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# Evaluation of cover system field trials with compacted till layers for waste rock dumps at the Boliden Aitik copper mine, northern Sweden

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## ABSTRACT

The Boliden Aitik copper mine is located outside Gällivare, northern Sweden. Since mining started in 1968, more than 500 Mt of waste rock have been deposited in waste rock dumps (WRDs). In the 1990s, a dry cover system was designed to reduce oxygen diffusion to the underlying waste rock and limit the subsequent formation of metal leaching and acid rock drainage (ML/ARD). The original cover system (applied to WRD5 and parts of WRD2) consists of 1.0 m compacted till placed in two lifts covered by 0.3 m organic material. Recent studies concluded that predicted annual diffusion flux estimates based on calibrated soil-plant-atmosphere modelling were similar in magnitude, but greater than, rates predicted in the 1996 design. Therefore, to increase the level of water retention within the compacted till and reduce oxygen ingress to the underlying waste rock, increased compaction from the current practice is required.

Multiple field and laboratory studies were completed to evaluate the cover system design and performance. Field compaction trials conducted in 2012 confirmed that increased compaction would enhance water retention characteristics within the cover system. A field study of freeze / thaw effects on the compacted till highlighted frost penetration to the compacted layer as an area of concern for long term performance of the cover system. Cover system trials implemented in 2013 were instrumented with monitoring instrumentation that will allow performance to be evaluated over time under site-specific conditions, providing essential insight into cover system response to climatic variations in terms of temperature and water storage dynamics.

**Key Words:** field performance monitoring, water retention capability, oxygen ingress

## INTRODUCTION

The Boliden Aitik copper mine (Aitik) is located outside Gällivare, in northern Sweden. Since mining started in 1968, more than 500 Mt of waste rock have been deposited in waste rock dumps (WRDs). The Aitik site is located in a seasonally humid environment, subjected to frozen conditions for approximately half the year. Major seasonal weather events include spring snow melt and heavy rains in the late fall. In the 1990s, a dry cover system was designed to reduce oxygen diffusion to the underlying waste rock and limit the subsequent formation of metal leaching and acid rock drainage (ML/ARD). The original cover system consists of 1.0 m compacted till placed in two lifts covered by 0.3 m organic material. As part of ongoing reclamation activities at Aitik, this dry cover system design has been applied to WRD5 and parts of WRD2.

Recent studies found that predicted annual diffusion flux estimates based on calibrated soil-plant-atmosphere modelling were similar in magnitude, but greater than, rates predicted in the 1996 design. It was hypothesized that increased compaction from the current practice was a feasible option to increase the water retention capability of the compacted till layer, and reduce oxygen ingress to the underlying waste rock. To test this hypothesis, a compaction field trial program was completed to evaluate the relationship between compaction methods and achievable water retention characteristics (as determined by measurements of *in situ* dry density and hydraulic conductivity). Based on this relationship, an improved cover system design was developed. To improve understanding of the *in situ* performance of this cover system, cover system trials were designed, constructed, and instrumented.

## METHODOLOGY

Methodology for this study involved compaction field trials, completed in September 2012, to measure achievable *in situ* dry density and hydraulic conductivity. A follow up testing program was completed in May 2013 to determine the effect of a freeze / thaw cycle on the compacted till layers. Cover system field trials were then designed using results of the compaction field trial program to determine optimum compaction methodology for the compacted till layers. Instrumentation installed in the cover system field trials allow for assessment of the cover system performance under site-specific conditions.

### Compaction field trials

Compaction field trials were conducted in September 2012 for the purpose of determining the optimal method of construction and achievable level of compaction in terms of *in situ* dry density and minimum field permeability for a compacted till layer at Aitik. The previous methodology for constructing compacted till layers at Aitik consisted of compacting six passes with a 6 ton smooth-drum roller over ~50 cm lifts. The purpose of the compaction trials was to replicate and assess the level of compaction achieved for a compacted till layer using the previous construction methodology and evaluate the level of compaction achieved on a 50 cm lift compared to that achieved on a thinner 30 cm lift. Additional testing evaluated alternative compaction equipment (a 10 ton smooth-drum roller, and 6 ton pad-foot roller) on the 30 cm lift.

The compaction trials were established in an area approximately 60 m x 40 m wide on a surface of compacted, relatively smooth, waste rock that included both a relatively flat and a sloped surface. Each trial pad was approximately 60 m in length and 10 m in width, which accommodated the compaction equipment to create at least a three-pass-wide compacted surface.

For the reason that a significant potential exists for the permeability of a compacted layer to increase as a result of freeze / thaw cycling, a follow-up test program was implemented in the spring of 2013 to assess the effect of one freeze / thaw cycle on *in situ* density and field permeability of the compacted layers. Following completion of the compaction trial test program in 2012, the trial area was covered with a geotextile fabric and a layer of overlying till approximately 0.5 m thick. The fabric was placed immediately over top of the compacted layers to allow for differentiation between the overlying till and the compacted till layer.

### *Sampling and Laboratory Analyses*

Two large samples (~40 kg) of till were collected from each compaction trial pad. Laboratory analyses included determination of particle size distribution (SS-EN 933-1, 2012), compaction testing (SSEN 13286-2, 2010), Atterberg limits (ASTM, 2010), and determination of specific gravity (ASTM, 2010). Distributions of particle sizes larger than 75 μm were determined by sieving, while the distributions of particle sizes less than 75 μm were determined by a sedimentation process using a hydrometer. Standard Proctor and Modified Proctor compaction tests were conducted on each sample to determine compaction characteristics.

### *In Situ Testing*

A nuclear densometer was used to measure *in situ* density and water content (ASTM D 2922, 2005). During the 2012 compaction trials, 86 nuclear densometer measurements were taken at the surface (from a depth of 0 – 20 cm), while 12 nuclear densometer measurements were taken at depth on the 50 cm trial (20 – 40 cm). Small samples of till were collected throughout the testing program for laboratory determination of gravimetric water content (ASTM D2216, 1992); the primary purpose of this sampling effort was to use gravimetric water content results to correct *in situ* dry density measurements taken with the nuclear densometer. A total of 32 additional nuclear densometer tests were completed during the 2013 testing program (after freeze / thaw). Three techniques were used to measure *in situ* permeability, or field saturated hydraulic conductivity ($K_{fs}$) of the compacted layers: a Guelph permeameter (described in Mohanty et al., 1994) a pressure infiltrometer (described in Reynolds and Elrick, 1990), and borehole permeameters (ASTM, 2011).

### **Cover system field trial design and construction**

Two cover system trials were constructed in the summer of 2013 over waste rock on WRD6. Based on results obtained during the compaction field trial program, a maximum till lift thickness of 0.3 m was implemented for construction of the compacted till layers, compacted at 1 – 2% wet of optimum water content to increase dry density through the lift profile and minimize hydraulic conductivity. In terms of methodology, a minimum of six passes with a 10 ton smooth-drum roller (using maximum vibratory action) was used. Cover System Field Trial # 1 was constructed using the ‘preferred’ design alternative: 0.3 m compacted till, overlain by 1.0 m non-compacted till, overlain by 0.3 m till and organic mixture. Cover System Field Trial #2 is the ‘conservative’ design alternative, consisting of 0.3 m compacted till, overlain by 1.5 m non-compacted till, overlain by 0.3 m till and organic mixture. Both trials are comprised of relatively flat plateau sections approximately 50 m wide by 50 m in length, and sloped areas (~3H:1V). The total footprint of the cover system field trials is approximately 1 ha.

The purpose of the cover system field trials is to track the evolution of the cover systems in response to site-specific processes (physical, chemical, and biological) to enhance understanding of key characteristics and processes that control cover system performance, and to assess and compare performance of the two cover system design alternatives. Cover system performance will be assessed in terms of susceptibility of the compacted till layer to freezing, the degree of saturation through the cover system profile, and net percolation to the underlying waste rock. To evaluate cover system performance, the cover system trials were instrumented with:

- A meteorological station, including:
  - a tipping bucket rain gauge for continuous monitoring of rainfall at the site;
  - a net radiometer to record daily totals of net solar radiation;
  - a sonic ranging sensor for continuous monitoring of snowpack depth; and
  - an air temperature sensor.
- Automated monitoring stations for measuring *in situ* volumetric water content, matric suction (i.e. negative pore-water pressure), temperature, and oxygen concentration in the cover system / upper waste rock profile every six hours.
- Manual gas sampling stations for monitoring the oxygen content within the cover system and upper waste rock materials using a portable gas detector.

## RESULTS AND DISCUSSION

### Laboratory test results

Results of particle size distribution testing indicate that the till used for the compaction trial program was generally well-graded from 1 to 30 mm and deficient in the range of particles smaller than 1 mm. The samples collected contained a range of 30 - 50% gravel, 33 - 52% sand, 15 - 20% silt, and less than 1% clay (Figure 1). The till material was screened to a maximum particle size of 100 mm. Atterberg Limits testing indicated that the till material is non-plastic.

Both Standard and Modified Proctor tests were employed for determining the compaction characteristics of the till material. The average maximum dry density and corresponding optimum water content as determined by the Standard Proctor test were 2.13 t/m$^3$ and 6.8%, respectively. The higher compaction energy of the Modified Proctor compaction test resulted in an average maximum dry density of 2.20 t/m$^3$ and a corresponding optimum water content of 6.2%. Density testing during the field program indicated that the higher compaction energy of the Modified Proctor test is more representative of the level of compaction achieved in the field.

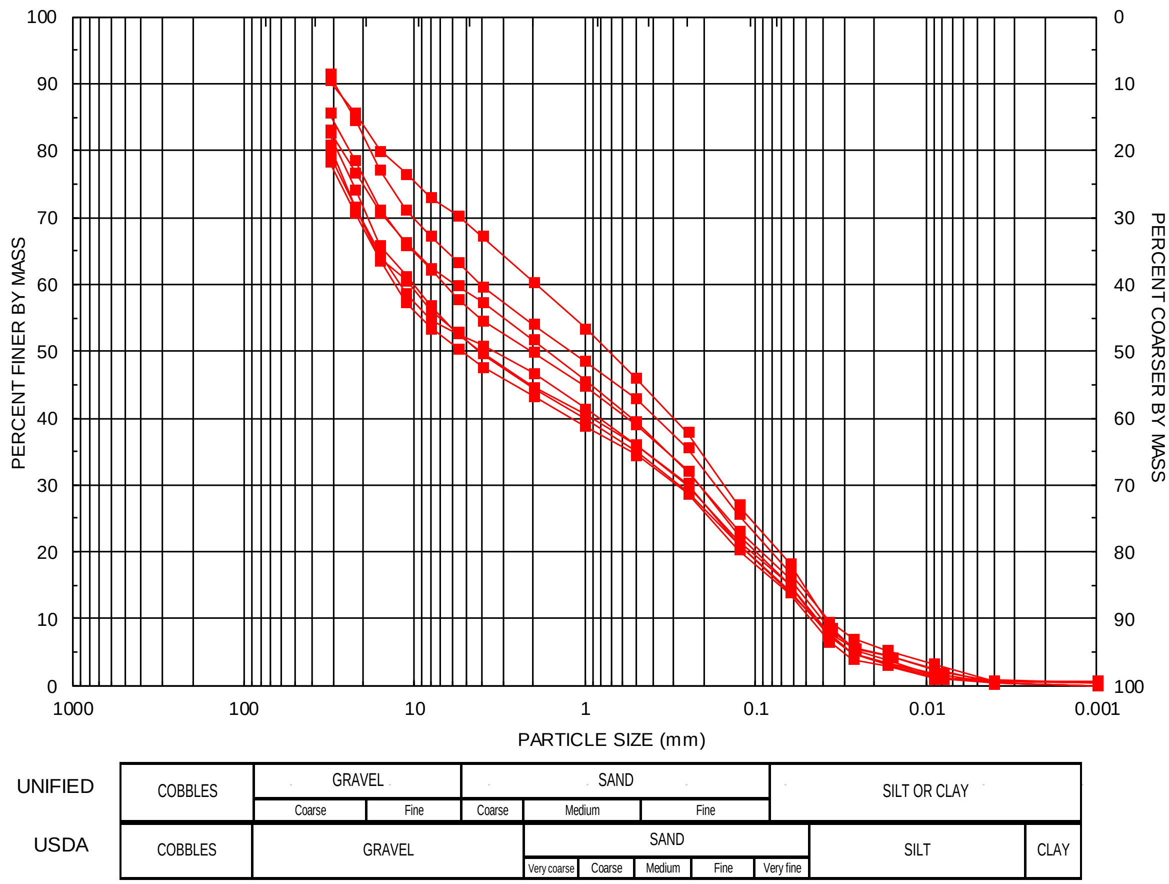


**Figure 1** Particle size distributions for till used in compaction trial test program

### Evaluation of compaction methodology

Results of compaction testing are summarized in Table 1. Six passes were sufficient to reach a maximum dry density for each test pad. Average dry density and water content values are presented for each test surface. Unless otherwise noted, nuclear densomer measurements were taken at the surface (0 to 20 cm depth).

**Table 1** Average *in situ* nuclear densometer measurements after various compaction treatments

| Lift thickness | Compaction treatment | Plateau $\rho_d$ (t/m³) | Plateau W.C. (%) | Slope $\rho_d$ (t/m³) | Slope W.C. (%) |
|---|---|---|---|---|---|
| (~50 cm) | 6 t smooth-drum roller | 2.09 ±0.03 | 9.1±1.0 | 2.10±0.05 | 8.4±1.0 |
| | 6 t smooth-drum roller (20 - 40 cm depth) | 2.03±0.07 | 8.6±1.0 | 2.01±0.07 | 7.7±1.5 |
| (~30 cm) | 6 t smooth-drum roller | 2.18±0.07 | 9.2±1.5 | 2.13±0.04 | 9.1±0.7 |
| (~30 cm) | 6 t pad-foot roller | 2.14±0.05 | 8.8±0.9 | 2.18±0.03 | 7.9±0.7 |
| (~30 cm) | 10 t smooth-drum roller | 2.23±0.09 | 8.2±1.3 | No data | |

Dry density in the 50 cm compacted layer was found to decrease with depth (Figure 2); this is attributed to the dissipation of compaction energy over the thicker lift. Results show that a higher dry density was achieved on a 30 cm lift compared to a 50 cm lift when subjected to the same compaction methodology (six passes with a 6 ton smooth-drum roller). It follows that the bottom 20 – 25 cm of material in the 50 cm compacted layer would not add any value in terms of increased cover system performance, and would therefore be more beneficial as part of the overlying till layer.

Evaluation of alternative compaction equipment on 30 cm lifts showed that compaction with a pad-foot roller was not beneficial in terms of achieving a higher dry density. The highest average dry density was achieved with a 10 ton smooth drum roller on the 30 cm lift (Figure 3).

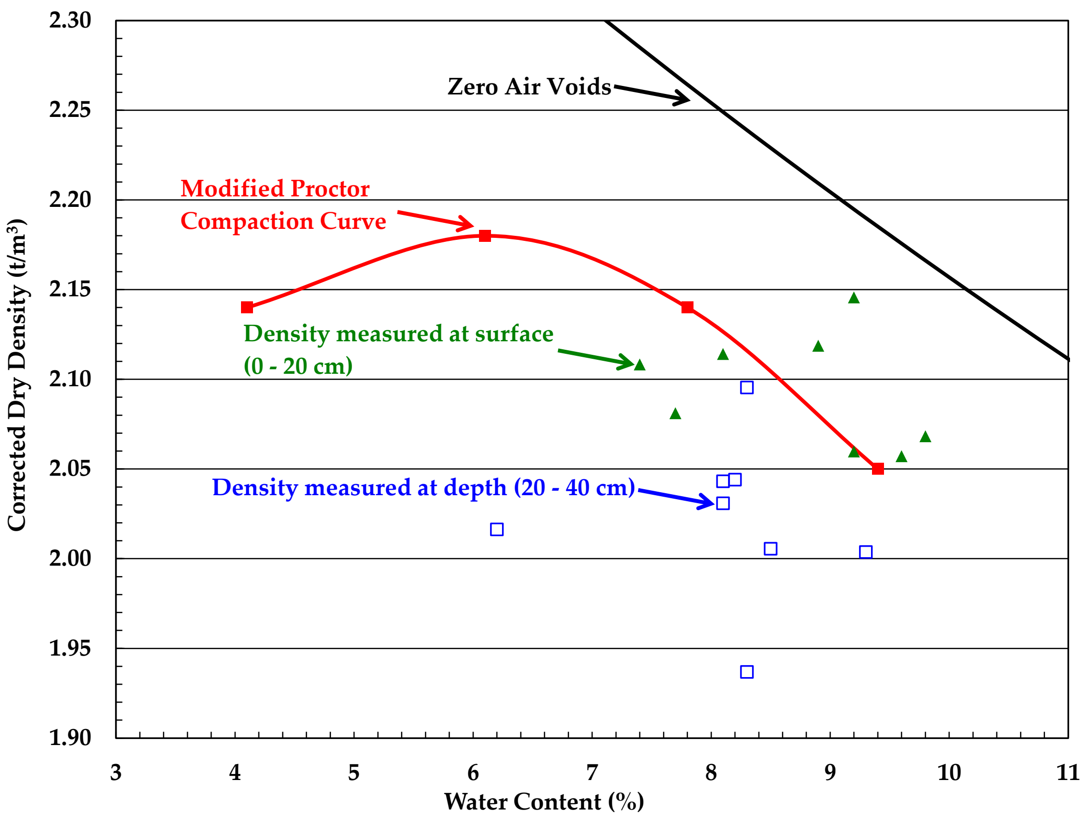


**Figure 2** Comparison of *in situ* density measurements at surface – 20 cm and 20 – 40 cm depth within 50 cm lift

The zero air void line shown in Figure 2 and Figure 3 represent the theoretical line at which the till layer is 100% saturated (i.e. pore space is occupied by water). The zero air voids line is an approximation based on a specific gravity value of 2.74 (based on laboratory results), but it is still useful for illustrating trends. It is apparent from Figure 3 that compaction of a 30 cm lift resulted in reduced porosity (void ratio), and thus would potentially result in a higher degree of saturation and be more beneficial to performance of the cover system.

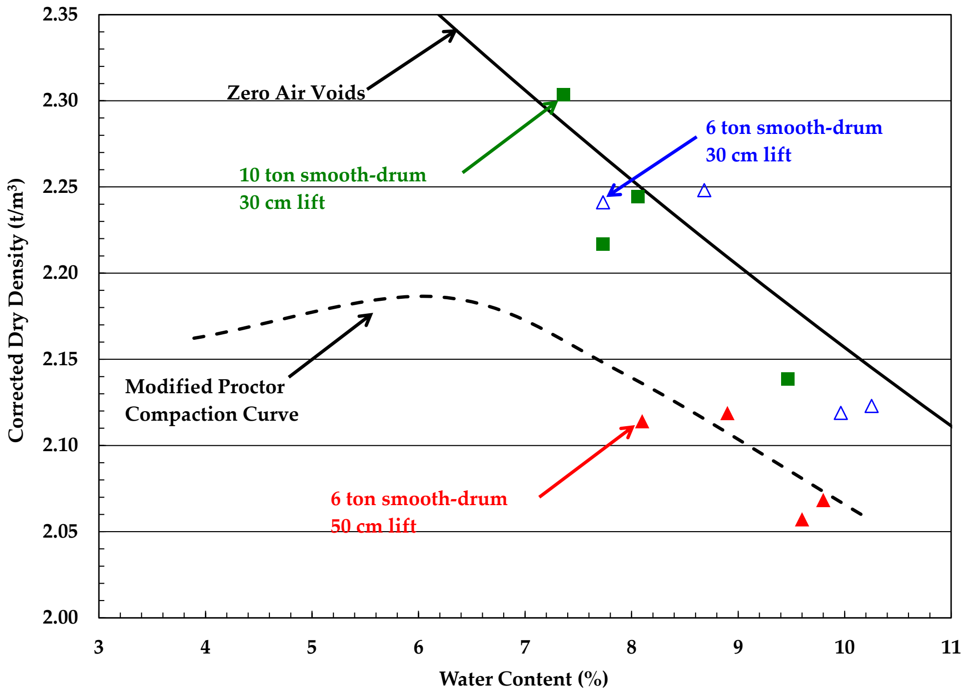


**Figure 3** Comparison of dry density measurements on plateau surfaces

$K_{fs}$ measured on the 30 cm thick test pads were in the range of 3 – 5 x $10^{-6}$ cm/s, while values measured on the 50 cm thick test pad were in the range of 6 – 8 x $10^{-6}$ cm/s. The lower $K_{fs}$ values measured on the 30 cm test pads compared to the 50 cm test pad were expected because of the higher density measured on the thinner lift. Compaction increases material dry density by decreasing void space within the compacted material. Decreased void space within the compacted till layer increases the tortuosity and, as a result, there are fewer open paths for water (or gas) to move through. For a compacted soil layer, an inverse relationship exists between the capacity to retain and transmit water (i.e. a lower $K_{fs}$ will generally result in higher levels of saturation). Thus, increased compaction achieved on the 30 cm lift leads to increased levels of water retention (degree of saturation) and lower rates of oxygen ingress.

### Follow-up testing on compaction field trials to assess effect of one freeze / thaw cycle

A follow up test program in the spring of 2013 evaluated how the compacted layers were affected by a single freeze / thaw cycle. Results of density testing showed that average dry density did not substantially increase or decrease after one freeze / thaw cycle for any of the compaction trial test pads. Results of $K_{fs}$ testing showed that the mean $K_{fs}$ did increase for each test pad, and maximum $K_{fs}$ increased by more than an order of magnitude for each test pad. Figure 4, a histogram (cumulative percentage) of $K_{fs}$ measurements before and after the freeze / thaw, shows that before the freeze / thaw, 100% of measured $K_{fs}$ measurements were lower than 6 x $10^{-6}$ cm/s, while in 2013, 0% were lower than 6 x $10^{-6}$ cm/s. The measured increase in $K_{fs}$ is attributed to the effects of freeze / thaw processes on internal structure of the compacted layer.

Svensson and Knutsson (2012) investigated how hydraulic conductivity in till at Aitik changes upon freezing and thawing in a laboratory setting. Results showed little change in hydraulic conductivity after four to eight freeze / thaw cycles for samples that were well compacted prior to freezing, and hydraulic conductivity never exceeded 2 x $10^{-5}$ cm/s. When soils are subjected to freeze / thaw cycling, layers of soil are separated by volumetric expansion of ice lenses that form during freezing. In a cohesive soil these fractures may not close fully during thawing; however, in a non-cohesive soil, some degree of self-healing will take place and hydraulic conductivity can be re-established. Therefore, a smaller increase in hydraulic conductivity is expected to result from freeze / thaw cycling in non-cohesive soils compared to cohesive soils (Eigenbrod, 1996; Viklander, 1998). Viklander (1998) found that the hydraulic conductivity of initially dense silty till generally increased by a factor of less than two when subjected to repeated freeze / thaw cycling. Viklander notes, however, that if the till includes stones there is a potential for the soil structure to be affected by movements of the stones during the freeze / thaw cycling.

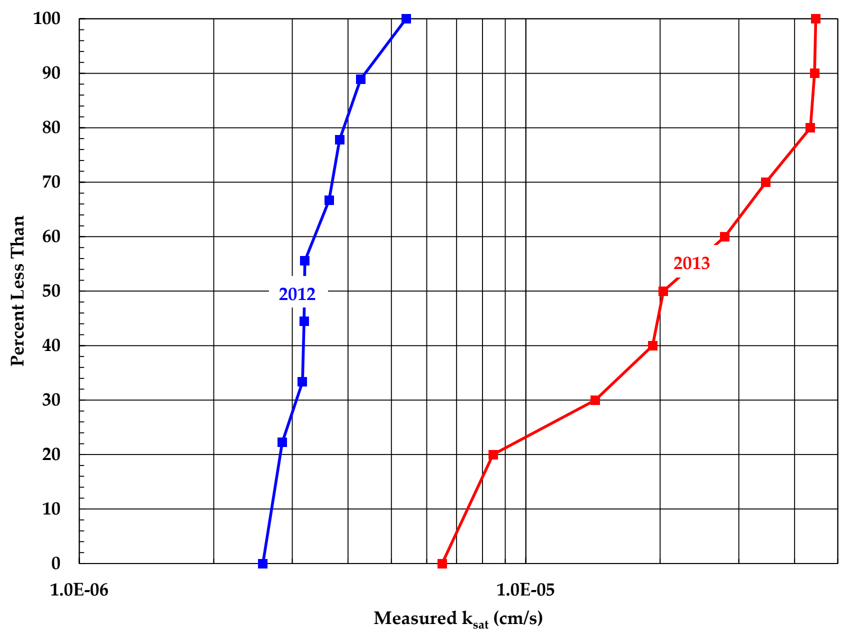


**Figure 4** Cumulative histogram of $K_{fs}$ values measured on compacted till layers in 2012 and 2013

In a compacted layer composed of non-cohesive till (such as that at Aitik) with stone inclusions, there is a potential for a single freeze / thaw cycle to result in an increase in hydraulic conductivity that would not have otherwise occurred in the same soil without stone inclusions (Viklander and Eigenbrod, 2000). Till used for the compaction trial study included stones of varying sizes; results of particle size distribution testing indicate that materials greater than 30 mm comprised, on average, 16% (by mass) of the till material. The presence of stones and the subsquent alteration of structure within the compacted layer caused by freeze / thaw processes was identified as a contributing factor to the measured increase in hydraulic conductivity on the compaction trial pads. Susceptibility of the compacted till layer's hydraulic conductivity to increase as a result of a single freeze / thaw cycle should be highlighted as a potential area of concern for the long-term performance of the cover system.

### *Depth of freezing front*

Findings from the compaction trial study highlight the importance of designing appropriate overlying layers and construction sequencing to complete construction of the cover system before freezing temperatures can alter the structure of the compacted layer. Temperature monitoring of the WRD6 cover system trials using profiles of thermal conductivity sensors show *in situ* temperatures within the cover system and waste rock profile for the first year of monitoring (Figure 5 and Figure 6). Data shows that the freezing front did not reach the compacted layer of either of the cover system trials during this period. While neither compacted layer was affected by frost penetration in this scenario, it is evident that there is an increased buffer zone for Cover System Trial #2 provided by the additional covering layer thickness compared to Cover System Trial #1.

The average air temperature for the winter of 2013-14 (November to April) was -5.4°C, which is significantly ($p > 0.05$) higher than the 5 year site average measured at the WRD5 monitoring station (-6.9°C). It should be noted, however, that penetration of freezing temperatures for a given soil is not dependent solely on air temperature. Additional factors include, vegetative cover, snow cover, and antecedent water content within the cover system profile. The cover system trials were completed in the summer of 2013, providing time for the overlying layers of the cover system to wet up in response to climatic events, and for some vegetation to become established. The compacted layer is likely to be particularly susceptible to freeze / thaw cycling in the first year following construction as vegetation coverage will not be fully established before winter. Snow is an effective insulator, inhibiting the transfer of energy out of the cover system that would be necessary to decrease temperatures within the cover system profile. Lack of vegetative cover during the first winter following installation of monitoring instrumentation, and consequent lack of snowpack would contribute to lower temperatures within the cover system profile. High water contents within the cover system profile may result in a greater amount of energy required to be released for the cover system profile to freeze. If the cover system performs as designed, water content within the profile will remain high, resulting in higher *in situ* temperatures for a longer period of time relative to a cover system with a lower water content. Monitoring of *in situ* water storage dynamics and thermal regimes as well as meteorological parameters at site is necessary to confirm the cover system is performing as designed.

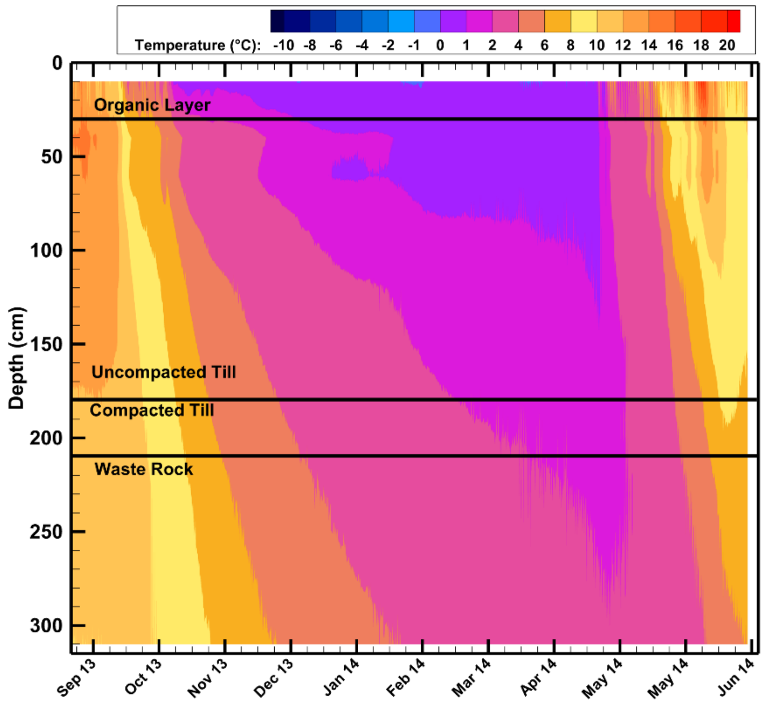


**Figure 5** *In situ* temperature measured within the cover system and waste rock profile of cover system field trial #1.

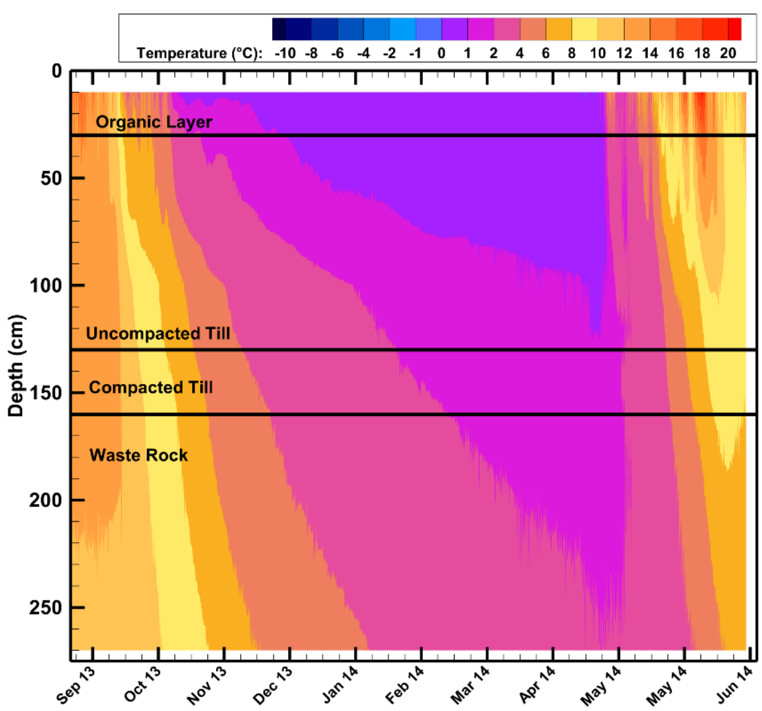


**Figure 6** *In situ* temperature measured within the cover system and waste rock profile of cover system field trial #2.

## CONCLUSIONS

Multiple field and laboratory studies have been completed at Aitik to achieve the overall objective of developing a reclamation design for the WRDs that will provide the necessary control on oxygen diffusion rates to waste rock material over the long term. Recent studies found that predicted annual diffusion flux estimates based on calibrated soil-plant-atmosphere modelling were similar in magnitude, but greater than, rates predicted in the 1996 design. It was hypothesized that by improving the methodology of compaction for the compacted till layer within the cover systems at Aitik, increased levels of water retention (degree of saturation) could be achieved, reducing potential oxygen ingress into the underlying waste rock. This hypothesis was tested by completing compaction field trials in 2012. Findings from this study confirmed the hypothesis; results showed that dry density was higher and $K_{fs}$ was lower in a 30 cm layer when compared to a 50 cm layer when subjected to simliar compaction energy.

Two cover system field trials were designed based on results of the compaction trial testing. The cover system trials included various monitoring instrumentation that allow the performance to be evaluated over time under site-specific conditions, providing essential insight into cover system response to climatic variations in terms of temperature and water storage dynamics., thus providing greater confidence in full-scale cover system design.

Results of a field investigation in 2013 showed that increased $K_{fs}$ as a result of freeze / thaw processes should be highlighted as a possible area of concern for the long term performance of the cover system. The potential for the freezing front to penetrate to the compacted layer is dependent on factors such as air temperature, snowpack, antecedent water content, thickness and composition of the overlying layer, and vegetative cover. First year monitoring data from the cover system field trials show that the freezing front did not reach the compacted till layers. Continued monitoring of meteorological and water balance components is necessary to determine an accurate representation of *in situ* cover system performance.

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