Preliminary study of the influence of temperature and salinity on the thermal properties of hardening cemented paste backfill

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ABSTRACT
Thermal curing conditions of cemented paste backfill (CPB) in mine stopes with frozen walls in the permafrost can be assessed using numerical modeling. For this purpose, thermal conductivity and capacity functions of CPB with respect to curing time and temperature are required. In permafrost regions, CPB mixing water is expected to contain brine. The goal of this study was to investigate the influence of temperature and salinity on CPB’s thermal properties. KD2 Pro apparatus was used to determine these properties for different CPB mixtures prepared at a solid mass concentration of 76.3\%, with 0\% (control) and 5\% contents of type HE Portland cement. Mixing water with salt concentrations from 0 to 1\% was also studied. Changes in thermal properties of CPB were measured at temperatures of -8\°C, 2\°C and 22\°C. Results indicated that binder content (0, 3, and 5\%), salt concentration in the mixing water (0 – 1\%) and positive temperatures (2 and 22\°C) have a negligible influence on thermal properties with curing time (0 - 28 d). However, freezing conditions (-8\°C) has significant effect on these thermal properties.

RÉSUMÉ
Les conditions thermiques de cure du remblai en pâte cimenté (RPC) dans les chantiers miniers avec des parois gelées dans le pergélisol peuvent être évaluées par la modélisation numérique. Pour cela, les fonctions de conductivité et de capacité thermiques du RPC par rapport au temps et à la température de cure sont requises. De plus, l'eau de gâchage du RPC dans les régions de pergélisol peut contenir de la saumure. L'objectif de cette étude était d'étudier l'influence de la température et de la salinité sur l'évolution des propriétés thermiques en fonction du temps de cure. L'appareil KD2 Pro a été utilisé pour déterminer ces propriétés pour différents mélanges de RPC préparés à un pourcentage solide de 76,3 \% avec 0 \% (témoin) et 5 \% du ciment Portland type HE. Des eaux de gâchage avec des concentrations en sel variant de 0 à 1 \% ont été utilisées. Les variations des propriétés thermiques ont été mesurées à des températures de -8 °C, de 2 °C et 22 °C. Les résultats indiquent que la teneur en liant (0 et 5 \%), la concentration de sel dans l'eau de gâchage (0 – 1 \%) et des températures positives (2 et 22 °C) ont une influence négligeable sur les propriétés thermiques au cours du temps de cure. Cependant, l'existence du gel a une grande influence sur ces propriétés thermiques.

1 INTRODUCTION
Mining industry generates important incomes for the economy of many countries around the world, but also generates nevertheless large quantities of liquid and solid wastes. When the solid wastes, mainly waste rocks and tailings, contain sulfide minerals they can lead to environmental impacts in terms of acid mine drainage. Nowadays, environmentally friendly and economically viable waste management techniques are implemented to address these concerns. The existing techniques include the reuse of tailings for underground cemented paste backfill (CPB) preparation. Indeed, the use of CPB allows sending back large amount (up to 50\%) of tailings to underground excavations, therefore reducing the quantity to be stored on the surface. At the same time CPB plays the role of secondary ground support. (e.g., Hassani and Archibald, 1998). CPB is made of filtered mill tailings, water and a binding agent such as Portland cement or blends of cement and mineral additives such as pulverized fly ash and ground granulated blast furnace slag. The role of the binding agent is to provide cohesive strength to the CPB mixtures.

Most research projects worldwide focused on CPB characterization in temperate and semi-arid climates. These studies mainly addressed the optimization of mix recipes to satisfy the strength requirement in order to ensure the stability of backfilled stopes with one exposed face (e.g., Landiault 1995; Benzaazoua et al. 2004a; Belem and Benzaazoua 2008) and rheological requirements to ensure CPB transportation in pipeline from the plant to underground stopes (e.g., Cooke 2007; Boger et al., 2006; Ouattara 2011; Ouattara et al., 2010, 2013). Other researchers also addressed the geomechanical behavior (Belem et al., 2000, 2013a,b), the chemical and geochemical behavior (Benzaazoua et al., 2004b; Ouellet et al., 2006) of CPB after deposition.

The practice of CPB technique in underground mines stopes within permafrost in the Northern regions is poorly documented (Bandopadhyay and Izaxon, 2004), although CPB is increasingly tipped as viable given its numerous advantages. But in northern climates one of the main challenges is the formulation of CPB mix recipes that can
be prepared in the backfill plant at surface, transported through pipelines and placed in underground stopes without being frozen. Another challenge is that these mix recipes should produce a CPB able to achieve the required strength (generally within 28 days) for stability and ground control reasons.

Since the hydration of hydraulic binders used in the CPB will be affected by curing temperature, knowing the temperature distribution within the CPB confined in walls of permafrost is crucial for the adequate formulation in the laboratory of the mix recipes developing the required mechanical strength. If the thermal curing conditions of CPB can be known primarily, the formulation of the mix recipe for northern cold climates can be performed safely. As a matter of fact, it would then be possible to set laboratory CPB specimens curing temperature for the purpose of optimizing the mix recipes for the required strength.

The temperature distribution across the confined CPB body in frozen walls of permafrost should depend on the amount of mixing water, the mineralogical composition of tailings, the backfill deposition temperature, the stope size as well as the wall and the ambient air temperatures. The natural salinity (brine) of frozen water in the permafrost (Hivon and Sego; 1993) and the salinity added by ore deicing salts represent another factor of influence so far not being much considered in the CPB.

As the temperature distribution within a backfilled stope in permafrost is very difficult to reproduce in laboratory scale, the use of numerical modeling with a calibrated model of heat transfer represents a good alternative (Bandopadhyay and Izaxon, 2004; Ghereishi-Madiseh et al., 2011). Indeed, the knowledge of thermal properties of CPB curing under decreasing temperature becomes important for such numerical modeling. Some research has been conducted on the thermal behavior (heat transfer properties) of CPB (Abssay et al., 2014) and its impact on strength development (e.g. Wu et al., 2013; Ghirian and Fall, 2013; Wu et al., 2012; Nasir and Fall, 2009, 2010; Putkonen, 1998). In the past few years, frozen backfill without binders was also investigated (Cluff and Kazakidis, 2012).

The objective of this paper is to study the influence of varying temperature (positive and negative) and mixing water salinity on the thermal conductivity (\(\lambda\)) and volumetric heat capacity (\(C_v\)) of paste tailings (uncemented) and curing CPB (0 and 5% binder).

2 MATERIAL CHARACTERISATION AND METHODOLOGY

2.1 Tailings and mixing water characteristics

The tailings sample used was subjected to a complete characterisation including physical (grain size distribution, specific gravity) chemical and mineralogical characterization. The grain size distribution was obtained using a Malvern Mastersizer laser particle sizer. Several analyses were performed and the cumulative grain size distribution curve mean is shown in Figure 1.

Table 1 shows the main characteristics of the tailings (diameter corresponding to x% passing on the cumulative grain size distribution curve \(D_x\), coefficients of uniformity \(C_u\) and of curvature \(C_c\) percent \(P_z\) and \(P_{50}\) passing through the 2 \(\mu\)m and 80 \(\mu\)m meshes, respectively). The percentage of the fine fraction (particle diameter less than 20 \(\mu\m) was 53%.

The relative density of tailings grains \(D_r\) or specific gravity \(G_s\) was determined using a Micromeretics helium pycnometer. The measured \(D_r\) value is 2.9.

The mineralogical composition of the tailings sample was determined using Bruker D8 Advance AXS X-ray diffraction (XRD). The results are presented in Table 2.

![Figure 1. Cumulative volume percentage vs volume percentage](image)

Table 1. Grain size distribution parameters of the tailings used

<table>
<thead>
<tr>
<th>Parameter</th>
<th>(D_{10})</th>
<th>(D_{50})</th>
<th>(D_{90})</th>
<th>(P_2)</th>
<th>(P_{50})</th>
<th>(C_u)</th>
<th>(C_c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>((\mu\m))</td>
<td>((\mu\m))</td>
<td>((\mu\m))</td>
<td>(%)</td>
<td>(%)</td>
<td>(-)</td>
<td>(-)</td>
</tr>
<tr>
<td>Value</td>
<td>3.5</td>
<td>10</td>
<td>27.5</td>
<td>5.5</td>
<td>85</td>
<td>7.86</td>
<td>1.04</td>
</tr>
</tbody>
</table>

Table 2. Mineralogical composition of the tailings used

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Mass proportion (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>40.32</td>
</tr>
<tr>
<td>Pyrite</td>
<td>0.35</td>
</tr>
<tr>
<td>Muscovite</td>
<td>14.65</td>
</tr>
<tr>
<td>Chlorite</td>
<td>8.07</td>
</tr>
<tr>
<td>Calcite</td>
<td>2.43</td>
</tr>
<tr>
<td>Microcline</td>
<td>1.33</td>
</tr>
<tr>
<td>Magnetite</td>
<td>4.55</td>
</tr>
<tr>
<td>Ankerite</td>
<td>8.77</td>
</tr>
<tr>
<td>Albite</td>
<td>19.49</td>
</tr>
</tbody>
</table>

In order to study the influence of the salinity of mixing water on the mechanical and thermal properties of CPB, a mix of fresh tap water with salt concentrations of 0.025%, 0.5%, 0.75% and 1.0% (i.e. 0, 2.5, 5, 7.5 and 10 g/L) are used for the backfill preparation. These saline solutions are prepared based on the following salts (Ouellet, 2015 pers. communication): calcium chloride (\(CaCl_2\)), potassium chloride (\(KCl\)), sodium chloride (\(NaCl\)), magnesium sulfate heptahydrate (\(MgSO_4\cdot7H_2O\)), magnesium chloride hexahydrate (\(MgCl_2\cdot6H_2O\)), sodium
metabisulphite (Na₂S₂O₃), and copper sulfate pentahydrate (CuSO₄·5H₂O).

To prepare 1 liter (L) of mixing water for each saline solution, the different salts were used in the proportions shown in Table 3.

Table 3: Mass proportion of salts for 1 liter of saline water

<table>
<thead>
<tr>
<th>Salts</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.25%</td>
</tr>
<tr>
<td>CaCl₂ (g/L)</td>
<td>0.23</td>
</tr>
<tr>
<td>NaCl (g/L)</td>
<td>1.53</td>
</tr>
<tr>
<td>KCl (g/L)</td>
<td>0.03</td>
</tr>
<tr>
<td>MgSO₄·7H₂O (g/L)</td>
<td>0.36</td>
</tr>
<tr>
<td>MgCl₂·6H₂O (g/L)</td>
<td>0.33</td>
</tr>
<tr>
<td>Na₂S₂O₃ (g/L)</td>
<td>0.34</td>
</tr>
<tr>
<td>CuSO₄·5H₂O (g/L)</td>
<td>0.07</td>
</tr>
</tbody>
</table>

For the chosen mix recipes the CPB were prepared using dry tailings and type HE Portland cement. Mixtures of less than 5 kg were prepared using a Hobart mixer at a solid concentration Cw of 76.3%, i.e. a water content of 31.1% (paste tailings with a slump height of 7 inches), with binder contents Bw of 0, 3 and 5%. The mixing time was set to 7 minutes.

2.2 Measurement of thermal properties

The portable KD2 Pro thermal properties analyser from DECAGON Inc. was used. This analyser complies with the IEEE 442-1981 and ASTM D5334-08 standards and can be used in the laboratory or in the field. Its principle is based on the hot wire method (Gobbe et al., 2004) for measuring the thermal conductivity/resistivity (accuracy of ± 5 to ± 10%), the specific heat (accuracy of ± 10%), as well as the diffusivity (accuracy of ± 10%). For simultaneous measurement of the thermal conductivity and volumetric heat capacity for most granular materials, the double needle « SH-1 » sensor is used (needles with 1.3 mm in diameter and 30 mm in length and a spacing of 6 mm). The KD2 Pro thermal properties analyser has been used successfully by various researchers (e.g., Célestin and Fall., 2009; Meibodi et al., 2010; Pawan and Sreedep, 2011; Pawan and Sreedep, 2013; Abassy et al., 2014; Kyu and Shang, 2014; Lee et al., 2014).

2.3 Experimental program

For this preliminary study, the CPB was prepared at the prescribed solid mass concentration Cw of 76.3% (corresponding to a targeted slump of 7 inches). The CPB mixture is then poured in 29 plastic molds (6” height and 3” diameter) as shown in Figure 2. A previous study (Beya, 2014) had shown that this mold size did not affect the thermal properties measurement as no difference was noticed when compared to data obtained from larger size molds (6” height and 3” diameter). The repeatability was also previously studied using triplicates samples. Negligible errors (standard deviation less than 0.01) were observed for paste tailings and CPB with 3% and 5% binder contents. Table 4 shows the characteristics of the mix recipes, namely the mixing water salt content, the % of binder Bw (0, 3 and 5%) and the curing conditions in a temperature controlled room at 22, 2 and -8°C. For most samples, the fresh backfill is left to cure directly at the targeted temperature. Some samples were cured for 3 and 7 days at 22°C before being subjected to -8°C. This scenario aims in studying the effect of freezing on the thermal properties of already placed backfill and undergoing curing. The testing program in Table 4 will allow evaluating the effects of curing time and temperature, binder content and temperature, salt content and curing time, and binder hydration on the thermal conductivity and volumetric heat capacity of the backfill.

Table 4: Sample characteristics and testing conditions

<table>
<thead>
<tr>
<th>Salt content (%)</th>
<th>T = 22°C Bw (%)</th>
<th>T = 2°C Bw (%)</th>
<th>T = -8°C Bw (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>X</td>
<td>X</td>
<td>XYZ</td>
</tr>
<tr>
<td>0.25</td>
<td>K</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>0.5</td>
<td>XYZ</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>0.75</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>1</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

1: sample cured directly at 22°C; 2°C and -8°C (curing times of 0, 3, 7, 14 and 28 days)
2: sample cured for 3 days at 22°C and then at -8°C.
3: sample cured for 7 days at 22°C and then at -8°C

In Figure 2 it can be seen one backfill sample during thermal properties measurement with the SH-1 sensor and the KD2 Pro analyser. The measurements were performed by running the auto mode which takes at least 4 measures (per hour) and the average value is taken as the final value measured. Measurements were performed at curing times of 0, 3, 7, 14 and 28 days.

![Figure 2. Photo of Molded backfills showing thermal properties measurements using KD2 Pro analyser](image-url)
of 0%, 3% and 5% to investigate the effect of curing time. For each mixture, a sample was placed at temperatures of -8°C, 2°C and 22°C. Figures 3 and 4 show typical variations in the thermal conductivity $\lambda$ and volumetric heat capacity $C_v$ of the backfill with 5% binder and 0% salt. The results for uncememted paste tailings and for CPB with 3% binder were relatively similar to those shown in Figures 3 and 4.

![Figure 3](image1.png)  
**Figure 3.** Variation in the thermal conductivity with respect to the curing time for CPB samples with 5% of binder and 0% of salt

![Figure 4](image2.png)  
**Figure 4.** Variation in the volumetric heat capacity with respect to the curing time for CPB samples with 5% of binder and 0% of salt

The small reduction in thermal conductivity may be due to the binder hydration and hardening processes (e.g., Bentz, 2007; Kyu and Shang 2014). Indeed, Kyu and Shang (2014) studied the thermal properties of tailing mixtures with substantial proportions (20 to 60%) of fly ashes and their results showed that the hydration of the fly ashes played a significant role on the thermal conductivity decrease and the heat capacity increase over the curing times. This could be explained by the low thermal conductivity and high heat conductivity of hydrates and precipitates formed from the fly ashes reactions.

![Figure 5](image3.png)  
**Figure 5.** Variation in the thermal conductivity of tailings and CPB with respect to the curing temperature after a curing time of 7 days and 0% of salt

![Figure 6](image4.png)  
**Figure 6.** Variation of the heat capacity of tailings and CPB as a function of curing temperature after a curing time of 7 days and 0% of salt

For backfill samples placed directly after preparation in the cold chamber, freezing temperature affected the hydration process of the binder. Therefore, the thermal properties of the frozen backfill samples with binder (3 and 5%) were close to the results obtained from uncememted paste tailings.

These observations about the effect of temperature on $\lambda$ are consistent with data on CBP from the literature (Célestin and Fall 2009) and for soils and rocks (e.g., Vosteen and Schellschmidt, 2003; Miao et al., 2013). For CBP’s heat capacity, however, literature data on soils indicated that the $C_v$ of soils decreases with decreasing temperature (Putkonen, 2003), which also corroborates the observations in this study.

22°C. The heat capacity increased with temperature (2.92 MJ/m$^3$/K at $T= -8°C$; 3.17 MJ/m$^3$/K at $T= 2°C$ and 3.32 MJ/m$^3$/K at $T= 22°C$) (see Figure 6); from -8 to 22°C, the increase is about 13.7%.

Overall, the thermal conductivity $\lambda$ decreased from 1.84 to 1.63 W/mK and the volumetric heat capacity $C_v$ increased from 3.15 to 3.32 MJ/m$^3$/K when the binder content varied from 0% to 5%. These variations are negligible compared to the accuracy of the SH-1 sensor given in the section 2.2. Similar behavior was observed with other types of mine backfills (e.g., Abassy, 2009; Célestin and Fall, 2009).
3.2 Effect of salt concentration

To investigate the effect of salt concentration on the conductivity and heat capacity of the CPB, four samples with 5% type HE cement were prepared using water with salt concentrations varying from 0% to 1% as shown in Table 3. For a given temperature and at a given curing time, no variation was observed in measured thermal conductivity (Figure 7). The heat capacity tends to increase very slightly with increasing salt concentration (Figure 8).

![Figure 7. Variation in the thermal conductivity of CPB with 5% binder as a function of salt concentration at a curing time of 7 days](image)

![Figure 8. Variation in the heat capacity of CPB with 5% binder as a function of salt concentration at a curing time of 7 days](image)

No available data were found in the literature on the thermal properties of CPB prepared with saline mixing water to allow comparisons. For studies conducted on soils, the effect of NaCl concentration on thermal conductivity was influenced both by the water content of the soil and by the nature of the soil. For sand and glass beads, the thermal conductivity varied almost linearly when NaCl concentration increases (from 0 to 165 g/L) (Mochizuki et al., 2008). This trend was also observed by Abu-Hamdeh and Reeder (2000) for the thermal conductivity of clayey soils containing up to 100 g/L salt. These literature results are somewhat similar to those ensuing from the tests carried out in this study, although the materials are different and very low salt concentrations (up to 1 g/L) were studied.

3.3 Effect of delayed freezing

The freezing impact on the thermal conductivity and heat capacity of CPB already curing was carried out on 4 samples prepared with type HE cement at 5%. Two samples were prepared with fresh tap water and the other two using water containing 0.5% salt content. One sample of each duplicate was first cured at 22°C for 3 days and then at -8°C. The other sample was first cured at 22°C during 7 days and then at -8°C. Figures 9 and 10 show the results of the CPB prepared saline water. It can be observed that almost similar results were obtained for samples prepared with fresh tap water. Figure 9 shows that the thermal conductivity \( \lambda \) increased very slightly during the first 3 and 7 days of curing at 22°C. From the 4th day of curing and when the CPB is frozen at -8°C, the value of \( \lambda \) increased progressively to reach 2.05 W/mK. From the 8th day of frozen (at -8°C) CPB curing the value of \( \lambda \) jumped steeply up to around 2.1 W/mK.

![Figure 9. Variation in the thermal conductivity of CPB with 5% of binder and 0.5% of salt as a function of curing time](image)

![Figure 10. Variation of the heat capacity of CPB with 5% of binder and 0.5% of salt as a function of curing time](image)

Figure 10 shows that the heat capacity was close to 3.12 MJ/m\(^2\)K during the 3 and 7 day curing time at 22°C and then decreased to around 2.94 MJ/m\(^2\)K when the CPB was frozen. For CPB samples placed directly in the cold chamber, the average thermal conductivity was 2.09 W/mK (see Figure 4) and heat capacity was 2.92 MJ/m\(^2\)K (see Figure 5) over the whole curing time of 28 days. The delayed freezing seems to induce a decrease in thermal conductivity while the heat capacity remained nearly unchanged after a curing time of 28 days. As mentioned
above, the CPB binder hydration contributed to the
decrease in thermal conductivity.

4 DISCUSSION

As stated in the introduction, empirical equations
describing the thermal properties of CPB curing under
decreasing temperature are very important for numerical
modeling of the thermal curing of CPB confined in frozen
walls of permafrost. This paper presents preliminary
investigation for this purpose. These empirical functions
may be developed by extending existing equations for
estimating the thermal properties to include the effects of
binder content, curing time and salt concentration.

In a first stage, estimated and measured thermal
properties for unfrozen and uncemented paste tailings are
compared below. Thermal properties estimation, based on
the mineralogy of the tailings can help validating the
measurements made using the KD2 Pro analyser. A
simple case of uncemented paste tailings was used.
Thermal properties of CPB were not estimated due to the
complexity of the phenomenon of binder hydration. For a
saturated porous material, the thermal conductivity can be
estimated by equation 1 (Côté and Konrad, 2009; Côté et
al., 2013):

\[ \lambda = \frac{\left( k_{2p} \lambda_s - \lambda_f \right) (1 - n) + \lambda_f}{1 + (k_{2p} - 1)(1 - n)} \]  \[1\]

where, \( k_{2p} \) is an empirical parameter accounting for inner
structure effects (distribution of grain size, pore size,
tortuosity and pore fluid); \( \lambda_s \) and \( \lambda_f \) are the thermal
conductivity of the solid and liquid phases, respectively;
and \( n \) is the porosity.

The thermal conductivity of the solid phase \( \lambda_s \) can be
obtained from the mineralogy as follows:

\[ \lambda_s = \prod_j \lambda_{mj}^{x_j} \]  \[2\]

where \( \lambda_{mj} \) is the thermal conductivity of the mineral \( j \) with a
volume fraction \( x_j \) in the whole material. The empirical
parameter \( k_{2p} \) is defined as follows:

\[ k_{2p} = 0.29 \left( \frac{15 \lambda_s}{\lambda_f} \right)^\beta \]  \[3\]

where \( \beta \) is an empirical constant. For conductivity ratios of
\( \lambda_f/\lambda_s = 1/15 \), \( \beta \) equals 0.81 for natural soils, 0.54 for
crushed rock, and 0.34 for cemented materials. For
conductivity ratios superior to 1/15, the structure has no
significant effects and \( \beta \) equals 0.46 for all types of
materials (Côté et al., 2013).

The volumetric heat capacity of saturated porous
materials can be obtained with equation 4 as follows
(Musy and Soutter, 1991):

\[ C_v = \rho (1 - n) C_{ps,0} + n C_{pw} \]  \[4\]

where \( \rho \) is the density of the material, \( \theta_w \) is the volumetric
water content, \( C_{ps,0} \) is the mass heat capacity of solid and
\( C_{pw} \) is the mass heat capacity of water.

The heat capacity of the solid phase can be estimated
form the mineral composition using the weighted
arithmetic mean with the mass fraction of each mineral
(Nimick and Connolly, 1991). Using thermal conductivity
data of minerals (see Table 5) taken from Côté and
Konrad (2005) and Eppelbaum et al. (2014), the thermal
conductivity of the solid phase in the tailings \( \lambda_s \) given by
Eq. [2] is 4.342 W/mK. The thermal conductivity of the
saturated uncemented paste tailings estimated with equation
1 is 1.74 W/mK (see Table 6) while the one
measured with the KD2 Pro device is 1.84 W/mK, which
implies a difference of 0.1 W/mK or 5.4%. Taking into
account the accuracy of the SH-1 sensor on the
measured values (±10%), it can be concluded that the
Côté and Konrad model (2009) predicts fairly accurately
the thermal conductivity of the uncemented paste tailings
used in this study.

Table 5. Estimation of the average thermal conductivity
of solid grains from different minerals

<table>
<thead>
<tr>
<th>Mineral</th>
<th>( \lambda_{mj} ) (W/mK)</th>
<th>( \rho_s ) (g/cm³)</th>
<th>( x_j )</th>
<th>( \lambda_{mj} ) (W/mK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>7.69</td>
<td>2.65</td>
<td>0.379</td>
<td>2.169</td>
</tr>
<tr>
<td>Pyrite</td>
<td>19.21</td>
<td>5.10</td>
<td>0.006</td>
<td>1.019</td>
</tr>
<tr>
<td>Muscovite</td>
<td>3.48</td>
<td>2.85</td>
<td>0.148</td>
<td>1.203</td>
</tr>
<tr>
<td>Chlorite</td>
<td>5.15</td>
<td>2.75</td>
<td>0.079</td>
<td>1.138</td>
</tr>
<tr>
<td>Calcite</td>
<td>3.59</td>
<td>2.71</td>
<td>0.023</td>
<td>1.030</td>
</tr>
<tr>
<td>Microcline</td>
<td>2.04</td>
<td>2.58</td>
<td>0.012</td>
<td>1.009</td>
</tr>
<tr>
<td>Magnetite</td>
<td>5.10</td>
<td>5.15</td>
<td>0.084</td>
<td>1.146</td>
</tr>
<tr>
<td>Ankerite</td>
<td>2.11</td>
<td>2.75</td>
<td>0.086</td>
<td>1.066</td>
</tr>
<tr>
<td>Albite</td>
<td>1.96-2.63</td>
<td></td>
<td>0.182</td>
<td>1.130</td>
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</tbody>
</table>

Table 6. Estimated thermal conductivity for the tailings
sample used at 76.3% solid content

<table>
<thead>
<tr>
<th>( \beta )</th>
<th>( k_{2p} ) (W/mK)</th>
<th>( \lambda_s ) (W/mK)</th>
<th>( n )</th>
<th>( \lambda_f ) (W/mK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.46</td>
<td>0.41</td>
<td>4.342</td>
<td>0.59</td>
<td>0.48</td>
</tr>
<tr>
<td>0.48</td>
<td>1.74</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7. Specific heat capacities (taken from Waples
and Waples, 2004 and Eppelbaum et al., 2014)

<table>
<thead>
<tr>
<th>Mineral</th>
<th>( C_v ) (J/kg K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>740</td>
</tr>
<tr>
<td>Pyrite</td>
<td>510</td>
</tr>
<tr>
<td>Muscovite</td>
<td>760</td>
</tr>
<tr>
<td>Chlorite</td>
<td>600</td>
</tr>
<tr>
<td>Calcite</td>
<td>815</td>
</tr>
<tr>
<td>Microcline</td>
<td>700</td>
</tr>
<tr>
<td>Magnetite</td>
<td>586</td>
</tr>
<tr>
<td>Ankerite</td>
<td>802</td>
</tr>
<tr>
<td>Albite</td>
<td>730</td>
</tr>
</tbody>
</table>

Using heat capacity data of minerals taken from
Waples and Waples (2004) and Eppelbaum et al. (2014) (see
Table 7), the volumetric heat capacity \( C_v \) estimated from
equation 4 is 4.69 MJ/mK (see Table 8). This value is
different to the one measured with the KD2 Pro device. Therefore, the predictive model of the volumetric heat capacity of porous materials developed by Musy and Soutter (1991) predicts in a relatively less accurate manner the volumetric heat capacity of the uncemented tailings sample used.

Table 8. Heat capacity for the used tailings sample at 76.3% solid content:

<table>
<thead>
<tr>
<th>Heat Capacity (J/kg K)</th>
<th>Density (kg/m³)</th>
<th>Specific Heat (J/kg K)</th>
<th>Thermal Conductivity (MJ/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cₚ,ω</td>
<td>P</td>
<td>n</td>
<td>C</td>
</tr>
<tr>
<td>721.6</td>
<td>4175</td>
<td>1970</td>
<td>0.48</td>
</tr>
</tbody>
</table>

5 CONCLUDING REMARKS

This paper presents preliminary results of the influence of temperature and salinity (used for mining and ore manutention purposes) on the thermal properties (conductivity and heat capacity) of uncemented tailings and cemented paste backfill samples. It was noted that curing time has a negligible influence on thermal properties and that freezing showed a major influence. For the testing conditions it was observed that freezing of CPB significantly increased the thermal conductivity (22%) and decreased heat capacity (12%). Laboratory measurements have revealed little influence of the salt concentration (0 to 1%) in the CBP mixing water on thermal properties. Freezing of pre-cured and hardened CPB increased the thermal conductivity but did not significantly affect the heat capacity.

This study was based on one type of tailings only, one fixed solid concentration (76.3%), one type (HE) and percentage (0, 3 and 5%) of binder, and salt concentrations from 0 to 1%. Additional tests are ongoing in order to extend the study to other mixtures, particularly in the range of temperature between -8°C and 2°C. Data gathered from the whole study will be used to develop empirical equations to estimate the thermal properties of CPB. Once developed, these equations will be implemented in a numerical code for evaluating the flow behavior of CPB in pipelines. Furthermore, ongoing 1D and 3D heat transfer in CPB is being simulated using laboratory physical models (columns and large barrel). The expected results will help calibrating the numerical models.

6 ACKNOWLEDGEMENTS

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7 REFERENCES


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