1.49×10^{-9}

Table 2. Thermal conductivity waste rock at Diavik and other mines (Rich Amos, 2008).

Minesite	Range ($W\ m^{-1}\ K^{-1}$)	Average ($W\ m^{-1}\ K^{-1}$)
Diavik – Type 3	**1.00 – 2.73**	**1.79 ± 0.6**
Diavik – Type 1	**1.34 – 2.77**	**1.86 ± 0.3**
Diavik - Covered	**1.00 – 2.18**	**1.72 ± 0.6**
Aitik Mine, Sweden	0.71 – 1.63	1.2 ± 0.4
Heath Steele, Canada	1.04 – 1.22	1.2 ± 0.1
Kelian, Kalimantan	1.57 – 3.31	2.1 ± 0.6
Rum Jungle, Australia	1.77 – 3.12	2.2 ± 0.5

3.2 Results of Numerical Modeling

The modelled temperatures of test pile 1 and 2 at 5m from the central line are shown in Figure 19 for an intrinsic air permeability $K=3\cdot10^{-9}$ m^2. Comparing with field results demonstrates a good match with the field data for the maximum temperature but not for the minimum temperatures. As mentioned previously, the maximum temperature during summer in which conduction is dominated, mainly depend on the thermal conductivity, which was measured exactly. The minimum temperatures, on the other hand, are controlled by convection during winter, and convection is controlled by the thermal conductivity and the air permeability. The later is difficult to measure accurately due to the heterogeneity of the waste rock pile.

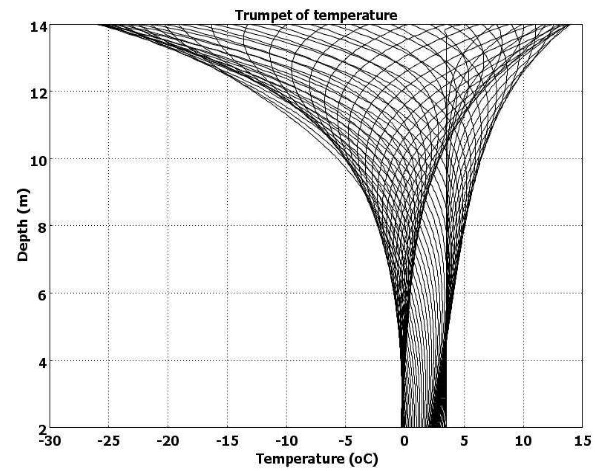

Figure 19. Trumpet of temperature at line shifted 5m from center line 650days after construction with K = 3.10^{-9} m^2

If K is small, the heat transfer is conduction dominated during winter. Resulting consequence, the modeled temperatures do not match with the field data.

By increasing the value of K to $1.10^{-7}m^2$ the values of the minimum temperature are close to field data at the lower part (deeper than -5m) but not at the upper part (Figure 20). The modeling shows that it is impossible to reproduce the field data using homogenous conditions. In addition, heat release by oxidation is not integrated in the numerical models. However, in order to get results comparable to field data, it is necessary to couple chemical reaction (oxidation of pyrite) with heat and mass transfer.

During convective heat transfers, cold air flows into the waste rock pile through the side slopes and leaves through the top during winter. In contrast, during summer warm air flows in from the top and leaves through the side slopes (Figure 21& 22).

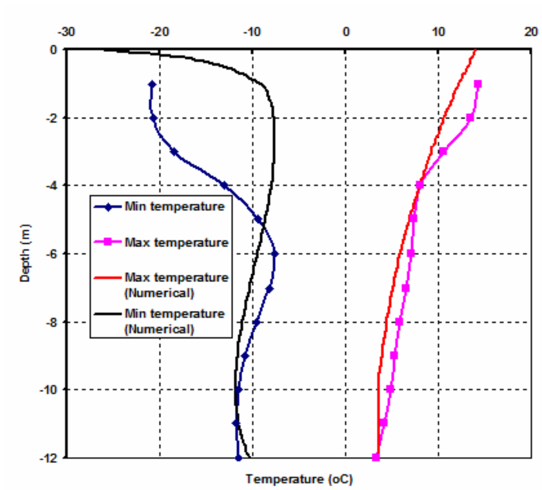

Figure 20. Comparison between field data (5m-10m(3)) with numerical modeling with air permeability **K = 1.10^{-7} m^2**

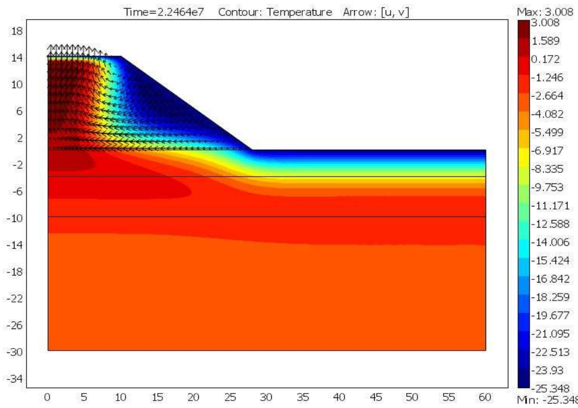

Figure 21. Temperature profile at the first winter with K = $1.10^{-7}m^2$

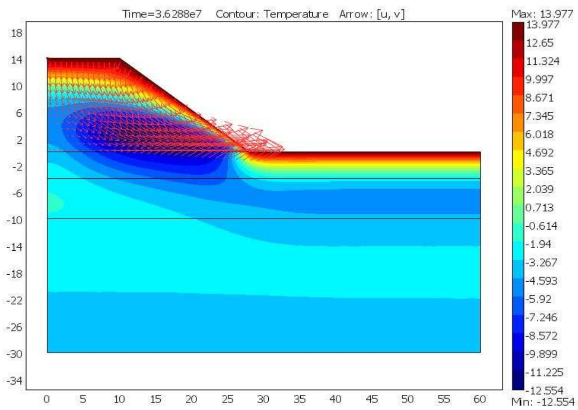

Figure 22. Temperature profile at the first summer with K = $1.10^{-7}m^2$

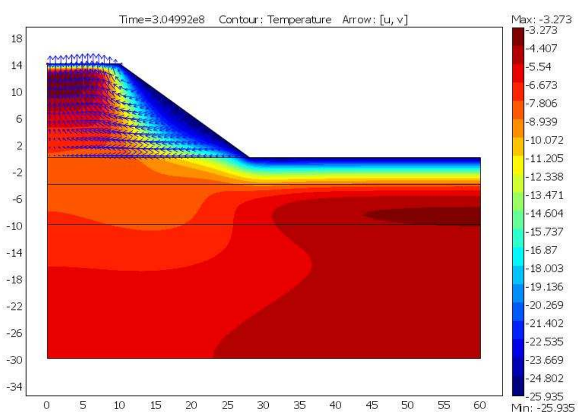

Figure 23. Temperature profile at the ninth winter with K = 1.10^{-7} m^2

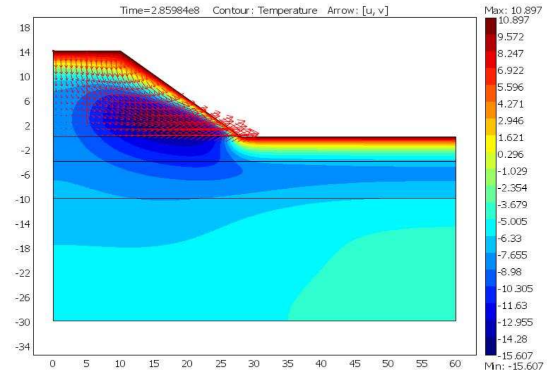

Figure 24. Temperature profile at the ninth summer with K = 1.10^{-7} m^2

During convective heat transfers, cold air flows into the waste rock pile through the side slopes and leaves through the top during winter. In contrast, during summer warm air flows in from the top and leaves through the side slopes (Figure 21& 22).

By comparing Figures 21 and 23, it can be shown that after nine years the core of the waste rock pile is about 5℃ colder than after the first year. Due to the change in temperature difference between the air temperature and the pile temperature the magnitude of air velocity in the waste rock pile is smaller after nine years. Similar results are presented in Figure 22 and 24. The active layer of the waste rock pile is reduced to 3m.

The active layer of test pile 1 and 2 for the case of K = $1\cdot10^{-7}$ m^2 is deeper than that for pure conduction (Figures 25 and 26). In the case for K=$1\cdot10^{-7}$ m^2 heat transfer is convection dominated with a deeper active layer, but temperatures below the active layer are significantly colder than in the case of pure conduction. The temperatures vary between -10℃ to -15℃ compared to -5°C for the conduction case (Figure 26). The temperature below the active layer is approximately 5℃ colder if convection occurs compared to conduction alone.

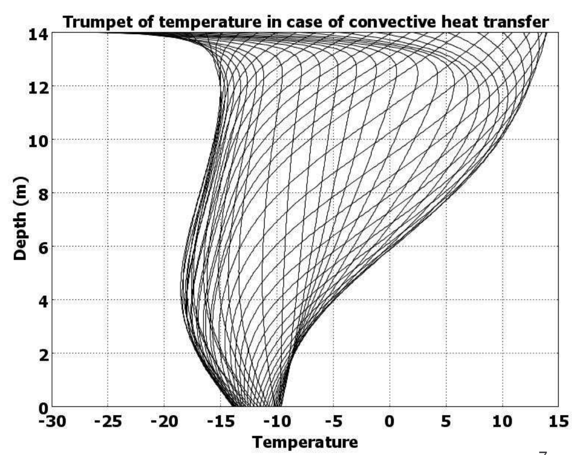

Figure 25. Trumpet of temperature in case of K=10^{-7} m^2

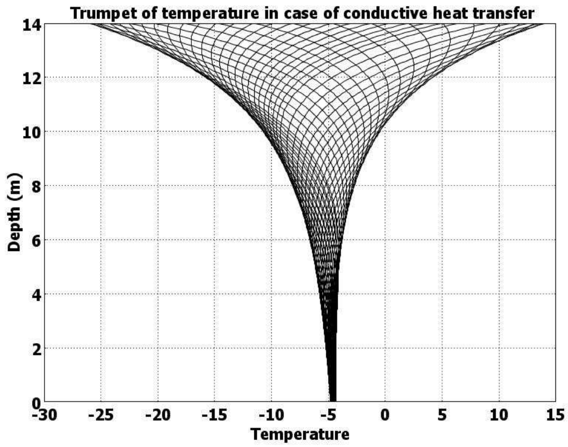

Figure 25. Trumpet of temperature in case of conduction or low values of air permeability ($K < 3.10^{-9}$ m^2)

4. CONCLUSIONS

Heat and mass transfer in porous, heterogeneous waste rock materials under permafrost conditions are complex. Based on in situ temperature monitoring and numerical modeling the following conclusions can be drawn:

- The existence of layers with low air perm abilities in the waste rock piles can reduce not only the penetration of heat (by latent heat of water) during summer but also the diffused oxygen concentration (from 21% to 14%) beneath the layer. As a result, AMD is reduced.
- In the two non-layered test piles, the core temperature after 9 years is approximately 5℃ lower than after the first year.
- It is difficult to match results from numerical modeling with the field data recorded where convective heat transfer dominates because of the heterogeneity within the waste rock piles.
- Cold air penetrates into the waste rock through the side slopes and rises through the center during winter.
- Without a low permeability layer convective heat transfer results in an increase in active layer depth, but the permafrost temperatures are significantly colder than for conduction alone.

ACKNOWLEDGEMENTS

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