Investigating Frozen Paste Surface Disposal as a Climate Change Adaptation Strategy

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Abstract
The mining industry faces evolving challenges in adapting to the impacts of climate change. Among these challenges is the management of tailings. Traditional methods of tailings disposal, primarily utilizing water-based tailings dams, are increasingly vulnerable to the shifting climate patterns, making alternative approaches imperative. This study focuses on investigating surface disposal of frozen non-cemented paste tailings, particularly the effect of water content (ie, 20 and 30%) and ambient temperature (ie, -5 and -15 °C) on the mechanical characteristics and the thermophysical properties of the frozen paste tailings. Results of thermophysical properties suggested an enhanced conduction medium for paste tailings compared with dry porous tailings. Unconfined compression strength (UCS) test results deemed the effect of the ambient temperature to be the most dominant, despite having additional influence from water content. The highest UCS observed is 0.62 MPa for a sample with 30% water content, tested at -15 °C. The lowest UCS observed is 0.26 MPa for a sample with 20% water content, tested at -5 °C. This study suggests further investigation to the characteristics and variables that are important in cold regions, such as freeze-thaw cycles and thermal behavior at sub-zero temperatures.

Key words: unconfined compression strength, water content, thermal properties, paste temperature

Introduction
Throughout history, mining has played an important role in shaping economies and societies, extracting valuable resources to meet the growing demands of industries worldwide (MAC, 2022). However, mining operations extend beyond the extraction of valuable minerals, as they also deal with the challenge of managing tailings: the waste generated by mechanical and chemical processes after the extraction and separation of the desired mine ore in a processing plant (Engels, 2021; Kossoff et al., 2014). It has been common practice to store tailings in designated facilities known as tailings management facilities (TMFs). TMFs can take various forms, such as embankments, dams, or surface impoundments, that host wet tailings (ie, tailings with high water content). Another method involves utilizing tailings for backfilling purposes in abandoned open pit mines or underground mines (Ma et al., 2023).

Exacerbated by climate change, the management of mine tailings presents important challenges worldwide, and Canada has emerged as a leading innovator in tailings management practices (Alzoubi et al., 2021; Hashem et al., 2023; Zueter et al., 2021). In recent years, the use of paste tailings, a dewatered and densified form of tailings, has garnered considerable attention as a potential solution for improving tailings disposal methods (Hassani et al., 2021). In Canada, different aspects of paste tailings are being utilized, including cemented paste tailings (CPT), non-cemented paste tailings (NCPT), and paste tailings using water as a binder (PT).

CPT involve the use of cement as a binder to achieve the desired strength and stability of the tailings material. This method has been widely adopted in Canada and has proven effective in mitigating environmental risks associated with tailings storage (Benkirane et al., 2023; Hassani et al., 2001; Hassani et al., 2021). The incorporation of cement in CPT enhances strength properties, reduces seepage potential, and increases geotechnical stability (Chang, 2016; Chang and Fall, 2022). However, using cemented tailings in northern Canada is also associated with high costs. This is due to the high costs associated with logistics, including transportation, and the limited availability of local resources in northern Canada (Klohn-Crippen-Berger, 2017).

In contrast, PT has gained prominence as a cost-effective alternative to CPT. This method involves the addition of water to the dewatered tailings to form a paste-like consistency, which can then be transported and deposited (Hou et al., 2020). PT offers advantages such as lower binder costs, reduced water consumption, and improved environmental performance (Alakangas et al., 2013; Aldhafeeri, 2018). Thermal properties of tailings paste also play a crucial role in its behavior. Thermal conductivity, heat capacity, and thermal diffusivity are among the key properties that influence the behavior of tailings paste (Abbasy et al., 2014). Understanding these properties is essential for predicting the thermal response of paste in different climatic conditions, as well as for assessing the potential impacts on the surrounding environment. Moreover, the thermal properties of tailings paste may affect the efficiency of processes such as freeze consolidation, heat transfer, and temperature control during tailings storage and reclamation operations (Alzoubi et al., 2021; Boulanger-Martel et al., 2021; Elberling, 2004). Furthermore, it is important to consider the role of water content on paste tailings, as it can influence the paste mechanical characteristics significantly (Hane et al., 2017).

Considering the effects of water content and temperature on the tailings behavior is crucial for the comprehensive evaluation of its performance and suitability as a tailings management method. By examining these aspects, this paper aims to contribute to the understanding and advancement of tailings management practices in Canada, ultimately promoting sustainable and responsible mining operations. Therefore, this study investigates the use of frozen paste as a replacement for flooded fine tailings as a climate change adaptation strategy.

Experimental procedure

Particle size distribution (PSD)

Understanding the particle size distribution (PSD) along with other mechanical properties in the study of fine tailings is crucial for various aspects of research and development. It aids in tailings management and reclamation strategies. In this study, the tailings were received from the mine in a wet state. In order to examine their characteristics and properties, the tailings had to be dried and crushed back to their original size, having a solid density of 2700 kg/m^3. Following ASTM-D6913-04 (2009), PSD (Figure 1) was obtained for the tailings using sieve analysis; since > 25% of tailings passed the 75 µm sieve, hydrometer analysis following ASTM-D7928 (2017) had to be done. The studied tailings are classified as well graded with D60, D50, D30, and D10 of 0.15, 0.13, 0.09, and 0.017 mm, respectively (Table 1).

X-ray diffraction (XRD)

The mineralogical composition of the tailings was obtained from Mahmood and Elektorowicz (2018) and consisted of: sandstone (quartzite), mica schist, amphibolite, Gabroïque granite, Gabroïque feldsphate, specular hematite, specular magnetite, quartz, diopside, tremolite, actinolite and gruenerite.

Porosity

Similar to Zueter et al. (2020), in order to find the porosity of the tailings, a 1 L vessel packed with dry tailings was first weighed. Then, water was added gradually to the vessel until the tailings became fully saturated, and the new weight of the vessel was again measured. The weight of the water was found by calculating the difference between the weights of fully saturated tailings and dry tailings. The porosity was then evaluated by dividing the volume of the water by the overall volume of the vessel. The porosity of the studied tailings was estimated to be 0.45 from an average of 5 repetitions.

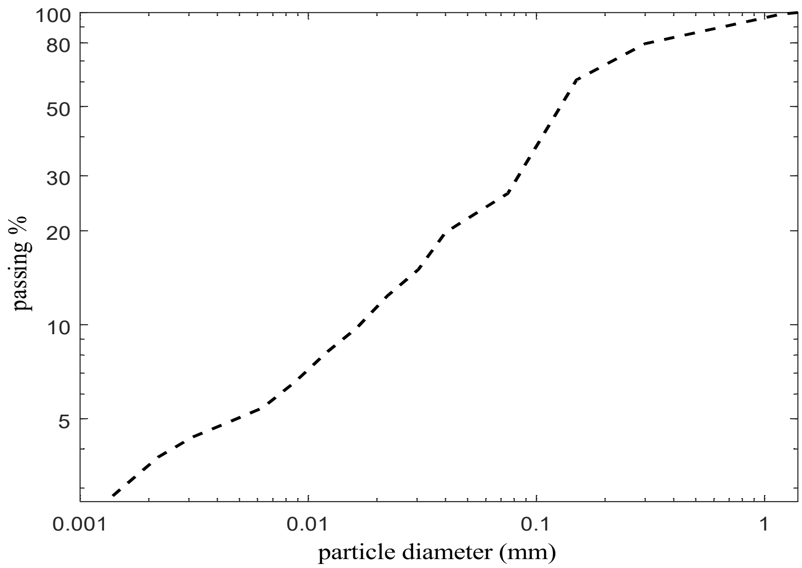

Figure 1. Particle size distribution (PSD) gradation curve.

Table 1. Particle size distribution (PSD) properties

Tailings properties	
D10 (mm)	0.017
D30 (mm)	0.09
D50 (mm)	0.13
D60 (mm)	0.15
Cz	3.17
Cu	8.82
Density (kg/m^3)	2700
USCS	well graded sands

Thermophysical properties

Considering conduction as the main heat transfer mechanism, thermal conductivity () and specific heat capacity are recognized as important factors in assessing the heat transfer characteristics of paste tailings. Thermal conductivity of composite materials (ie, effective thermal conductive) can be estimated through methods and models that is used to estimate the overall thermal conductivity of materials. The KD2 Pro device from Decagon Devices Company, which applies unsteady-state measurement technique, is used to estimate k. KD2 Pro uses is line source theory for calculating thermal properties of a material (Equation 1) (Carslaw et al., 1948).

$$k=\frac{Q}{4\pi}\left(\frac{dT}{dln(t)}\right)^{-1} \quad \text{Equation 1}$$

where (k) is estimated by analyzing the change of temperature versus logarithm of time (t), in which (T) is the temperature recorded from at the heat source, and Q is the heat power per unit length of probe.

The DSC 2500, a high-precision Differential Scanning Calorimeter (DSC), is a valuable tool for estimating the specific heat capacity of materials. This instrument analyzes sample thermal behavior by measuring the heat flow into or out of it as it undergoes controlled temperature changes. By subjecting a material to known heating or cooling rates and observing the heat flow, the specific heat capacity can be determined accurately. In this study, three DSC tests were conducted, including tests on dried tailings and paste tailings with water contents of 20 and 30%. Both thermal conductivity and specific heat capacity presented in this study represent the thermal behavior at room temperature of 20°C.

Dry tailings

Table 2 shows the thermophysical properties of the dry porous tailings, with thermal conductivity and specific heat capacity of 0.127 W/(m.K) and 780 J/(kg.K), respectively. The exceptionally high porosity of dried tailings highlights a substantial volume of void spaces within the material. This porous structure greatly influences material thermal behavior. The low thermal conductivity exhibited by dried tailings is intricately tied to the presence of air within these void spaces. Given that air has a low thermal conductivity, it hinders the efficient transfer of thermal energy within the material. Consequently, dried tailings characterized by both high porosity and the low thermal conductivity of air demonstrate a reduced ability to conduct heat.

Table 2. Thermophysical properties of dry tailings.

Dry tailings	
Specific heat capacity [J/(kg.K)]	780
Thermal conductivity (porous) [W/(m.K)]	0.127
Thermal conductivity (solid) [W/(m.K)]	4.15

Table 3 shows the thermophysical properties of PT with 20% and 30% water content. At 20% water content, paste tailings had a thermal conductivity of 2.09 W/(m.K) and a specific heat capacity of 1660 J/(kg.K). As the water content increased to 30%, thermal conductivity decreased slightly to 1.91 W/(m.K), while the specific heat capacity increases to 1870 J/(kg.K).

Interestingly, at 30% water content the thermal conductivity was slightly lower than that of 20% water content, while the specific heat capacity was higher. When porous tailings approach full saturation, it means that the air pores are filled with water to their maximum capacity. Beyond this point, adding more water may not contribute to enhancing the heat transfer process, and can even lead to a decrease in thermal conductivity if the solid particles have a higher thermal conductivity than water. Therefore, observing a slightly lower thermal conductivity for 30% water content compared to 20% water content could be attributed to going beyond full saturation. On the other hand, specific heat capacity tends to increase with higher water content due to the higher specific heat capacity of water compared to the solid components. Water has a higher specific heat capacity than most solid materials, and as the water content increases, it contributes more significantly to the overall heat storage capacity of the mixture.

Table 2. Thermophysical properties for PT with 20 and 30% water content.

Paste tailings		
Thermophysical Property Water content %	Specific heat capacity [J/(kg.K)]	Thermal conductivity [W/(m.K)]
20%	1660	2.09
30%	1870	1.91

UCS

A schematic approach followed to investigate some mechanical properties under different thermal conditions. A total of 12 samples were prepared and tested, comprising 6 samples with a water content of 20% and 6 samples with a water content of 30%. The paste was prepared using an automatic mixer, employing a controlled addition of water over the first minute of a 5 min mixing period, producing a mix enough for 3 samples. The paste was compacted through 20 rod insertions to remove any potential air gaps, at each 1/3 of mold capacity. The molds used for samples preparation were 5 cm (diameter) by 10 cm (height) cylindrical molds that complied with ASTM and ISRM. Finally, the samples were placed at a freezer with temperature of -20°C.

To examine the strength characteristics, a digital master loader machine (HM-3000) was used to perform UCS testing and thereby obtain stress for the paste samples. The strength characteristics were examined at two different sub-zero temperatures, -5°C and -15°C, to investigate the thermal effect on paste strength. To ensure precise ambient temperature control during UCS testing, a cooling system was utilized. Figure 2 shows the UCS experimental setup, with the cooling system fixed on the digital master loader machine.

Analysis and discussion

Effect of ambient temperature

The average UCS values demonstrated a substantial increase at -15°C, measuring 0.515 MPa, in contrast to the value at -5°C, which recorded 0.34 MPa. This represents a large difference of 41%. Further emphasizing the temperature effect, the extremes of UCS values exhibited a higher range at -15°C, with the highest recorded at 0.62 MPa (Figure 3b; 30% water content 2) and the lowest at 0.33 MPa [Figure 3 b (20% water content 1)]. In comparison, the extremes at -5 °C ranged from 0.39 MPa [Figure 3a; 30% water content 3) to 0.26 MPa (Figure 3a; 20% water content 1). The percentage differences for the highest and lowest extremes were notably elevated at 45.5% and 24%, respectively.

Since water is the only binder, at lower temperatures, more significant portion of water freezes into ice crystals, potentially contributing to a stronger, more interlocked structure. However, extremely low temperatures are generally associated with making materials more brittle. For instance, the post-peak sudden drop (Figure 3b; 30% water content 2) was mostly attributed to the extremely low temperature, coupled with the effect of higher water content.

Effect of water content

Figure 3 (c) shows the UCS for all 12 specimens, based on their water content. UCS of 30% water content shows a maximum stress of 0.62 MPa and a minimum stress of 0.36 MPa. While samples with 20% water content shows a maximum stress of 0.55 MPa and a minimum stress of 0.26 MPs. On average, samples with 30 and 20% water contents have compressive strength of 0.47 MPa and 0.38 MPa, respectively, suggesting that paste with 30% water content results in 19% higher compressive strength, compared to paste with 20% water content (Figure 3c). Despite that, some control samples with 20% water content have a compressive strength exceeds the compressive strength of samples with 30% water content. In addition, UCS of samples with 30% water content rose faster than samples with 20% water content, reaching a higher peak of 0.62 MPa (Figure 3b; 30% water content 2). The higher strength characteristics suggests that samples with higher water content have enhanced cohesion, as water bridges between particles resulting in a well-packed mix by reducing void spaces.

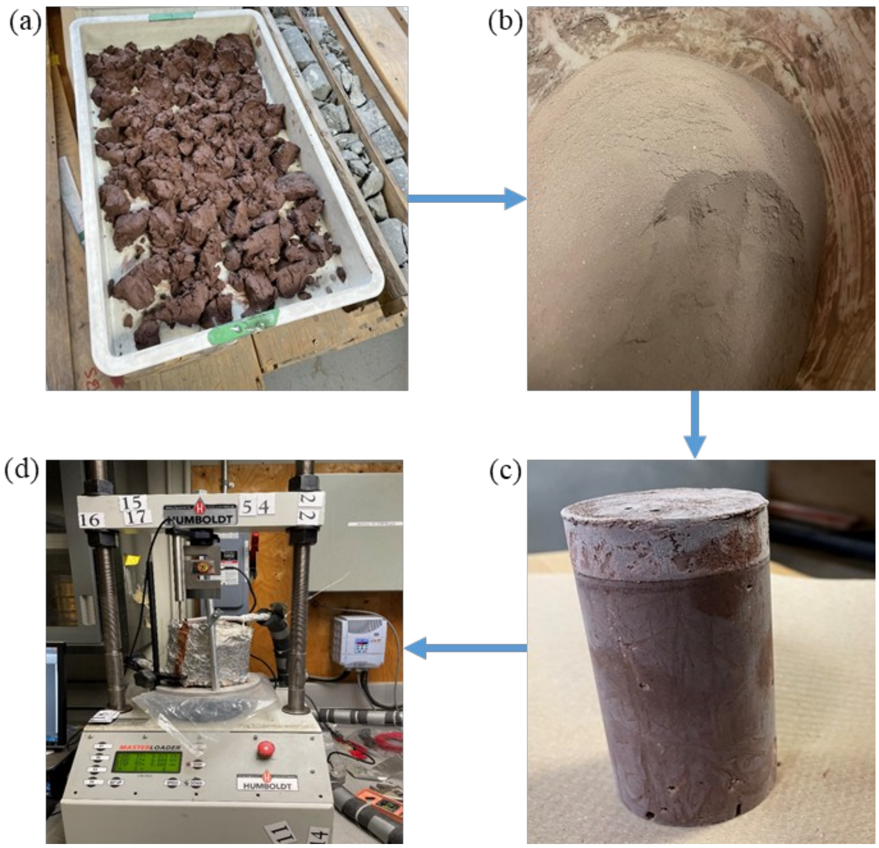

Figure 2. Schematic approach to prepare and investigate the mechanical properties of the studied tailings, (a) drying the tailings slurry, (b) crush tailings to original size, (c) prepare samples for testing, and (d) Unconfined compression strength (UCS) experimental setup.

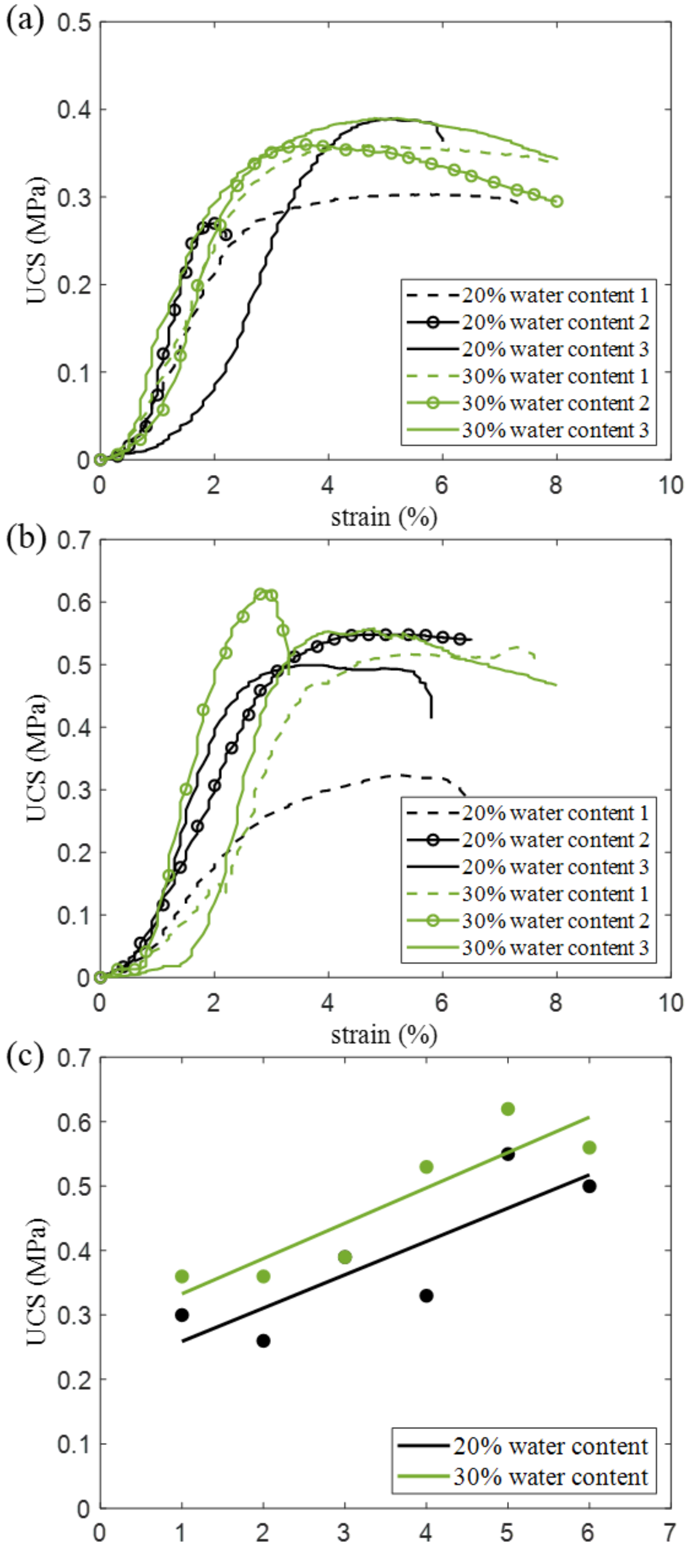

Figure 3. Stress-strain curves of paste tailings: a) at -5°C, and b) at -15°C, where c) shows the effect of water content on UCS.

As the goal is to store frozen tailings in a cold region and considering the properties investigated in this study, PT seems be an optimal option compared to dry stacking or using slurry with high water content. The transition from dried tailings to PT with water content results in a notable increase in thermal conductivity and specific heat capacity, enhancing the tailings heat transfer properties. The specific heat capacity values suggest that PT, especially at 30% water content, have a higher capacity to absorb and store heat, which can be advantageous in scenarios where thermal buffering is essential (ie, keeping the tailings frozen).

Conclusions

To investigate the influence of ambient temperature amd water content on the mechanical properties of paste tailings, four different categories of frozen paste tailings recipes were prepared and set to UCS test. The key conclusions in the investigations are:

1. Frozen PT have similar strength characteristcs with CPT, which can be important for tailings disposal in cold regions.
2. Among the two sudied variables, ambient temperature has the most inluence on the strength characteristics. In addition, it confirms that decreasing temperatures (ie, sub-zero temperatures) can result in a higher strength and potenially more ductile mix.
3. Using 30% water content resulted in enhanced mechanical characteristics when compared to 20% water content, espically when coupled with lower temperature.
4. In comparison with CPT, it is essential to study the effect of freeze-thaw cycles on the mechnical characteristics of the frozen PT backfill, since it can can enhance the strength characteristics as frost damage will be avoided due to cement absence.

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