Cyclic freeze–thaw to enhance the stability of coal tailings

Nicholas A. Beier*, David C. Sego

U of A Geotechnical Centre, Department of Civil and Environmental Engineering, 3-133 Markin/CNRL, Natural Resources Engineering Facility, University of Alberta, Edmonton, AB, Canada T6G 2W2

ABSTRACT

Laboratory freezing experiments were conducted to evaluate the feasibility of using cyclic freeze–thaw to enhance the surface stability of coal mine fine tailings. Undrained shear strength increased from non-measurable to 10 kPa after five cycles of freeze–thaw in tailings samples with initial moisture contents of 84% and 102%. Cyclic freeze–thaw also significantly dewatered the tailings samples. Decanting the melt water after each thaw reduced the water content of each sample by approximately 50%. A large scale one dimensional freezing test was also conducted to determine the advance of frost within the fine tailings and to understand how moisture migrates as the tailings freeze. Water was attracted to the freezing front from tailings ahead of the advancing front, decreasing the moisture content within the still unfrozen tailings. As the freezing front passed, the tailings were dewatered further at temperatures below 0 °C. Unfrozen microscale water from within the frozen tailings was attracted to a three dimensional network of ice lenses surrounding the frozen soil pedds. The laboratory experiments suggest freeze–thaw may be a technically feasible method to increase the strength and surface stability of fine tailings.

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1. Introduction

At one stage during mineral extraction and waste deposition at the Coal Valley mine, owned and operated by Coal Valley Resources Inc., fine grained tailings were deposited into an 18.2 ha impervious impoundment. The mine site is located approximately 96 km south of Edson, Alberta. The fine tailings were pumped to the impoundment at 35% solids by weight and were allowed to settle. Segregation of the tailings stream resulted in deposition of coarse materials near the pipe discharge and transportation of the fine fraction to a pond area. Reclamation of the impoundment was initiated in 1989, after reaching its full capacity (Stahl and Sego, 1995).

To achieve a dry, stable landscape, initial reclamation practices required capping of the weak, fine tailings portion with up to 3–6 m of waste rock. This substantial volume of cap rock was required because the soft saturated fine tailings squeezed under the applied load of the cap rock (Latimer et al., 1988). The large volume of cap rock required for conventional reclamation operations directly affect the production costs and profits at the mine. An alternative approach to reduce the volume of capping material and thus the reclamation costs is to utilize freeze–thaw to stabilize the surface of the tailings area. To initiate freeze–thaw of the saturated fine tailings, adequate drainage of the free pond water is required. This allows the exposed, never before frozen tailings surface to freeze through the winter and thaw/desiccate during the summer. Based on extensive work on freeze–thaw dewatering of oil sands tailings conducted at the University of Alberta (Bales, 2006; Dawson and Sego, 1993; Dawson et al., 1999; Proskin, 1998; Sego et al., 1993) it is expected that cyclic freezing and thawing and wetting and drying will cause moisture reduction and a potential strength increase with time. Both physical and mechanical transformations of various high moisture content materials following freeze–thaw including volume reduction, increased solids content, increased hydraulic conductivity and shear strength and reduced compressibility have been discussed by several authors and will not be discussed further (Stancyzk et al., 1971; Chamberlain and Blouin, 1978; Chamberlain and Gow, 1979; Johnson et al., 1989; Martel, 1989, 1994; Mao, 1997). The increase in strength and solids content has the potential to provide a surface layer capable of retaining a thinner layer of capping material to support re-vegetation and reclamation efforts.

In an effort to reduce the volume of capping material required for reclamation, cyclic freeze–thaw was evaluated in the laboratory as a technique to enhance the stability of the fine tailings surface. This paper presents the measured undrained shear strength increases in fine coal tailings due to repeated freeze–thaw cycles. Two different initial moisture and solids contents of the fine tailings were used for the cyclic freeze–thaw experiments. No attempt was made to simulate summer drying between freezing cycles. A large scale one dimensional freezing test was also conducted to simulate the advance of frost within the fine tailings to assist in understanding how frost and moisture would move in the field. These tests were conducted at the University of Alberta Geotechnical Centre and provided insight into...
the strength gains as well as frost and moisture migration during cyclic freeze and thaw within fine coal tailings.

2. Materials and methods

2.1. Fine tailings

The freezing experiments were carried out on fine tailings collected from the pond area within the tailings pond at Coal Valley mine site. In situ fine tailings exist as a fluid to semi-fluid with little strength to a depth of 1 to 2 m. The material was excavated and stored in separate drums in the field and subsequently shipped to the University of Alberta. Upon arrival, the drums were placed in warm storage to ensure they would not freeze.

Each drum was sampled to determine their initial moisture and solids content. Table 1 summarizes the basic physical properties of the fine tailings used for both the cyclic freeze–thaw and one dimensional freezing tests. The initial moisture contents vary between 83% and 102%, solids contents vary between 50 and 55 weight % (wt.%) with a total carbon content of 23.2 wt.%. The liquid limit is 53.8% and the plastic limit is 31.5% with a liquidity index between 2.3 and 3.2. Fig. 1 shows the grain size distribution of the fine grained tailings as measured using a hydrometer. The tailings contain 45 wt.% clay size with about 53 wt.% in the silt size range, and 2 wt.% in the fine sand size range. Under the Unified Soil Classification system, the fine tailings are classified as MH-OH material.

<table>
<thead>
<tr>
<th>Test #</th>
<th>Initial moisture content (%)</th>
<th>Final moisture content (%)</th>
<th>Initial void ratio</th>
<th>Final void ratio</th>
<th>Initial solids content (wt.%)</th>
<th>Final solids content (wt.%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2A</td>
<td>83.2</td>
<td>43.4</td>
<td>1.75</td>
<td>0.91</td>
<td>54.6</td>
<td>69.7</td>
</tr>
<tr>
<td>2B</td>
<td>101.5</td>
<td>50.5</td>
<td>2.13</td>
<td>1.06</td>
<td>49.6</td>
<td>66.4</td>
</tr>
<tr>
<td>3A</td>
<td>83.2</td>
<td>44.3</td>
<td>1.75</td>
<td>0.93</td>
<td>54.6</td>
<td>69.3</td>
</tr>
<tr>
<td>4A</td>
<td>83.2</td>
<td>44.1</td>
<td>1.75</td>
<td>0.93</td>
<td>54.6</td>
<td>69.5</td>
</tr>
</tbody>
</table>

Note: Final moisture and solids contents were measured from the middle of the sample (70 mm).

2.2. Cyclic freeze–thaw tests

The focus of these experiments was to understand the impact of cyclic freeze–thaw on the strength and dewatering of never before frozen saturated fine coal tailings. Prior to preparing the freeze–thaw test, the freezing apparatus (Fig. 2) was cleaned and filter paper was placed on the bottom porous stone. The slime sample was cooled to +1.0 °C and then stirred to ensure a uniform moisture content throughout. The sample was then poured into the freeze cell to a sample thickness of 150 mm.

The freezing cell and sample were transferred to a cold room maintained at +1.0 °C and the base plate was attached to a constant temperature bath maintained at −10 °C. The top cap was placed so it contacted the sample. It was attached to a constant temperature bath maintained at −6.0 °C. The sample was allowed to freeze from the bottom up and top down for 24 h. After the sample was frozen, the top cap was removed and the cell was disconnected from the constant temperature bath.

The cell and sample were removed from the cold room and allowed to thaw at room temperature (+20 °C). To assist thawing, a water line from the sink was attached to the freeze cell base plate. Warm water (+30 °C) was circulated through the base plate to thaw the sample from the base to the top.

Upon complete thaw, the free water was removed and any height change was recorded. The test cell was then centered beneath a Genor Laboratory Vane apparatus. A vane was penetrated to a depth of 35 mm and rotated to measure the undrained shear strength of the tailings. Measurement of the shear strength was repeated at depths of 70 and 120 mm within one vertical profile. After the shear strength measurements, the freezing cell and thawed sample were returned to the cold room, the constant temperature baths were re-attached and the sample was allowed to re-freeze and the cycle repeated. Subsequent vane strength measurements were conducted in a vertical profile which had not previously been disturbed. The freeze–thaw and strength measurements were repeated a maximum of eight times on one sample since this was the maximum number of undisturbed profiles available. Only one vertical measurement profile was used per freezing cycle. After the final strength measurements were conducted, the moisture contents were determined from the top, middle and bottom of the sample. A total of four samples were tested under one dimensional freeze–thaw using 29 freeze–thaw cycles. Samples 2A, 3A,
and 4A were replicate samples all having the same initial moisture content (Table 1).

2.3. One dimensional freezing test

The focus of the one dimensional freezing test was to understand frost and moisture migration within fine tailings in the field. Fine tailings from one of the drums received from the mine were thoroughly mixed to ensure uniform moisture content. A one dimensional freezing cell (Fig. 3) was assembled in a cold room maintained at +4.0 °C. The fine tailings with an initial moisture content of 85.2% and solids content of 53.9 wt.% were poured into the freezing cell to a sample depth of 820 mm.

A set of thermistors were placed in the centre of the sample at a distance of 0, 100, 200, 350, 500, and 650 mm above the copper coil which makes up the base of the freezing cell (Fig. 3). The outside and top of the freezing cell were insulated to encourage one dimensional heat flow from the fine tailings to the cooling coils at the bottom of the sample.

The tailings sample was permitted to reach equilibrium temperature in the cold room for 48 h. Then, fluid maintained at −9 °C was circulated through the cooling coils. The sample was cooled from the bottom up to guard against any expansion which would take place.

Fig. 2. Cyclic freezing cell apparatus.

Fig. 3. Vertical section through the one dimensional large scale freezing cell. All units in mm. Not to scale.
upon phase change of the water contained in the tailings. Temperatures were recorded at regular intervals during the 90 day test. The test conditions and duration were selected to simulate average surface temperatures and surface freezing index conditions at the mine site. After the test was terminated, samples were obtained by recovering the vertical core of both the unfrozen and the frozen portions of the sample. This allowed a moisture content profile to be determined through the sample. A photographic record of the frozen core was also obtained prior to the moisture content determination.

3. Results

3.1. Cyclic freeze–thaw tests

A summary of the measured final moisture content, solid content, and void ratios from the cyclic freeze–thaw experiments are included in Table 1. After eight cycles of freeze–thaw, the final water content and void ratio in all samples were reduced to approximately half their initial values indicating a significant volume of water was released during the freeze–thaw cycles. Table 2 summarizes the thaw strain measured upon thaw after a given number of freezing cycles. Thaw strain was calculated as the change in height after thaw (ΔH) divided by the frozen sample height (Ho). Sample 2B experienced the largest thaw strain upon thaw. No thaw strain was measured after the fourth cycle. However, undrained shear strength continued to increase as depicted in Fig. 4, which illustrates the undrained shear strength as measured at the middle of each sample for the given freeze–thaw cycle. The average shear strength from samples 2A, 3A and 4A gradually increased with freeze–thaw from no recorded resistance to approximately 10 kPa after 5 cycles. Beyond 5 cycles of freeze–thaw, the average shear strength remained relatively constant at approximately 10 kPa.

3.2. One dimensional freezing test

A complete summary of the recorded temperatures throughout the one dimensional freezing experiment is shown in Fig. 5. Some temperatures overlap those measured on previous times, thus suggesting the 0 °C isotherm did not advance in a continuous manner during this period. Fig. 6 shows the advance of the 0 °C isotherm as recorded from the thermistors embedded within the sample. The 0 °C isotherm advanced rapidly for the first 14 days and then continued more slowly. It remained stationary for extended periods after the initial 14 days of rapid advance.

The final moisture content profile of the tailings sample is compared to the initial profile in Fig. 7. The final moisture content profile is higher than the initial throughout the frozen zone as well as about 60 mm above the advancing 0 °C isotherm. The moisture content within the unfrozen tailings then drops to below the initial moisture content. Photographs of the frozen core from 40 to 350 mm above the base of the freezing cell (below the frozen front) illustrate a 3 dimensional network of ice lenses surrounding the soil peds (Fig. 8). A frozen core sample collected from the frozen front at 450 mm above the freezing cell base (no photograph available) contained ice lenses that were much thicker than core recovered from below the freezing front.

4. Discussion

4.1. Cyclic freeze–thaw tests

Final moisture and solids contents, measured thaw strains and strength gains for Samples 2A, 3A, and 4A were similar as expected.

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Table 2
Thaw strain data for fine tailings cyclic freeze–thaw tests

<table>
<thead>
<tr>
<th>Samplea</th>
<th>Ho (mm)</th>
<th>ΔH (mm)</th>
<th>% Thaw strain (ΔH/Ho)</th>
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</thead>
<tbody>
<tr>
<td>2AF1</td>
<td>150</td>
<td>18.9</td>
<td>12.5</td>
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<tr>
<td>2AF2</td>
<td>131</td>
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<td>127</td>
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<td>4.9</td>
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<tr>
<td>2AF4</td>
<td>121</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
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<td>150</td>
<td>19.2</td>
<td>12.8</td>
</tr>
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<td>3AF2</td>
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<td>4.6</td>
<td>3.5</td>
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<td>3.4</td>
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<td>3AF4</td>
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<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
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<tr>
<td>2BF4</td>
<td>109</td>
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</table>

a 2AF1 represents sample 2A after one freeze–thaw cycle.

b Ho is the frozen height of the sample prior to thaw for a given cycle.

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Fig. 4. Measured shear strength versus cycles of freeze–thaw.
Fig. 5. Temperature profiles within the one dimensional freezing cell.

Fig. 6. Advance of the 0 °C isotherm with time.

Fig. 7. Comparison of moisture content profiles before and after freezing.
because they had the same initial moisture and solids content. All cyclic freeze–thaw samples had final moisture contents approximately half the initial values. Smaller freezing temperature gradients in the field (top down freezing) as compared to the laboratory experiments (150 mm sample with doubled sided freezing), are expected to lead to greater moisture content reduction (Dawson, 1994). Due to the higher moisture content, sample 2B experienced the largest thaw strain after one cycle of freeze–thaw. The measured thaw strains for samples 2A and 2B after the first freezing cycle are compared with published thaw strain values for McKenzie Valley soils, Devon Silt and oil sands tailings materials (sump and mature fine tailings) in Fig. 9 (Andersland and Ladanyi, 2004; Bales, 2006). Thaw strains developed from one cycle of freeze–thaw of fine coal tailings are below the range of McKenzie Valley soils. Similar to Dawson’s (1994) freeze–thaw experiments and modeling with mature fine tailings, volume reductions were most pronounced in the first two freeze–thaw cycles. After two freeze–thaw cycles, volume change is reduced and increases in undrained shear strength are more significant. In fact, the peak undrained shear strength (approximately 10 kPa) achieved in the fine coal tailings (void ratio of 0.91–0.93) following freeze–thaw treatment was similar to the peak shear strength achieved after freeze–thaw of mature fine tailings (11.4–14.6 kPa, at void ratio of 0.92–0.96; Proskin, 1998). The strength gain and solids enhancement measured after 5 cycles of freeze–thaw suggest the tailings surface layer in the impoundment could retain a thinner layer of capping material and allow reclamation activities to proceed simply by exposing the tailings to the atmosphere.

Free melt water was removed from the surface of the samples after each thaw cycle. Removal of the water contributed to the increase in solids content of the samples and will be discussed further in the following section. This illustrates the importance of providing adequate surface drainage for the tailings in a field setting. The tailings surface must be kept free of water (melt water and precipitation) to allow it to dry during the summer and to freeze during the winter months. This will maximize the depth of moisture reduction and thus strength increases, as both drying and freezing will have an influence to a maximum depth.

4.2. One dimensional freezing test

To understand the advancement of the 0 °C isotherm we must first look at the final moisture contents (Fig. 7). The final moisture content profile suggests moisture was attracted to the advancing 0 °C isotherm from the unfrozen tailings as the 0 °C isotherm advanced into the unfrozen material. As water arrived at the 0 °C isotherm, it changed phase, releasing heat. This heat maintained an energy balance which allowed the 0 °C isotherm to remain stationary for an extended period of time as observed in Figs. 5 and 6. The process just described is termed “open system” freezing and a mechanistic theory is described in Konrad and Morgernstern (1980).

This explanation is further supported based on observations of frozen core samples. Observations indicate there was substantial ice lense formation near the maximum advance of the 0 °C isotherm. The water which produced the ice lenses at this depth came from the unfrozen tailings above the slowly advancing 0 °C isotherm (Konrad and Morgernstern, 1980). Conversely, “closed system” freezing occurs below the 0 °C isotherm, within the already frozen tailings. In a core sample 300 mm below the maximum 0 °C isotherm advance (Fig. 8), a

![Fig. 8. Photographs of the frozen core.](image)

![Fig. 9. Thaw strain versus water content for fine coal tailings, oil sands tailings, and McKenzie Valley soils (modified after Bales, 2006; Andersland and Ladanyi, 2004).](image)
unique ice and soil ped structure is illustrated. In this “closed” freezing system, the ice lenses surrounding the soil pedds are formed by attracting moisture, at the micro scale, from within the partially unfrozen soil pedds as the freezing front advances through the tailings. Continued localized moisture migration results in the consolidation of the mineral component of the tailings (Nixon and Morgenstern, 1973; Stahl and Sego, 1995).

Between 200 and 400 mm from the base of the freezing cell, the moisture content only increased from 84% to about 94%, suggesting that the majority of the ice observed was derived from the in situ moisture. However, near the slowly advancing 0 °C isotherm the much higher moisture content is consistent with the moisture content profile of frozen mature fine tailings (Bales, 2006).

Two dewatering processes are underway as the freezing front advances within the tailings. Ahead of the advancing freezing front, water is attracted to the front causing a decrease in moisture content within the still unfrozen tailings. Then, as the 0 °C isotherm passes, the tailings are dewatered at temperatures below 0 °C. Water from within the tailings is attracted to the three dimensional network of ice lenses which surround the soil pedd. The water originally contained in the uniform tailings is now partitioned into water locked in ice lenses and/or which remains within the frozen soil pedds as included ice. The dewatering process which allows the unfrozen shear strength to increase actually only occurs as the tailings thaw. Upon thawing, the ice lenses become water while the heavier soil pedd settle and allow the free water to remain on the surface. The soil pedds will not re-absorb the original water unless mixed. This allows for dewatering to occur provided the free water can be drained from the surface of the tailings. The freezing also causes the soil pedd to have an internal attraction which provides each pedd with some strength as well as a new structural arrangement of the individual particles (Proskin, 1998). This allows the melt water to rise to the surface since channels within the thawed tailings remain open where once and ice lense existed. The internal strength of each pedd contributes to the measured shear strength of the thawed tailings (Dawson, 1994).

4.3. Cyclic freeze–thaw as a reclamation strategy

Since an abundance of Canada’s mineral resources are situated in cold regions, a viable tailings management and reclamation strategy for existing fine grained tailings deposits could take advantage of the cold climate. The experimental results have shown cyclic freeze–thaw of fine grained tailings lead to an increase in strength and a significant reduction in moisture content. Therefore, freeze–thaw may enable the development of a dry landscape reclamation option. Relying on natural climatic conditions for in situ strength and solids content enhancement will negate the need for re-handling of the impounded fine tailings and/or addition of chemical amendments, thereby reducing reclamation costs. To initiate freezing, adequate drainage should be incorporated into the impoundment to remove precipitation and melt water and expose the tailings to climatic conditions. As most western Canadian coal mines do not have sulphidic ore bodies, removal of the pond water and exposure to the atmosphere (oxygen) should not lead to the development of acid generating conditions. Where there is a potential for acid drainage, this tailings management strategy may not be feasible and should be investigated on a case by case basis. Once exposed to the atmosphere, annual freezing will induce moisture migration and lead to dewatering through open and closed system freezing. Thawing of the frozen tailings in the spring and summer months will lead to increased shear strength and solids content, provided melt water is removed. Freezing and thawing could be continued for several years until the fine tailings develop sufficient strength to support reclamation activities. At the Coal Valley fine tailings deposit, it is expected 5 cycles of freeze–thaw would be sufficient to support reclamation activities.

5. Conclusions

Cyclic freeze–thaw tests showed that the undrained shear strength of fine grained coal tailings can be increased by exposing the tailings to the atmosphere. Tailings with initial moisture contents of 84% and 102% and measurable strength developed shear strengths of 10 kPa after five cycles of freeze–thaw. Therefore, reduction of waste rock required for reclamation of ponded fine tailings may be achieved simply by exposing the tailings surface to the cold natural environment. This will allow the tailings to freeze during the winter and thaw/desiccate during the summer. After five seasons of only freeze–thaw, the tailings surface should be enhanced sufficiently to support a thinner layer of reclamation materials.

Significant moisture migration, both to the advancing 0 °C isotherm and within the freezing and frozen fine coal tailings below 0 °C, was demonstrated by the one dimensional freezing test. Using tabulated values of thermal properties for water, the advance of the 0 °C isotherm within the tailings is over-predicted. This suggests that a better understanding of the thermal properties of fine tailings from coal mine operations are required to give a representative prediction of the freezing front advance.

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References


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