Thermal conductivity of Meadowbank's mine waste rocks and tailings

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RÉSUMÉ

Les propriétés des matériaux des recouvrements isolants et des résidus et stériles miniers sous-jacents sont requises pour permettre une conception adéquate et pour prédire les performances thermiques à long terme. Cette étude détermine à l'aide d'essais de laboratoire et de modèles estimatifs, la conductivité thermique des solides et la conductivité thermique non gelée / gelée en fonction de la saturation des résidus miniers, d'une unité de stériles non-potentiellement génératrice d'acidité et d'une unité de stériles potentiellement génératrice d'acidité de la mine Meadowbank. Un modèle de prédiction de la conductivité thermique a été calibré pour représenter les données obtenues au laboratoire. Puisque aucun effet d'échelle et de structure significatif sur la conductivité thermique n'ont été observé pour les unités de stériles miniers, les modèles calibrés peuvent être étendus aux conditions de terrain.

ABSTRACT

The thermal properties of insulation cover materials and their underlying mine wastes must be known in order to adequately design covers and predict their long-term thermal performance. This study used laboratory measurements and predictive models to assess the thermal conductivity of solid particles and the unfrozen / frozen thermal conductivity as a function of saturation for a non-potentially acid-generating waste rock unit, a potentially acid-generating waste rock unit, and tailings from Meadowbank mine. A predictive thermal conductivity model was calibrated to best represent the data obtained in the laboratory. Because no significant scale and structural effects on the thermal conductivity are observed for the waste rock units, the calibrated models can be extended to field conditions.

1 INTRODUCTION

In Canada's northern regions, many mining operations face challenges related to the reclamation of potentially acid-generating (PAG) tailings and waste rocks storage facilities. One of the most used and well-documented reclamation option developed for continuous permafrost regions is the insulation cover (e.g. Kyhn and Elberling, 2001; Coulombe, 2012). This reclamation strategy consists of placing one or more layers of non-reactive materials over the reactive tailings or waste rocks. In doing so, the cover materials act as a thermal barrier that has two main objectives: (i) to maintain the active layer within the cover materials (to promote freezing and limit contaminated seepage), and (ii) to control the reactive material's temperature (i.e. to limit the reactivity).

The Meadowbank gold mine (Agnico-Eagle Mines Ltd.; AEM) is located in the Kivialliq region in Nunavut (65°N 96°W). Meadowbank mine is currently producing PAG tailings and waste rocks resulting from its open pit mining operations. A non-potentially acid-generating (NPAG) ultramafic waste rock unit is also being extracted in sufficient quantity to be used as cover materials. At closure, the tailings and waste rock storage facilities are intended to be reclaimed using an insulation cover made with these NPAG waste rocks (see Awoh et al., (2016) for details concerning the tailings storage facility).

The effectiveness of insulation covers is primarily based on the thermal regime in the cover materials and, more specifically, the temperature at the cover/reactive material interface. Therefore, in order to adequately design an insulation cover, the thermal properties of the cover materials and underlying waste rocks or tailings must be known. Because insulation covers are strictly based on controlling the temperature of reactive mine wastes in order to limit the production of acid mine drainage (AMD), the long-term performance of this reclamation approach must be evaluated using site-specific conditions and with considerations to climate change. This type of long-term performance evaluation is generally performed by predicting the cover's thermal behavior using numerical modelling (e.g. Kyhn and Elberling, 2001; MEND, 2012).

In most partially saturated soils, heat conduction is usually considered the most dominant mechanism governing heat transfer (e.g. Johansen, 1975). Consequently, it is important to obtain reliable thermal conductivity functions (thermal conductivity vs saturation) for the cover materials and tailings in order to accurately design and model the long-term thermal behavior of insulation cover systems. Therefore, one objective of this study is to determine, using various laboratory methods, the key properties related to heat conduction for Meadowbank's waste rocks (NPAG and PAG) and mine tailings. These thermal properties include both the thermal conductivity of the solid particles, and the unfrozen and frozen thermal conductivity functions. The potential for scale and structural effects on the thermal conductivity of the two tested waste rock units was also investigated. A second objective of this study was to calibrate a thermal conductivity model that can be used for the purposes of evaluating and predicting the effectiveness of several different insulation cover configurations.

2 BACKGROUND - THE CÔTÉ AND KONRAD THERMAL CONDUCTIVITY MODEL

Several thermal conductivity models currently exist to estimate and model the thermal conductivity of partially saturated soils and granular materials. Amongst these models, the generalized Côté and Konrad (2005a, 2009) model computes the thermal conductivity (λ) of unfrozen and frozen granular materials as:

$$\lambda_{(u,f)} = \frac{(\kappa_{(u,f)}\lambda_{sat(u,f)} - \lambda_{dry})S_{r(u,f)} + \lambda_{dry}}{1 + (\kappa - 1)S_{r(u,f)}} \qquad [1]$$

where κ (-) is a soil type-based empirical parameter; λ_{sat} and λ_{dry} are the thermal conductivities of the material at the saturated and dry states; and S_r is the degree of saturation. In Equation 1, the *u* and *f* subscripts refer to the unfrozen and frozen states, respectively.

Typical values of κ range from 1.90 for silty and clayey soils to 4.60 for gravels and coarse sands in the unfrozen state. In the frozen state, values of κ usually range from 0.85 to 1.70 for the same soils, respectively.

The computation of $\lambda_{sat(u)}$ is performed using the geometric mean method (Johansen, 1975) based on the thermal conductivity of the solid particles (λ_s) and water (λ_w) as well as their respective volumetric fractions (Equation 2).

$$\lambda_{sat(u)} = \lambda_s^{1-n_u}\lambda_w^{n_u} \qquad [2]$$

where n_u is the porosity of the unfrozen soil.

In saturated soils, a 9% void volume increase can be observed when all interstitial water is frozen (Côté and Konrad, 2005b). Therefore, the porosity of a frozen saturated soil (n_f) can be estimated using the following equation (Côté and Konrad, 2005b):

$$n_f = \frac{1{,}09n_u}{(1+0.09n_u)} \qquad [3]$$

Accounting for phase change and unfrozen volumetric water content (θ_u), $\lambda_{sat(f)}$ is computed using Equation 4:

$$\lambda_{sat(f)} = \lambda_s^{1-n_f}\lambda_i^{n_f-\theta_u}\lambda_w^{\theta_u} \qquad [4]$$

where λ_i is the thermal conductivity of ice.

The volume change of freezing water also affects the degree of saturation (Côté and Konrad, 2005b), which can be expressed in its generalized form as (Côté and Konrad, 2005a):

$$S_{r(f)} = \frac{1{,}09S_{ru}n_u - 0{,}09\theta_u}{n + 0{,}09(S_{ru}n_u - \theta_u)} \qquad [5]$$

Based on the work of Côté and Konrad (2005a), Côté and Konrad (2009) developed a dual-phase thermal conductivity model that takes into consideration the effect of matrix structure, including porosity, particle shape and cementation. A formulation of the Côté and Konrad (2009) model is presented in Equation 6 for a case where the interstitial fluid is air (as is the case for dry soils).

$$\lambda_{2P} = \frac{(\kappa_{2P}\lambda_s - \lambda_a)(1-\theta_a) + \lambda_a}{1 + (\kappa_{2P} - 1)(1-\theta_a)} = \lambda_{dry} \qquad [6]$$

where λ_{2P} is the thermal conductivity of a two-phase porous media, θ_a is the volumetric air content, λ_a is the thermal conductivity of air, and κ_{2P} is an empirical parameter accounting for structure.

For dry soils, the κ_{2P} parameter is expressed as a function of the λ_a/λ_s ratio and an empirical parameter (β) accounting for the effect of structure on the thermal conductivity (Equation 7). For λ_a/λ_s ratios less than 1/15, the value of β is typically equal to 0.81, 0.54, and 0.34 for natural soils (i.e. rounded particles), crushed rock (i.e. angular particles), and cemented materials, respectively (Côté and Konrad, 2009). For λ_a/λ_s ratios greater than 1/15, β tends to be equal to 0.46 for all types of materials. For water saturated soils, the much simpler Equations 2 and 4 should be used to compute the unfrozen and frozen thermal conductivities.

$$\kappa_{2P} = 0.29\left(15\frac{\lambda_a}{\lambda_s}\right)^{\beta} \qquad [7]$$

In most of the equations presented above, the value of λ_s is required to compute model parameters. Côté and Konrad (2005a) suggest estimating λ_s using a mineralogy-based geometric mean approach (Equation 8).

$$\lambda_s = \prod_{j=1}^{z}\lambda_{mj}^{x_j} \quad \text{with} \quad \sum_{j=1}^{z}x_j = 1 \qquad [8]$$

where λ_m is the thermal conductivity of rock-forming mineral *j* and *x* is the volumetric fraction of mineral *j*.

Based on reliable thermal conductivity measurements (i.e. λ_s, λ_{dry} and moist materials), the Côté and Konrad (2005a, 2009) model can be easily calibrated to obtain representative (unfrozen and frozen) thermal conductivity functions. The model could also be used to characterize the effects of the structure of the solid matrix with the κ_{2P} and β parameters.

3 MATERIALS AND METHODS

3.1 Materials

The materials tested in this study were NPAG and PAG waste rocks, as well as mine tailings from Meadowbank mine. By definition, NPAG and PAG waste rocks are materials with no economic value that must be extracted during the mining operations to access and extract the ore deposit. Therefore, in most cases, these materials are stored directly at the surface without any particle-size classification. At Meadowbank mine, the NPAG and PAG waste rocks' particle sizes usually range from fine particles (< 80 μm) to < 1 m blocks. The in-situ particle-size distribution is typically characterized by values of d_{10}, d_{30}, d_{50}, d_{60}, d_{90} and d_{100} (d_x is the diameter corresponding to x wt/wt % passing on the cumulative grain-size distribution curve) of 1.5, 9, 20, 25, 55 and 92 cm, respectively for the NPAG; and of 2, 10, 22, 28, 58 and 100 cm, respectively for the PAG waste rocks. These values were obtained from imagery-based particle size analyses performed using rock fragmentation analysis software (data provided by AEM). However, for practical reasons and considering limitations in terms of equipment size, it is nearly impossible to test the thermal properties of such large particle size materials. Therefore, in this study, the thermal properties were assessed based on representative NPAG and PAG waste rocks samples that were sieved at 20 mm (0-20 mm samples). Based on the 0-20 mm samples, 0-1.25 mm and 1.25-5.00 mm sub-samples were prepared for testing. Intact NPAG and PAG rock cores were also sampled from large blocks (> 30 cm in diameter) using a portable 4-in diamond core drill. The tailings samples were taken with a shovel directly from the tailings storage facility.

The mineralogical compositions of the NPAG and PAG waste rocks as well as the tailings samples were quantified based on semi-quantitative X-ray diffraction (XRD) analyses. The diffractograms were acquired using a Brucker AXS D8 Advance system displaying a θ-2θ configuration. The acquisition was made at a scanning rate of 0.02°s^{-1} over a diffraction angle (2θ) range from 5° to 70°. Mineral phases were identified using the DIFFRACT.EVA program and quantification was performed using the Rietveld refinement method and the Brucker's TOPAS 4.2 software. The mineralogical compositions of the tested materials are presented in Table 1. The NPAG waste rock sample was primarily composed of talc (31%), chlorite (26%), and dolomite (19%), while the PAG waste rock consisted mainly of quartz (44%), chlorite (14%), stilpnomelane (12%), and magnetite (9%). The tailings, had a high quartz content (48%) with lesser amounts of albite (15%), muscovite (9%), and chlorite (8%).

The basic physical properties of the tested materials are presented in Table 2. Specific gravity (G_s) was measured with a helium pycnometer (Micromeritics AccuPyc 1330) following ASTM standard D5550-14. The average measured values were 2.89, 2.92, and 3.02 for the NPAG and PAG waste rocks and the tailings, respectively. The grain-size distributions of the waste rock samples were obtained by mechanical sieving (following ASTM D422-63) for particle sizes coarser than 425 μm and by laser diffraction (Malvern Instruments Mastersizer S) for finer grain sizes. The tailings' grain-size distribution was determined using only laser diffraction. Field and laboratory evidence showed that the NPAG waste rock has a relatively low resistance to compaction; particles break and fine particles are generated after compaction (Boulanger-Martel et al., 2017). The parameters related to the NPAG waste rock's grain-size distribution are presented in Table 2 for both the loose and the compacted states and illustrate this particular behavior. Such behavior can be explained by the NPAG unit's high weak mineral content (i.e. chlorite and talc). The grain-size distribution parameters obtained for the PAG waste rock show typical values for a waste rock's fine fraction (i.e. < 20 mm) (Peregoedova, 2012). The grain-size distribution of Meadowbank's tailings is also typical of hard rock mining tailings (Bussière et al., 2007).

Table 1. Mineralogical compositions of the tested materials

Mineral phase	Mineral content (wt %)		
	NPAG	PAG	Tailings
Actinolite	9.26	-	-
Albite	-	-	15.00
Anthophyllite	-	-	1.51
Calcite	7.95	3.72	-
Chlorite	26.38	13.75	7.55
Dolomite	18.71	3.60	1.76
Magnetite	-	8.72	10.66
Muscovite	-	7.34	8.77
Quartz	6.98	43.98	48.15
Stilpnomelane	-	11.53	-
Pyrite	-	0.49	1.93
Talc	30.72	6.87	4.68

Table 2. Basic physical properties of the tested materials

Parameter	NPAG[1]	NPAG[2]	PAG	Tailings
G_s (-)	2.89	2.89	2.92	3.02
d_{10} (μm)	27	14	160	5
d_{50} (μm)	4700	2300	5900	32
d_{90} (μm)	15000	13500	1700	155
Cu (-)	270	300	48	9
Cc (-)	11	3	5	0.8

[1] loose 0–20 mm; [2] compacted 0–20 mm

3.2 Experimental approach

The testing program was designed to: (*i*) determine λ_s, (*ii*) obtain thermal conductivity measurements of the moist materials, and (*iii*) determine λ_{dry}. The characterization work also included additional tests on the dry NPAG waste rock samples to assess potential scale and structure effects on thermal conductivity. All test results were used and interpreted to best fit the Côté and Konrad (2005a, 2009) thermal conductivity model. A summary of the tested materials and experimental program is presented in Table 3.

For the NPAG and PAG waste rock units, λ_s was determined using two main methods. First, direct measurements were made on intact, cylindrical rock samples. Two cylinders were used for the NPAG and one cylinder was used for the PAG materials. Additional indirect λ_s measurements were also made using the water-saturated material thermal conductivity interpretation method described by Côté and Konrad (2007) (i.e. using Equation 2). The saturated thermal conductivity was also measured on 0-1.25 and 1.25-5.00 mm samples of the

NPAG and PAG materials to assess potential scale effects. The saturated material thermal conductivity interpretation method was also used to assess the tailings' λ_s. Complementary quantitative XRD mineralogical analyses were carried out to estimate λ_s using the geometric mean method (Equation 8) and validate laboratory results.

The value of λ_{dry} was assessed for the all materials based on thermal conductivity measurements made on dry samples. The NPAG's high chlorite and talc content raised uncertainties concerning the effects of structure on the thermal conductivity; it was suspected that the finer fraction might display a different thermal behavior than the coarser fractions. To assess such effects, measurements were conducted on dry 0-20 mm (4×) and 0-1.25 mm (2×) samples for which the porosities ranged from 0.19 to 0.32 and from 0.37 to 0.46, respectively (Table 3). The tested porosities covered a range representative of both the compacted and loose NPAG materials. Based on these results, the effects of structure on the thermal conductivity were assessed using Côté and Konrad's (2009) κ_{2P} and β parameters (used in Equations 6 and 7 to estimate λ_{dry}). Because no particular differences in terms of structure were anticipated for the PAG waste rock and tailings, the obtained values of λ_{dry} were used for the calibration of the β parameter (i.e. β was determined based on a single λ_{dry} measurement). Measurements were made using a dry 0-20 mm PAG sample and a dry tailings sample.

Table 3. Summary of the tested materials and experimental program

Materials	**Type of sample**	**Purpose**	**No. of tests**		**Range of:**		**Measurement method***
			Unfrozen	**Frozen**	**n (-)**	**S_r (%)**	
NPAG	Cylinder	λ_s	2	-	-	-	Direct measurement (HFM)
	0-1.25 mm	λ_s	1	-	0.44	~100	Indirect measurement (NP)
	1.25-5 mm	λ_s	1	-	0.44	~100	Indirect measurement (NP)
	0-20 mm	λ_{dry} / β	4	-	0.19-0.32	0	Direct measurement (HFM)
	0-1.25 mm	λ_{dry} / β	2	-	0.37-0.46	0	Direct measurement (HFM)
	0-20 mm	λ-S_r	5	5	0.19-0.21	33-90	Direct measurement (HFM)
PAG	Cylinder	λ_s	1	-	-	-	Direct measurement (HFM)
	0-1.25 mm	λ_s	1	-	0.38	~100	Indirect measurement (NP)
	1.25-5 mm	λ_s	1	-	0.42	~100	Indirect measurement (NP)
	0-20 mm	λ_{dry} / β	1	-	0.23	0	Direct measurement (HFM)
	0-20 mm	λ-S_r	2	2	0.21-0.26	21-67	Direct measurement (HFM)
Tailings	As	λ_s	1	-	0.43	~100	Indirect measurement (NP)
	sampled	λ_{dry} / β	1		0.40	0	Direct measurement (HFM)
	materials	λ-S_r	3	3	0.39-0.40	46-89	Direct measurement (HFM)

* HFM = heat flux meter; NP= needle probe

The materials used in the construction of the different insulation cover options currently under study at Meadowbank mine include: loose (n = 0.35–0.40) and compacted (n = 0.17–0.20) NPAG waste rock, PAG waste rock (n = 0.30–0.35), and tailings (n = 0.40–0.44). The in situ saturation conditions for the compacted NPAG waste rock and the tailings are expected to be close to saturation (S_r > 70%). As for the loose NPAG and PAG waste rocks, in situ conditions are more likely to be close to residual saturation conditions (S_r < 10–15%). Because saturation conditions over the whole range of saturation (0 to ~100%) are expected for the NPAG waste rock, five samples with degrees of saturation between 33 and 90% were used to measure the unfrozen and frozen thermal conductivities as a function of saturation (Table 3). These measurements were made on compacted samples with porosities between 0.19 and 0.21. No other measurements were made on looser NPAG waste rock samples; instead a structural analysis based on dry samples (presented later) was carried out in order to enable the extrapolation of the results to field conditions using the Côté and Konrad (2005a, 2009) model. For the PAG waste rock, two samples were used to determine the unfrozen and frozen thermal conductivity at degrees of saturation of 21 and 67%. Tests were performed on samples with porosities of 0.26 and 0.21 (Table 3). Because it was expected to observe fairly dry in situ conditions, such a small amount thermal conductivity tests on moist materials, combined with a measurement of λ_{dry}, was sufficient to characterise the λ-S_r function of the PAG waste rock. As for the tailings, three samples were used to measure the unfrozen and frozen thermal conductivity over saturations ranging from 46 to 89% (Table 3). These measurements were performed on samples with porosities between 0.39 and 0.40.

Ultimately, all λ_s, λ-$S_{r(u,f)}$, and λ_{dry} measurements were used to best fit the Côté and Konrad (2005a, 2009) model to laboratory data for each material. The developed models were used to extrapolate laboratory data in order to adequately represent field conditions.

3.3 Laboratory apparatuses

As shown in Table 3, the thermal conductivity of the intact rock cores as well as the dry and moist NPAG and PAG waste rock samples was measured using a heat flux meter thermal conductivity cell (e.g. Côté et al., 2013; Côté and Konrad, 2005a,b). The tested samples consisted in whether, intact rock core specimens (of 10.0 cm in diameter by 7.5 cm in height) or granular samples (placed at a specific target density and saturation in a 10.0×8.0 cm PVC mold). Due to the difficulty of sample moulding and preparation, different granular samples were used for each tested saturation. The thermal conductivity was measured using the steady state method with an average temperature gradient of 1.03 °C/cm. More details on the apparatus and the testing method can be found in Côté and Konrad (2005b) or Côté et al. (2013). The thermal conductivities of the water saturated NPAG and PAG materials as well as the tailings samples were measured using a Hukseflux TP02 thermal needle probe. Measurements were performed following a method similar to ASTM D5334-14 on samples placed in a 7.5 cm diameter by 18.5 cm high PVC mold. The thermal conductivity was obtained based on the average of 24 individual measurements taken over a period of 24 hours. The various different thermal conductivity tests were conducted at mean target temperatures of 5 °C and -5 °C for the unfrozen and frozen states, respectively.

4 RESULTS AND DISCUSSION

The main results that were obtained in the laboratory are presented and discussed in this section. The results are used to assess potential scale and structure effects as well as to calibrate the Côté and Konrad (2005a, 2009) thermal conductivity model.

4.1 Thermal conductivity of the solid particles

The measured and estimated values of λ_s that were obtained for the NPAG and PAG waste rocks and tailings are presented in Table 4.

Table 4. Measured and estimated values of λ_s for the NPAG and PAG waste rocks and tailings

Materials	Sample / testing Method*		$\lambda_{s\text{-measured}}$ (W/m K)	$\lambda_{s\text{-mineralogy}}$+ (W/m K)
NPAG waste rock	Cyl. A	HFM	3.34	3.61^1
	Cyl. B	HFM	4.11	3.88^1
	0-1.25 mm	NP	6.70	6.66^2
	1.25-5 mm	NP	6.47	6.77^2
	0-20 mm	HFM	-	5.29^3
	Mean	-	5.15	4.68
PAG waste rock	Cyl. A	HFM	4.96	-
	0-1.25 mm	NP	5.74	-
	1.25-5 mm	NP	5.10	-
	0-20 mm	HFM	-	5.35
	Mean	-	5.27	5.35
Tailings		NP	5.80	5.51^2

* HFM = heat flux meter, NP= needle probe; +$\lambda_{s\text{-mineralogy}}$ is evaluated using: ^{1} $\lambda_{talc} \perp$, ^{2} $\lambda_{talc} \parallel$, and ^{3} λ_{talc} Table 6

The results that were obtained for the NPAG waste rock unit indicate that quite different λ_s values were measured for the cylindrical samples (3.34 to 4.11 W/m K) compared to the granular fractions (6.47 to 6.70 W/m K). This disparity is probably not attributable to a difference in material properties but is rather related to the kind of samples that were tested and their associated measurement technique. The cylinders were obtained from cores drilled normal to rock bedding. Thus, the thermal conductivity that was obtained for the cylinders is based on thermal conductivity cell measurements of heat fluxes, which were mostly flowing perpendicularly to the structure of rock-forming minerals. As for the 0-1.25 mm and 1.25-5.00 mm water saturated materials, the samples were placed and slightly compacted, causing a parallel preferential orientation of the sheet-like particles such as talc. Because the needle probe apparatus induces a radial heat flow, it is suspected that mostly the parallel component of thermal conductivity (heat flow along the particles) was measured for those materials. In order to confirm this behavior, additional quantitative XRD analyses were conducted on the two cylinders and the two granular NPAG waste rock samples. The results of the various mineralogical analyses are presented in Table 5. The mineralogical composition of the 0-20 mm fraction (same as Table 1) is also shown for comparison purposes.

Table 5. Mineralogical composition of the various NPAG samples quantified by XRD analyses

Mineral phase	Mineral content (wt %) / sample				
	0-20	**0-1.25**	**1.25-5**	**Cyl. A**	**Cyl. B**
Actinolite	9.26	6.68	10.09	-	-
Calcite	7.95	4.69	3.14	-	-
Chlorite	26.38	38.64	37.96	37.36	28.67
Dolomite	18.71	9.77	4.82	27.27	20.85
Ilmenite	-	-	-	2.03	2.54
Quartz	6.98	-	-	-	-
Talc	30.72	40.21	44.00	33.35	47.94

The XRD analyses indicate that talc and chlorite are the two main rock-forming minerals in all NPAG rock samples. To assess the effects of perpendicular versus parallel heat flow, the geometric mean method was used to estimate the thermal conductivity of the various different samples using the thermal conductivities of the rock-forming minerals presented in Table 6 and oriented thermal conductivity values for talc. Talc was shown to be the only mineral phase with a marked anisotropy of its thermal conductivity. λ_s calculations were performed with perpendicular ($\lambda_{talc} \perp$ = 1.76 W/m K) and parallel ($\lambda_{talc} \parallel$ = 10.69 W/m K) talc thermal conductivity values (from Clauser and Huenges, 1995) for the cylinders and the granular materials, respectively. A geometric mean estimation of λ_s was also made for the 0-20 mm fraction based on the general talc thermal conductivity value presented in Table 6 (close to the average value of $\lambda_{talc} \perp$ and $\lambda_{talc} \parallel$). The comparison of the measured and estimated λ_s values presented in Table 4 indicates that the perpendicular versus parallel heat flow theory could explain the large difference between the thermal conductivity cell and needle probe measurements. Based on this interpretation, it is expected that the NPAG waste rock's general value of λ_s should fall between the perpendicular and radial heat flow values. Therefore, at this stage, a λ_s of 4.92 W/m K, which is the mean value of all measured and estimated λ_s values, can be considered as an acceptable initial approximation.

The measurements and estimations of λ_s made on the NPAG waste rock samples with different grain size fractions do not show a clear trend with respect to scale effects. Because the mineralogical composition of all samples is fairly similar, no significant scale effects on λ_s are expected to occur.

For the PAG waste rocks, similar values of λ_s were obtained for the intact rock cylinders, the 0-1.25 mm and the 1.25-5.00 mm samples (Table 4). The mean measured λ_s is of 5.27 W/m K. These similar measured λ_s values confirm that the PAG waste rock's λ_s does not significantly vary with grain size and suggest that no scale effects on λ_s should be anticipated for this unit. Thus, the mean value of the measured λ_s can be extrapolated with confidence to adequately represent field conditions. A geometric mean estimation of λ_s was also performed based on the mineralogical composition of the 0-20 mm fraction of the PAG waste rock (refer to Table 1 for mineralogy). This estimation was based on the rock-forming mineral thermal conductivity values presented in Table 6 and a thermal conductivity of 1.88 W/m K for stipnomelane (a phyllosilicate of the smectite group; value taken from Côté and Konrad, (2007) for smectite). The estimated λ_s (5.35 W/m K) is very similar to the measured value and confirms laboratory data.

For the tailings, a single measurement of 5.80 W/m K was recorded (Table 4). The obtained value is also well estimated by the geometric mean method (using the mineralogy in Table 1; λ_s = 5.51 W/m K).

Table 6. Thermal conductivity of relevant rock-forming minerals (from Côté and Konrad, 2005a)

Minerals	λ_s (W/m K)
Actinolite	3.48
Albite	1.96
Calcite	3.59
Chlorite	5.15
Dolomite	5.51
Magnetite	5.10
Ilmenite	2.38
Muscovite	2.85
Quartz	7.69
Pyrite	19.21
Talc	6.10

4.2 Thermal conductivity of moist and dry materials

A summary of all the thermal conductivity measurements that were made on dry and moist NPAG and PAG waste rock and tailings samples is presented in Table 7. For the moist NPAG materials, thermal conductivities were between 2.12 and 2.99 W/m K and between 2.22 and 3.56 W/m K for the unfrozen and frozen states, respectively. These measurements were obtained at an average porosity of 0.20 over saturations ranging from 31 to 90%. These conditions are representative of compacted NPAG waste rocks. At a porosity around 0.20, the mean dry thermal conductivity was 1.06 W/m K.

For the PAG waste rock unit, the measured thermal conductivities ranged from 0.72 to 2.68 for the unfrozen state and reached up to 3.09 W/m K for the frozen state. These measurements were obtained for saturations ranging from 0 to 67% and for an average porosity of 0.23. In this case, the laboratory porosities were lower than what is expected to be encountered in the field.

The measured dry thermal conductivity for the tailings was 0.25 W/m K. The tailings' thermal conductivity gradually increased to values of 2.12 and 3.46 W/m K when measured at the unfrozen and frozen states, respectively for a water saturation of 89%.

As expected, the results indicate that the thermal conductivity increases with increasing saturation. Additionally, higher thermal conductivities are measured at the frozen state compared to the unfrozen state. The λ_u and λ_f are the same at the dry state and with increasing degree of saturation, the λ_f increases faster than the λ_u with a maximum difference between λ_f and λ_u at S_r = 100%.

Table 7. Thermal conductivity of moist and dry NPAG waste rocks, PAG waste rocks, and tailings

Materials	n_u (-)	S_{ru} (%)	λ_u (W/m K)	λ_f (W/m K)
0-20 mm NPAG waste rock	0.19	90	2.99	3.54
	0.21	80	2.96	3.56
	0.19	75	2.85	3.49
	0.21	55	2.64	3.03
	0.21	31	2.12	2.22
	0.19	0	1.05	-
	0.20	0	1.07	-
0-20 mm PAG waste rock	0.21	67	2.68	3.09
	0.26	21	1.43	1.59
	0.23	0	0.72	-
Tailings	0.39	89	2.12	3.46
	0.40	71	1.99	2.94
	0.40	46	1.49	2.07
	0.40	0	0.25	-

4.3 Assessment of NPAG waste rocks' structural effects on thermal conductivity

An assessment of the NPAG waste rocks' structural effects on thermal conductivity was carried out based on additional λ_{dry} measurements made on the 0-20 mm and 0-1.25 mm fraction samples. The λ_{dry} values that were obtained from the measurements are plotted as a function of porosity in Figure 1. The measurements taken for the dry 0-20 mm NPAG samples show a decreasing thermal conductivity with an increasing porosity; the value of λ_{dry} ranged from 1.05 W/m K to 0.58 W/m K for porosities ranging from 0.19 to 0.32. A similar trend was observed for the 0-1.25 mm samples for which dry thermal conductivities of 0.45 and 0.33 W/m K were measured for porosities of 0.37 and 0.46, respectively.

The λ_{dry}–n relationship shown in Figure 1 is first used to determine the β parameter, which is related to the calculation of κ_{2P} in Equation 7. The β parameter fitting procedure consists of iteratively calculating κ_{2P} and its associated λ_{dry} to best fit laboratory data. Such fitting is based on the physical limits of thermal conductivity in porous media, which imply that, at porosities of 0 and 1, the thermal conductivities of the media are equal to λ_s and λ_a, respectively (Côté and Konrad, 2009). Therefore, a reliable value of λ_s is required to conduct this kind of analysis. Due to variability of λ_s in the laboratory results that were obtained for the NPAG waste rock, it was decided to conduct a preliminary fit of the Côté and Konrad (2005a) based on the λ-S_r data to validate λ_s. This preliminary analysis suggested a value of 4.80 W/m K as a representative λ_s for the NPAG waste rock. The obtained value is close to the 4.92 W/m K that was first assessed in Section 4.1; therefore, a λ_s of 4.80 W/m K was used. The best-fit curve to the experimental data indicated a β parameter of 0.60, corresponding to a κ_{2P} value of 0.06. Compared to the β values suggested by Côté and Konrad (2009), the NPAG waste rock has a structure similar to crushed materials. This behavior was expected because the NPAG waste rock is essentially a freshly blasted rock unit for which the particles break into angular/sub-angular particles.

The λ_{dry}–n relationship can also be used to assess structural effects on the thermal conductivity. Because the structure of the solid matrix defines the continuity of the solid phase and the contact resistance (Kaviany, 1995), the similar behaviors (characterized by the λ_{dry}–n relationship computed for the defined β parameter) observed for the 0-20 mm and 0-1.25 mm fractions indicates no significant structural effects between the two grain size fractions.

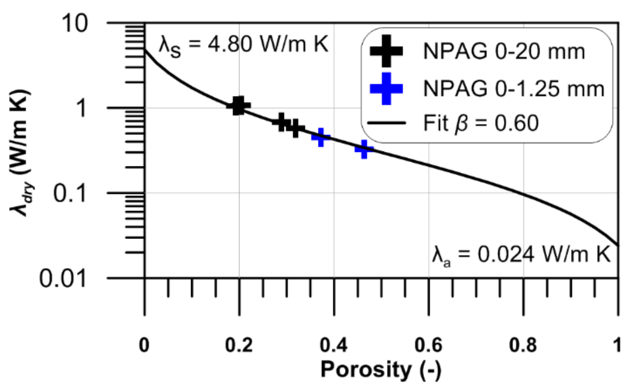

Figure 1. NPAG waste rocks' dry thermal conductivity as a function of porosity and best-fit curve to experimental data

4.4 Fitting of the Côté and Konrad model

The Côté and Konrad (2005a, 2009) model was calibrated using the experimental data that were obtained from the unfrozen (Figure 2) and frozen (Figure 3) states for all three materials. As explained in Section 4.3, a λ_s of 4.80 W/m K was used for the NPAG waste rock. The mean measured λ_s values were used for the PAG waste rock (5.27 W/m K) and the tailings (5.80 W/m K) to calibrate the Côté and Konrad (2005a, 2009) model. The previously determined β value of 0.60 was used for the NPAG waste rock, while a three-point calibration of β (λ_s-λ_{dry}-λ_a) indicated values of 0.68 and 0.85 for the PAG waste rock and tailings, respectively. These values are in accordance with the anticipated structural effects. The PAG waste rocks displayed a similar value of β as the NPAG waste rocks. A higher β was expected for the tailings because the millings process results in a particle shape that is close to natural rounded particles, which have been shown to have an average β value of 0.81.

In the unfrozen state, the modeled κ_u parameters were 2.70, 1.65, and 1.90 for the NPAG waste rocks, PAG waste rocks, and tailings, respectively (Figure 2). In the unfrozen state, the κ_f parameters were determined for a case with negligible unfrozen water contents and reached values of 1.50, 1.10, and 1.00, respectively, for the same materials. The values of the κ parameters that were obtained for the NPAG and PAG waste rocks were not precisely in agreement with the typical values suggested by Côté and Konrad (2005a). This difference could be due to the poorly-graded grain-size distribution and the petrological origin of the material. The values obtained for the tailings are similar to those obtained by Coulombe (2012) for other mine tailings. A summary of the fitted Côté and Konrad (2005a, 2009) model parameters is given in Table 8.

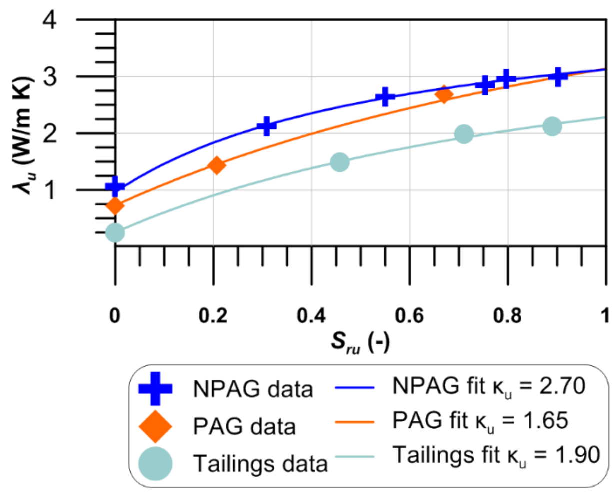

Figure 2. Calibrated Côté and Konrad (2005a, 2009) model for unfrozen materials

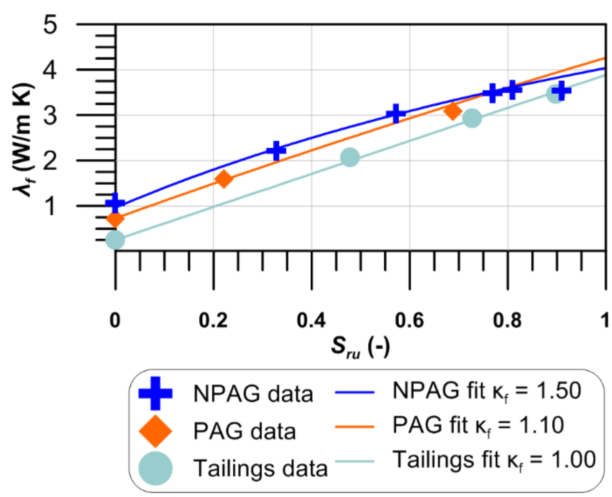

Figure 3. Calibrated Côté and Konrad (2005a, 2009) model for frozen materials

Generally, the fitted models represent the laboratory data well. For the two waste rock units, no particular scale or structural effects on the thermal conductivity are anticipated. Therefore, considering that the nature of the grain-to-grain contacts is the same for larger particles, a similar thermal behavior to the samples that were tested can be expected for in situ waste rocks. Based on this assumption, the Côté and Konrad (2005a, 2009) models developed for the NPAG and PAG waste rocks can be extrapolated to field conditions by varying the porosity. For example, for the NPAG waste rocks, values of 0.46, 2.12, and 3.51 W/m K are calculated for the λ_{dry}, $\lambda_{sat(u)}$, and $\lambda_{sat(f)}$, respectively when the porosity is changed to 0.38 (typical of loose NPAG waste rock conditions).

Table 8. Summary of the fitted Côté and Konrad (2005a, 2009) model parameters

Parameter	**NPAG waste rock**	**PAG waste rock**	**Tailings**
λ_s (W/m K)	4.80	5.27	5.80
κ_u (-)	2.70	1.65	1.90
κ_f (-)	1.50	1.10	1.00
β (-)	0.60	0.68	0.85

5 CONCLUSION

This study assessed the key thermal properties of NPAG and PAG waste rock units as well as tailings from Meadowbank mine. These properties included the thermal conductivity of the solid particles and the thermal conductivity function. The NPAG waste rocks' λ_s values showed that differences in the perpendicular and parallel heat flow for talc could explain the large difference between thermal conductivity cell and needle probe measurements. Combined with an analysis of λ-S_r data, the NPAG waste rocks' λ_s yielded a value of 4.80 W/m K. The PAG waste rocks' and tailings' measured λ_s values were 5.27 and 5.80 W/m K, respectively. Additional dry thermal conductivity measurements performed on the NPAG waste rocks showed that, for this material, a single β parameter could explain the observed λ_{dry}-n relationship for both the 0-20 mm and 0-1.25 mm fractions. Therefore, no major structural effects on the thermal conductivity should be expected for this unit. All λ_s, λ-S_r, and λ_{dry} results were used to calibrate the Côté and Konrad (2005a, 2009) thermal conductivity model. The models that were developed will be used for further assessment and prediction of the performance of several insulation cover configurations for the reclamation of Meadowbank's tailings and waste rock storage facilities.

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