THERMAL CONDUCTIVITY OF SULPHIDIC TAILINGS

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ABSTRACT

The design, operation and closure of tailings impoundments for any mining project need to be both environmentally-sound and cost-effective. For mining projects located in permafrost areas, the concept of using frozen tailings for both operations and closure has been previously suggested to achieve both of these objectives. In order for designs to be undertaken, an understanding of the climatic conditions (including climate change considerations) and the tailings physical properties is paramount. Predicting the thermal behaviour of tailings requires an understanding of their thermal conductivity. Thermal conductivity is a material property that depends on a number of factors including the mineralogy of the soil particles, how closely those soil particles are packed together, the degree of saturation and the moisture content. The thermal conductivity of tailings is often predicted using empirical methods that were developed based on tests using representative natural and processed soils. Use of these methods may be inappropriate if one or more of the controlling attributes of the tailings differ significantly from the representative soils used to develop the empirical correlations.

As a result, a study was undertaken to compile data on the thermal conductivity of mine tailings, and to compare the conductivity values for tailings with sulphide content to those without. Samples of tailings were collected from the Lupin and the Nanisivik Mines in Nunavut. The study confirms that the unfrozen and frozen thermal conductivity of sulphide-bearing tailings are typically 30% higher than for other tailings. The results also suggest that tailings with a high specific gravity will tend to have a high thermal conductivity. Mineralogy and associated weathering appears to play a significant role in determining the thermal conductivity of tailings. If either a high sulphide content or high specific gravity is suspected, consideration should be given to verifying thermal conductivity values through laboratory measurements.

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1.0 INTRODUCTION

The environmental management and cost-effective design, operation and closure of tailings impoundments are key components to the viability of any mining project, including those located in northern environments. Predicting the behaviour of tailings exposed to freezing and thawing conditions requires an understanding of their thermal conductivity. Thermal conductivity is a material property that depends on a number of factors including the mineralogy of the soil particles, how closely those soil particles are packed together, the degree of saturation and the frozen and unfrozen moisture contents.

The thermal conductivity of tailings is often predicted using empirical methods that were developed based on tests using representative natural and processed soils. Use of these methods may be inappropriate if one or more of the controlling attributes of the tailings differs significantly from the representative soils used to develop the empirical correlations. Only recently have tests been conducted on actual tailings materials, and the database of published values remains small. Most of the recent tests have been conducted on kimberlite tailings and gold tailings with a minor component of sulphide minerals. Tailings with higher sulphide contents are considered likely to demonstrate differing thermal properties from those of kimberlite and/or gold (although gold deposits can contain significant sulphide mineralization) tailings, where quartz and feldspars are likely to be dominant minerals.

Currently, there are only two published thermal conductivity values for tailings containing higher sulphide values (sulphidic tailings), and pore fluid properties are only reported for one of these samples. A larger database for use during preliminary planning stages would yield improved designs that integrate thermal properties specific to sulphidic tailings. As a result, Indian and Northern Affairs Canada (INAC) retained BGC Engineering Inc. (BGC) and Mehling Environmental Management Inc. (MEMi) to undertake a comprehensive review of the topic published in BGC/MEMi (2004). This research initiative was completed through sampling and laboratory testing of tailings from two northern Canadian mine sites that have deposited tailings with moderate to high sulphide content. The samples were tested for basic geochemical information and thermal parameters to add to the knowledge base. The paper provided herein summarizes only the background information, a summary of tailings thermal conductivity values collected and laboratory testing results from that research program.

2.0 THERMAL CONDUCTIVITY BACKGROUND

In the presence of a thermal gradient (units of $^{o}C/m$), the rate of heat flow by conduction per unit area (J/m^2s) is given by:

$$q = k*i$$

where q is the rate of heat flow, k is the thermal conductivity, and i is the thermal gradient. Thermal conductivity is expressed in units of $J/s \cdot m \cdot K$, $W/m \cdot K$, or $Btu/ft\text{-}hr\text{-}^{o}F$.

The constituents of a soil (air, water, ice, minerals, and organic matter) all have different physical and chemical properties that influence thermal conductivity. Some reported thermal conductivities of common materials are presented in Table 1. Compared to typical soil constituents, quartz displays a relatively high thermal conductivity while clay minerals have a relatively low value. Pure metals also display a relatively high thermal conductivity.

Table 1 Representative Properties of Selected Materials (Modified from Andersland and Ladanyi, 1994)

Material	Thermal Conductivity (W/m·K)	Sources
Air (10°C)	0.026	De Vries (1966)
Snow, loose	0.08	Alter (1969)
Snow, compact	0.7	Alter (1969)
Ice (-40°C)	2.66	Alter (1969)
Ice (0°C)	2.21	Alter (1969)
Water (0°C)	0.56	Alter (1969); Weast et al. (1984)
Water (10°C)	0.58	Weast et al. (1984)
Peat, dry	0.07	Alter (1969)
Clay, dry	0.9	Alter (1969)
Sand, dry	1.1	Alter (1969)
Quartz	8.4	De Vries (1966)
Feldspar	1.6 to 2.9	MEND (1998); Chesterman and Lowe (1979)
Biotite	2.0	Jessop et al. (1979)
Amphibolite	3.5	MEND (1998); Chesterman and Lowe (1979)
Granite	1.7 to 4.0	Johnston (1981)
Limestone	1.7 to 2.9	Andersland and Anderson (1978)
Dolomite	5.02	Andersland and Anderson (1978)
Shale	1.5	Johnston (1981)
Steel	43	Alter (1969)
Iron, ductile	50	Alter (1969)
Copper	375	Alter (1969)

It is important to realize the compilations of thermal conductivity values for soils, rock and minerals, such as those reported in Table 1, are inevitably comprised of data that are heterogeneous in many respects, such as mineral composition, porosity, saturation and experimental conditions (Clauser and Huenges, 1995). For example, data for a specific mineral may have been measured on a single crystal or a mineral powder. Thus, reported values for specific materials can be contradictory or indicate a wide range of values.

The thermal conductivity of an unfrozen soil tends to increase with an increase in dry density and an increase in the degree of saturation. As soils freeze, a portion of the pore water turns to ice. Since ice is approximately four times more conductive than water, this causes an increase in the thermal conductivity of the soil.

Not all water freezes as the temperature of a soil drops below freezing. The amount of water that remains unfrozen is a function of grain size and the specific surface area of the soil. Pore fluid chemistry, such as the presence of salts, will also impact the unfrozen water content of a frozen soil.

Thermal conductivities for site-specific soils can be measured in the laboratory, back-analyzed from field observations, or estimated through empirical correlation. Laboratory measurements tend to be rare, given the complexity of the testing program. A detailed review of methods used to predict thermal conductivity of soils is provided by Farouki (1981). Correlations developed by others include Kersten (1949) and Johansen (1975). These correlations were originally developed for use with natural soils, rather than manufactured 'soils' or tailings containing high sulphide content.

Within this study, no attempt is made to specifically quantify "higher content" suphide tailings, other that in relative proportions. Some tailings contain a relatively high proportion of sulphide minerals, such as lead-zinc mine tailings. Other tailings contain a moderate amount of sulphide minerals, such as gold mine tailings, while other tailings may contain only minor sulphide mineral content, such as processed kimberlite from diamond mines.

Sulphide minerals have a high specific gravity as noted in Table 2:

Table 2 Common Sulphide Minerals (After Chesterman and Lowe, 1979)

Mineral	Composition	Specific Gravity
Pyrite	FeS_2	4.9 to 5.2
Pyrrhotite	$Fe_{1-x}S$	4.5 to 4.6
Chalcopyrite	$CuFeS_2$	4.1 to 4.3
Arsenopyrite	FeAsS	6.0 to 6.2
Galena	PbS	7.4 to 7.6
Sphalerite	ZnS	3.9 to 4.1

As such, the combination of sulphide minerals proportion in tailings (from low to high) along with their high specific gravity values will result in higher density values for tailings. As such, it is possible that a correlation may exist between the tailings density and its thermal conductivity.

The presence of sulphide minerals may influence thermal conductivity values in other ways. Sulphide minerals can oxidize, generating acidity and potentially releasing soluble metals, which tends to increase the salt content of the pore fluid. This may increase the unfrozen water content of sulphidic tailings and potentially reduce their frozen thermal conductivity. Additionally, weathering of the sulphide minerals surfaces has been suspected of decreasing thermal conductivity values (MEND, 1998).

Limited work has been published on the thermal properties of sulphidic tailings with known sulphide contents. Exceptions include analysis of Wellgreen and Lupin Mine tailings conducted on behalf of MEND and sponsored by Environment Canada and the Department of Indian and Northern Affairs (MEND Project 1.62.2 1998), and work published by Meldrum et al. (2001) on the properties of tailings from the North Rankin Inlet Nickel Mine.

MEND (1998) measured the thermal properties of crusted tailings (slabs) and crumbs cut from a tailings hardpan at the inactive Wellgreen nickel, platinum, palladium and copper mine in southwestern Yukon. The ore body for this mine was hosted in ultramafic intrusive rocks and contained a high sulphur content that occurred predominantly as pyrrhotite. The distribution of mineralogy measured for the slabs was trace quartz, 9% calcite/aragonite, 51% iron oxide minerals, 40% iron sulphide minerals, while the mineralogy for the crumbs was 10% quartz, 11.5% calcite/aragonite, 48% iron sulphide minerals, 19% cuprite, and 11.5% sulphur. The material comprised a silty sand and had an average specific gravity ranging from 3.13 to 3.16.

The measured unfrozen and frozen thermal conductivities of the Wellgreen tailings appeared anomalously low (1.0 and 1.5 W/m·K, respectively) compared to values predicted by Johansen (1975) and those of other sulphidic tailings. A very low quartz content (typically resulting in a low thermal conductivity) may have only partially been offset by the presence of iron sulphides. MEND (1998) also suggested that weathering could have affected the surfaces of the minerals, inhibiting thermal conductivity.

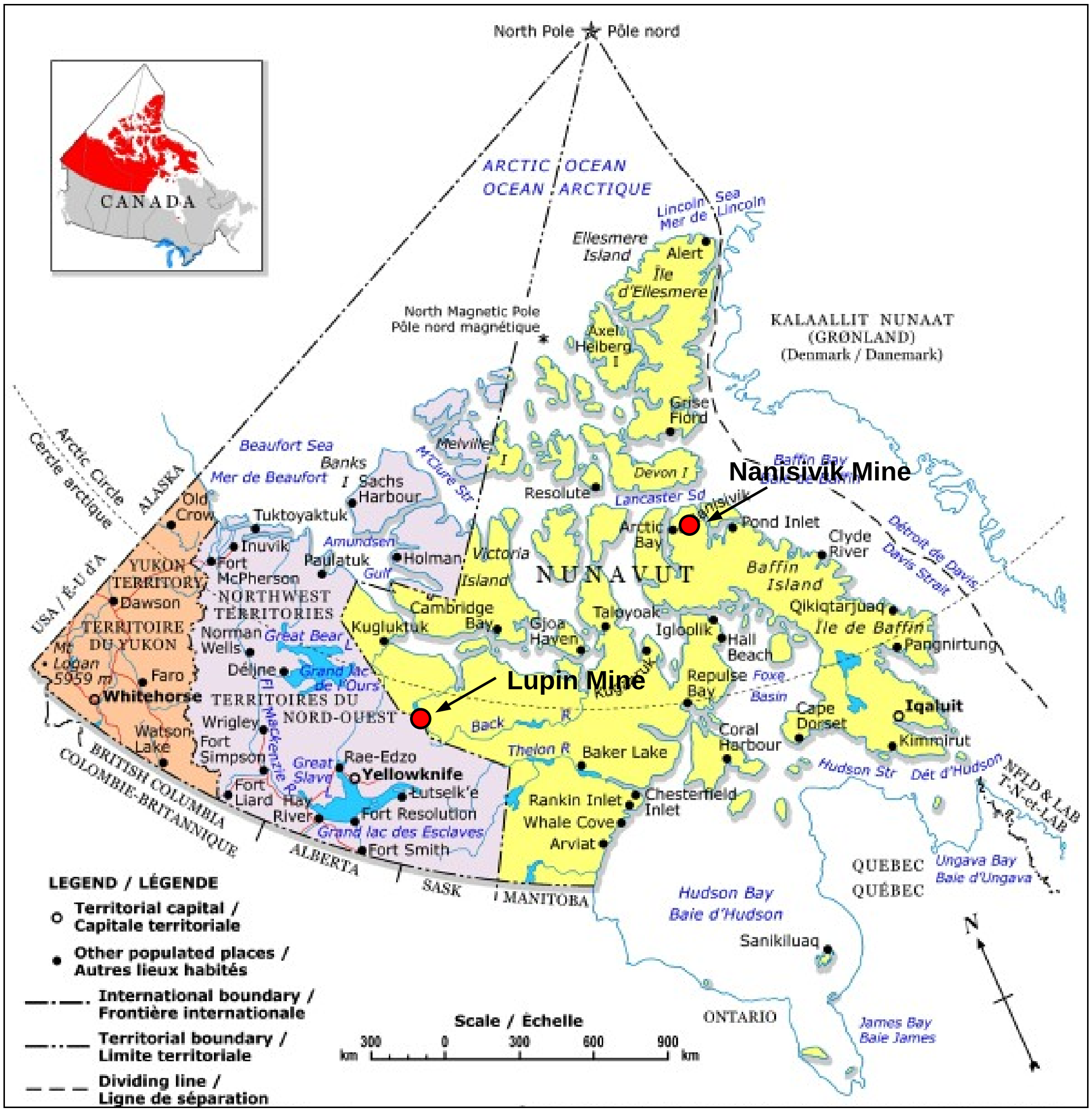
MEND (1998) also measured the thermal properties of tailings from the Lupin Gold Mine in Nunavut. These tailings reportedly contained 36% quartz and 45% iron sulphide minerals. However, the sulphide content value may be in question, as later discussed in Sections 3 and 4. The measured unfrozen and frozen thermal conductivities for the Lupin tailings were 1.7 and 2.7 W/m·K, respectively.

Meldrum et al. (2001) reported on the estimated thermal properties of sandy tailings from the North Rankin Inlet Nickel Mine. These tailings contained 5 to 20% pyrrhotite by volume. All pyrrhotite grains showed evidence of oxidation to secondary iron hydroxide. Based on a thermal simulation calibrated to subsurface temperature data, the unfrozen and frozen thermal conductivities were estimated at 1.8 and 3.0 W/m·K, respectively.

3.0 SULPHIDIC TAILINGS TEST SAMPLES

Tailings samples were obtained from the Lupin and Nanisivik Mines in Nunavut for the purposes of laboratory testing and assessment. Some basic background information on each mine is provided.

Figure 1: Location of Lupin and Nanisivik Mines
(Modified from The Atlas of Canada, 2003)



Lupin Mine is situated on the west shore of Contwoyto Lake in Nunavut, 400 km northeast of Yellowknife and 80 km south of the Arctic Circle, as shown on Figure 1. The mine is currently owned by Kinross Gold Corporation and the mine is now closed.

Gold is found primarily within a sulphide-rich iron formation. The ore at Lupin consists of amphibole, quartz, garnet, pyrrhotite, arsenopyrite, minor pyrite and traces of chalcopyrite. The gold is fine grained (generally less than 100 microns in diameter) and is associated mainly with pyrrhotite and arsenopyrite.

According to MEND (1998), the Lupin tailings comprise approximately 36% quartz, 2% calcite/aragonite, 45% iron sulphide minerals and 17% iron chlorite. MEND (1998) also reports a total sulphur content of 2.83%, which is not consistent with an iron sulphide content of 45%.

Klohn Leonoff (1992) reports a total sulphur content ranging from 2.53 to 4.01% from 20 tailings samples from Lupin Mine. If all sulphur were in the form of pyrrhotite, this would be equivalent to an iron sulphide content of 6.9 to 11.0%. MEND (1998) describes the grain size distribution as being 30% sand, 65% silt and 5% clay.

The Nanisivik lead-zinc mine is located on Borden Peninsula, northern Baffin Island, Nunavut, at approximately 73^{o} North, as shown on Figure 1. The mine is currently owned by CanZinco Ltd. (Breakwater Resources) and is undergoing reclamation activities.

The Nanisivik region is underlain by carbonate and terrigenous clastic strata. Dolostone hosts massive Zn-Pb-Ag sulphide mineralization at the Nanisivik deposit and several satellite massive sulphide bodies. Sulphide bodies at Nanisivik are dominantly pyrite. Sphalerite and galena are also present.

Tailings samples were collected from both mine sites by BGC staff during the spring and summer of 2003. At Lupin Mine, the tailings sample was obtained in August by shovel to a depth of about 30 cm and appeared to be fresh tailings, recently placed on surface. At Nanisivik Mine, the tailings samples were obtained in May from the Surface Cell, the main tailings solids deposition area. The samples were collected by shovel to a depth of about 60 cm and were approximately one year old, since tailings discharge was completed in September 2002. Two different samples were collected, one that consisted mostly of fines and the other mostly of sand sizes. These two samples were combined to create a third composite sand/silt sample for laboratory testing.

4.0 MINERALOGY AND ABA TESTING

Samples from both sites were described as “fresh” and “unweathered”, with essentially all of the samples in crystalline phases. Sulphides in samples from both sites were present as free grains, not being encapsulated within other minerals or showing weathered rims consisting of oxidation products. The Lupin sample consisted primarily of fine-grained silicates and pyrrhotite. Pyrrhotite was disseminated throughout the sample, and no carbonates were observed. The Nanisivik sample consisted of abundant pyrite and dolomite. Summaries of the mineralogical results are shown on Table 3.

Table 3 Mineralogy Summary

Mine Site	Sulphide (wt%)	Carbonate (wt%)	Textures	Other Minerals (order of abundance)
Lupin	Pyrrhotite (~7%)	None	Silt (and finer) particles; no rims or encapsulation, evenly distributed sulphides	Quartz, Garnet, Amphibole, Biotite, Chlorite
Nanisivik - sand	Pyrite (~56%)	Dolomite (~33%)	Sand size particles; no rims or encapsulation	K-feldspar, Quartz, Gypsum
Nanisivik - silt	Pyrite (~62%)	Dolomite (~29%)	Silt size particles; no rims or encapsulation	K-feldspar, Quartz, Gypsum

Detailed quantitative analysis of the crystalline phases from the tailings samples are shown on Table 4.

Table 4 Results of Quantitative Phase Analysis (wt%)

Mineral	Ideal Formula	Lupin	Nanisivik	
			Sand	Silt
Quartz	SiO_2	43.8	2.6	1.9
K-feldspar	$KAlSi_3O_8$		6.7	5.2
Biotite	$K(Mg,Fe^{2+})_3AlSi_3O_{10}(OH)_2$	5.4		
Chlorite	$(Mg,Fe^{2+})_5Al(Si_3Al)O_{10}(OH)_8$	1.8		
Gypsum	$CaSO_4 \cdot 2H_2O$		1.4	1.2
Ferroactinolite	$Ca_2Fe_5^{2+}Si_8O_{22}(OH)_2$	21.0		
Grunerite	$Fe_7^{2+}Si_8O_{22}(OH)_2$	14.3		
Dolomite	$CaMg(CO_3)_2$		33.0	29.2
Pyrite	FeS_2		56.3	62.4
Pyrrhotite	$Fe_{1-x}S$	7.0		
Almandine	$Fe_3^{2+}Al_2(SiO4)_3$	6.7		
Total		100.0	100.0	100.0

Results for the Lupin sample differed substantially from the composition of Lupin tailings reported in MEND (1998) of 45% iron sulphide. As discussed earlier, the 45% content value appears to be in error since the difference in values is likely greater than can be attributed to the heterogeneity of the tailings. In addition, results presented in Tables 3 and 4 are consistent with those reported by Klohn Leonoff (1992).

Results for the Nanisivik samples indicate somewhat lower pyrite content and higher carbonate as compared to the composition reported by Cassie and LeDrew (2001) of 80% pyrite and 18% dolomite. This may simply be attributed to inherent variability within the tailings deposit.

The samples were submitted for acid-base accounting (ABA) and a summary of results for the two sites is shown on Table 5.

Table 5 Acid-Base Accounting Results

Parameter	Unit	Lupin	Nanisivik Combined silt/sand
Rinse pH	pH unit	8.4	5.6
Paste pH	pH unit	8.4	8.4
Total S (%)	% S	2.98	33.30
Sulphate, as sulphur	% S	0.02	0.36
Sulphide, as sulphur	% S	2.92	31.9
Total S minus Sulphate S	% S	2.96	32.94
Standard Sobek NP	kg/t $CaCO_3$ equivalent	12.6	319.4
Siderite Corrected NP	kg/t $CaCO_3$ equivalent	12.4	332.5/316.5
Modified Sobek NP	kg/t $CaCO_3$ equivalent	6.8	320.6
Total Inorganic Carbon	% C	0.06	3.86
Carbonate NP	kg/t $CaCO_3$ equivalent	5.0	321.7
TAP (calculated from Total S%)	kg/t $CaCO_3$ equivalent	92.5	1040.6
TNNP (Sobek NP minus TAP)	kg/t $CaCO_3$ equivalent	-75.2	-721.2
TNPR (Sobek NP/TAP)		0.1	0.3
SAP (calculated from sulphide-sulphur)	kg/t $CaCO_3$ equivalent	92.5	1029.4
SNNP (Modified NP minus SAP)	kg/t $CaCO_3$ equivalent	-85.7	-708.8
SNPR (Modified NP/SAP)		0.1	0.3

For simplicity, only results for the combined sand/site Nansivik sample are presented here, with the exception of the siderite ($FeCo_3$) corrected NP values. Results for the sand and silt samples were similar, with the sand sample showing possible indications of slightly greater weathering as compared to the silt sample, such as slightly higher sulphate content and lower rinse pH.

Samples from both sites would be considered potentially acid generating with negative NNP values and NPR values less than 1. The Nanisivik sample contains substantially more total sulphur (33.30%) as compared to the Lupin sample (2.98%). Sulphate-sulphur content is often indicative of sulphide oxidation, and the Lupin sample demonstrated negligible sulphate-sulphur content (0.02%), consistent with its ’fresh’ description. The Nanisivik sample displayed a minor amount of sulphate sulphur (0.36%) suggesting that sulphide oxidation had begun over the exposure period, but oxidation was not sufficiently advanced to be visible in the petrographic analysis. Alternatively, gypsum content in the Nanisivik tailings may have been the source of the sulphate content.

5.0 THERMAL PROPERTIES TESTING PROGRAM

The thermal and geotechnical properties of the tailings samples were analysed for the following parameters:

- Moisture content;
- Frozen bulk density;
- Particle size distribution;
- Specific gravity;
- Thermal conductivity in both frozen and unfrozen states; and,
- Unfrozen water content versus freezing temperature.

Thermal conductivity was measured using the thermal needle probe method in accordance with the ASTM test procedure D5334-92. The unfrozen water content curve was determined using the Time Domain Reflectometry (TDR) technique (Topp et al. 1980; Patterson and Smith 1981; Smith and Tice 1988).

The results of the thermal and geotechnical testing are summarized in Table 6, as well as in Figure 2. For comparison, data reported by MEND (1998) for Lupin tailings are also reported.

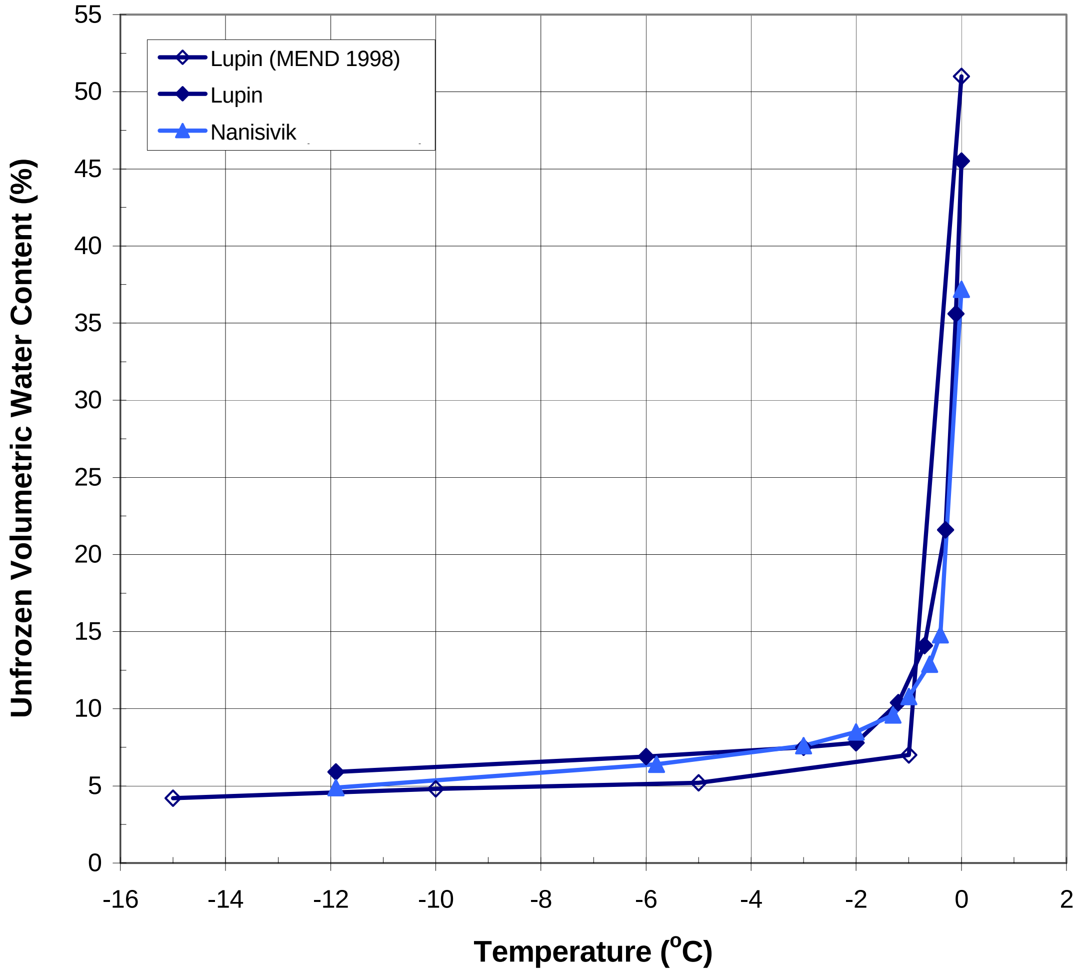
Table 6 Thermal and Geotechnical Test Results Summary

Property	**Lupin** (MEND 1998)	**Lupin** (current program)	**Nanisivik** (current program)
Gravimetric Moisture Content (%)	32.8*	26.3	15.5
Volumetric Moisture Content (%)	51*	45.5	37.8
Frozen Bulk Density (kg/m^3)	2064*	2070	2730
Specific Gravity	3.17	3.17	3.92
Sand (%)	30	8	42
Silt (%)	65	86	57
Clay (%)	5	6	1
Unfrozen Thermal Conductivity ($W/m \cdot K$)	1.7	1.6	1.9
Frozen Thermal Conductivity ($W/m \cdot K$)	2.7	3.0	3.2

* calculated based on reported 51% porosity and assuming saturated conditions

As seen in Table 6, reasonable consistency was found between the earlier Lupin sample testing done by MEND and the current testing from this program, although the frozen thermal conductivity value differed by approximately 11%. Thermal conductivity values for the Nanisivik sample were at least 7 to 11% higher than the Lupin sample.

Figure 2: Unfrozen Water Content versus Temperature



The three curves show little variation in the amount of unfrozen water at subzero temperatures. At –1°C, only 7 to 12% unfrozen water content was indicated.

6.0 COMPARISON AND SUMMARY

Within the overall study by BGC/MEMi (2004), 22 sets of thermal conductivity values for tailings were located within various papers and published reports. Of those values, 16 sets were determined by lab testing while the rest were inferred from noted correlations or back-analyzed from thermal analyses. Within that dataset, unfrozen thermal conductivities of sulphidic tailings (based on mineralogical information available) ranged from 1.6 to 1.9 W/m·K, while values ranging from 1.1 to 1.6 W/m·K were typically reported for the other tailings. Two significant exceptions were noted to that range. One is the "full-mix saturated" processed kimberlite where De Beers (2002) reported an unfrozen thermal conductivity of 2.1 W/m·K. The other is the weathered Wellgreen tailings (MEND 1998) where an unfrozen thermal conductivity of 1.0 W/m·K was reported, despite a high sulphide content of 12.8% sulphide-sulphur. MEND (1998) speculated that weathering of particle surfaces may have had a significant effect on the thermal conductivity.

The measured frozen thermal conductivities of the sulphidic tailings were also higher than those for tailings with a low (or none) sulphide mineral content. Frozen thermal conductivities of sulphidic tailings ranged from 2.7 to 5.1 W/m·K, while values ranging from 1.4 to 2.5 W/m·K were typically reported for the other tailings.

The median measured values of unfrozen thermal conductivity for non-sulphidic and sulphidic tailings from the survey were approximately 1.33 and 1.7, respectively. The median measured values of frozen thermal conductivity for non-sulphidic and sulphidic tailings were approximately 2.25 and 3.0, respectively. Thermal conductivity test results from the Lupin and Nanisivik Mines samples ranged from 1.6 to 1.9 (unfrozen) and 3.0 to 3.2 (frozen) W/m·K, respectively, basically in agreement with the literature survey results. Nanisivik tailings, with the highest proportion of sulphides, has the highest values. Thus, both the unfrozen and frozen thermal conductivities of sulphidic tailings appear to be about 30% higher than for non or low content sulphidic tailings.

As noted earlier, sulphide minerals possess high specific gravities. Average specific gravity of tailings solids may therefore provide a rough measure of sulphide content. For measured thermal conductivity values where specific gravity was reported or could be estimated, specific gravity was plotted against unfrozen and frozen thermal conductivity, as presented in Figure 3.

Figure 3: Specific Gravity versus Thermal Conductivity

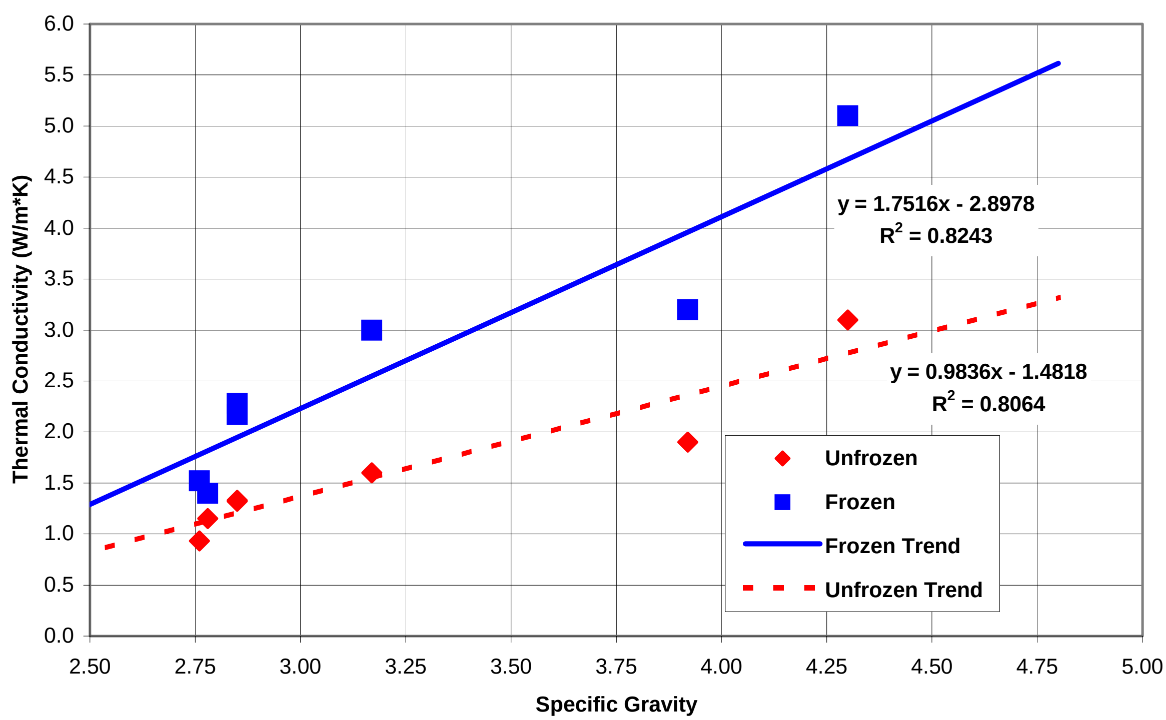


Figure 3 suggests there is a reasonable correlation between both frozen and unfrozen thermal conductivity and the average specific gravity of tailings solids. Tailings with a high specific gravity will tend to have a high thermal conductivity. This trend may not be applicable to highly weathered tailings such as those from the Wellgreen Mine.

The results of the literature review and laboratory testing confirm that sulphidic tailings generally possess a higher thermal conductivity than non-sulphidic tailings. The results also suggest that tailings with a high specific gravity will tend to have a high thermal conductivity. These factors should be given consideration if thermal conductivity values are to be estimated using empirical methods such as those recommended by Johansen (1975).

BGC/MEMi (2004) also noted that mineralogy and its associated weathering appears to play a significant role in thermal conductivity values. Quartz and pyrite have been identified as having unusually high mineral thermal conductivities, and therefore, significant influence on the overall tailings thermal conductivity value. Assessment of the thermal properties of other minerals should be undertaken to identify those with significant influence on thermal conductivities. If either a high sulphide content or high specific gravity is suspected, consideration should be given to verifying thermal conductivity values through laboratory measurements.

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REFERENCES

Alter, A.J. 1969. Water Supply in Cold Regions. US Army Cold Regions Res. Eng. Lab. Monograph 111-C5a.

Andersland, O.B. and Anderson, D.M. 1978. Geotechnical Engineering for Cold Regions. McGraw-Hill Inc., New York.

Andersland, O.B. and Ladanyi, B. 1994. An Introduction to Frozen Ground Engineering. Chapman & Hall Inc., New York.

BGC Engineering Inc. and Mehling Environmental Management Inc. 2004. Ice in Tailings Research, Phase II Study, Thermal Conductivities of Sulphidic Tailings. Report prepared for Indian and Northern Affairs, March 9, 2004.

Cassie, J.W. and LeDrew, K.G. 2001. Tailings deposition and dike construction at Nanisivik Mine, Nunavut. International Symposium on Mining in the Arctic, Nuuk, Greenland.

Chesterman, C.W. and Lowe, K.E. 1979. The Audubon Society Field Guide to North American Rocks and Minerals. Alfred A. Knopf Ltd., New York.

Clauser, C. and Huenges, E. 1995. Thermal Conductivity of Rocks and Minerals. Section in Rock Physics and Phase Relations, A Handbook of Physical Constants, AGU Reference Shelf 3, copyright 1995 by the American Geophysical Union, pages 105 to 124.

De Beers Canada Mining. 2002. Snap Lake Diamond Project – Environmental Assessment Report, Environmental Assessment Part 2 and Appendices. Submitted to Mackenzie Valley Environmental Impact Review Board.

De Vries, D.A. 1966. Thermal properties of soils. Chapter 7 in *Physics of Plant Environment*, 2nd Edition, ed. W.R. Van Wijk. Amsterdam: North-Holland, pp. 210-35.

Farouki, O.T. 1981. CRREL Monograph 81-1, Thermal properties of soils. United States Army Corps of Engineers, Cold Regions Research Laboratory, Hanover, New Hampshire, USA.

Jessop, A.M., Robertson, P.B., and Lewis. T.J. 1979. A brief summary of the thermal conductivity of crystalline rocks. Atomic Energy of Canada Ltd., Technical Report TR-12, Pinawa, Manitoba, January 1979, 19 p.

Johansen, O. 1975. Thermal conductivity of soils. Ph.D. thesis, Trondheim, Norway. CRREL draft translation 637, 1977. ADA 044002.

Johnston, G.H. (Ed.). 1981. Permafrost Engineering Design and Construction. Wiley, Toronto, Canada.

Kersten, M.S. 1949. Laboratory research for the determination of the thermal properties of soils. ACFEL Technical Report 23. AD712516. (Also, Thermal properties of soils. University of Minnesota Engineering Experiment Station Bulletin No. 28.)

Klohn Leonoff 1992. Acid Rock Drainage Study, Lupin Mine, Northwest Territories. Final report submitted to Echo Bay Mines Ltd., March 1992.

Meldrum, J. L., Jamieson, H. E., and Dyke, L. D. 2001. Oxidation of Mine Tailings from Rankin Inlet, Nunavut at Subzero Temperatures. Canadian Geotechnical Journal, Volume 38, Pages 957 - 966.

MEND Project 6.1. 1993. Preventing AMD by disposing of reactive tailings in permafrost. Canada Centre for Mineral and Energy Technology.

MEND Project 1.62.2. 1998. Acid mine drainage behaviour in low temperature regimes – thermal properties of tailings. Canada Centre for Mineral and Energy Technology.

Patterson, D.E., and Smith, M.W. 1981. The measurement of unfrozen water content by time domain reflectometry: results from laboratory tests. Canadian Geotechnical Journal, vol. 18, pp. 131-144.

Smith, M.W. and Tice, A.R. 1988. Measurement of the unfrozen water content of soils. Comparison of NMR and TDR methods. CRREL Report 88-18, 41p.

Topp, G.C., Davis, J.L., and Annan, A.P. 1980. Electromagnetic determination of soil water content: measurements in coaxial transmission lines. Water Resources Research, vol. 16, pp. 574-582.

Weast, R.C., Astle, M.J., and Beyer (Eds.). 1984. CRC Handbook of Chemistry and Physics. Boca Raton, Fla: CRC Press.