Freezing/Thawing Weathering Resistance of Solidified Mine Tailings Matrices

Ali A Mahmood¹ and Maria Elektorowicz²

¹Associate, Ash System International, 930 Av. Van Dyck, Brossard, Quebec, J4W 2E6, Canada
²Professor, Dept. of Building Civil and Environmental Engineering, Concordia University, Rm: EV-6.213, 1455 De Maisonneuve Blvd. W., Montreal, Quebec, H3G 1M8, Canada

Email: alimahmood45@yahoo.ca, mariae@encs.concordia.ca

Abstract. Mine tailings have been the source of water resources contamination over the years. This paper presents a novel approach for the solidification and stabilization of these mine tailings using Calsifrit binder and compares it to conventional Portland cement, slag, and fly ash. The resulting tailings matrices represent new materials with the potential of using them in construction processes in cold climates. Experimental results showed that the tailings binder matrices of concern passed the freezing/thawing durability tests. Furthermore, developed computer code Tailings-DEM™ was able to model successfully matrices’ freezing/thawing characteristics.

1. Introduction

In cold climates repeated cycles of freezing and thawing can cause physical deterioration of the solidified waste matrices thus exposing them to contact with water and leaching mediums. This can cause serious environmental consequences, e.g. underground water resources and living environment contamination. Mine tailings have been the origin of several environmental calamities [1][2]. Therefore to prevent such disasters from taking place, solidification of mine tailings is investigated using several binders and additives, to reduce as much as possible their detrimental environmental impact. In this study, a novel binder called Calsifrit™ was applied in comparison to traditionally used Portland cement, fly ash, and slag to solidify 2 different types of mine tailings from Eastern Canada, namely, Mont Wright and Musselwhite. The objective of this study is to assess the response of the binders-tailings matrices to freezing and thawing effects in order to evaluate their potential use as construction materials in cold climates. This will include an evaluation of the potential benefits of using Calsifrit compared to Portland cement and traditional additives. These experimental results will be further used to evaluate the applicability of the developed computer program Tailings-DEM™ in numerically modeling these freezing/thawing experimental results. The objective of this study is to quantify the response of the new tailings matrices to freezing and thawing cycles.
2. Methodology

Another incentive for this research is the fact that in 2011, the Quebec provincial government has instated an economic stimulus plan (Plan Nord) to invest C$80 billion in the northern region of the Province. This plan will be carried out for a period of about 25 years and is projected to create 20,000 jobs [3]. A big part of this economic stimulus will be directed towards the mining industry in that region, which, so far, has been active for many years.

Traditionally mine tailings have been treated as a waste material that requires landfilling inside specially created tailings dams. This approach has been practiced for many decades until these tailings dams started breaking up and causing substantial environmental damages, coupled in several instances with human fatalities [1][2].

In recent years there has been a new trend towards “managing” these tailings rather than treating them as a waste that requires dumping. Several investigators have attempted to re-use mine tailings in an environmentally sustainable manner. Examples include the works of Garand et al.[4], (Benzaazoua et al. [5], Theriault et al. [6], Roy at al. [7], Helinski et al. [8], Zhang [9], Ugama et al. [10] and Sabat et al. [11].

In order to assess the applicability of using mine tailings as construction materials, an experimental and computational program was designed to find their index properties and to assess their engineering properties with respect to the proposed function.

Investigations are composed of two phases: experimental and computational. The Experimental Phase 1 is divided into 3 stages: characterization of materials, formulation of tailing matrices and assessment of the matrices’ usefulness as road construction materials. Phase 2 consists of 3 stages: development of an adequate computer program predicting matrices usefulness as road materials, verification of the program for strength and weathering tests.

This study focuses on the freezing/thawing environmental tests. Details of other tests and the computational phase can be found elsewhere [12].

2.1 The tailings

Bench scale and pilot tests performed by Alcan International Ltd. on copper and gold tailings had shown the applicability of the thickening technology to a variety of tailings [13], in addition to the alumina tailings that were investigated by the latter authors. Therefore in this study, two different mine tailings were selected for evaluation; Musselwhite tailings from Placer Dome (gold) mine;, in Musselwhite, Ontario, and Mont Wright tailings from Quebec Cartier mineral company, from Mont-Wright (iron) mine, in Quebec.

These two types of tailings were chosen due to their availability in the northern territories of Eastern Canada; close to the area where Plan Nord will be employed. The adverse environmental impact that tailings cause to underground water resources and the environment warrant a detailed investigation into the potential of reusing them sustainably in a construction application. Table 1 shows their physical properties. Where: D_{10} = diameter corresponding to 10% finer, D_{30} = diameter corresponding to 50% finer, D_{60} = diameter corresponding to 60% finer, D_{30} = diameter corresponding to 30% finer, C_U = uniformity coefficient = D_{60}/D_{10}, C_G = coefficient of gradation = D_{60}^2/(D_{10}D_{60}), P_{4.75mm} (%) = percentage passing sieve no.4, P_{0.075mm} (%) = percentage passing ASTM sieve # 200, SW-SM = well graded sand with silt, SM = silty sand, SP = poorly graded sand, USCS [14] = unified soil classification system.

The mineralogical composition of Mont Wright tailings is: Sandstone (quartzite), Mica schist, Amphibolite, Gabroïque Granite, Gabroïque Feldspate, Specular Hematite, Specular Magnetite, Quartz, Diopside, Tremolite, Actinolite and Gruenerite. While Musselwhite is composed of Quartz (SiO_2), Birnessite-syn (MnO_2), Calcium manganese oxide hydrate (Ca_2Mn_4O_27.3H_2O) and Dannemorite (Fe,Mg,Mn)_2Si_3O_7(OH)_2.
2.2 Binding materials

The binding materials for the mine tailings, which have been tested in this study, consist of Type I ordinary Portland cement (OPC), fly ash, slag and Calsifrit.

Unconfined compressive strength of fly ash lies in the range 1.38 to 6.895 MPa with permeability between $10^{-5}$ to $10^{-8}$ cm/s [15]. The fly ash was obtained from St. Laurence Cement Company in Longueil, Quebec.

Ground granulated blast furnace slag used in this study was obtained from Lafarge North America Cement Company in Montreal, Quebec under the trade name NewCem®. It is a light grey odorless powder produced in accordance with ASTM C 989 [16]. It is composed of (30-50) % Calcium Oxide, (0-20) % Magnesium Oxide with less than 1% Crystalline Silica. Its specific gravity is between 2-3, water pH 8-11. Its boiling point is above 1000 °C [17].

Calsifrit™ is a totally amorphous siliceous material, a matrix of calcium and sodium fluoroaluminosilicate. This homogeneous solid substance has a blackish grey color, possesses a high reactivity potential and shows cementitious properties when finely ground. This product was obtained from the manufacturer NovaFrit International. Table 4 shows its chemical composition. Calsifrit has a pH (1% solution in water) of 6.5-7.5, a melting point of 800 °C, a specific gravity of 1.3 with a moisture content of less than 10% [18].

2.3 Testing Procedure

A procedure for measuring the solidified waste resistance to freezing and thawing was employed to determine its resistance to these environmental conditions [19]. This test is intended for the evaluation of the freezing/thawing resistance of monolithic solidified wastes.

| Type of Tailings | Musselwhite | Mont Wright |
|------------------|-------------|-------------|
| $D_{10}$ (mm)    | 0.0045      | 0.147       |
| $D_{50}$ (mm)    | 0.016       | 0.255       |
| $D_{60}$ (mm)    | 0.023       | 0.3         |
| $D_{90}$ (mm)    | 0.012       | 0.2         |
| $C_u$            | 5           | 2.04        |
| $C_z$            | 1.39        | 0.91        |
| $P_{4.75mm}$ (%) | 100         | 100         |
| $P_{0.075mm}$ (%)| 74.9        | 2.05        |
| Initial moisture content (%) | 30.15 | 4.27 |
| USCS             | SM          | SP          |
As such, small cylindrical specimens were molded in metallic molds measuring 44 mm diameter by 74 mm height. After casting the solidified tailings matrices in these molds, they were left to thaw and solidify in the moisture chamber for a period of 43 days. These specimens were then subjected to 12 cycles of freezing at -20 degrees Celsius for 24 hours, followed by thawing in water at room temperature for 24 hours. The weight loss of each specimen was measured and compared with that of a control specimen. The change in weight was used to determine the state of the structural integrity of the specimen. Six identical specimens were used for each mixture; three test (denoted by T) and three control specimens (denoted by C).

After removing the specimens from the freezing cabinet and the moisture chamber, 240 milliliters of distilled chilled water at 4 ºC was added to them. To the control specimens was added 240 milliliters of distilled water at room temperature (22 ºC) before plastic wrap was placed on the beakers and all water covered specimens were stored at room temperature (22 ºC) for a period of approximately 23 hours.

Afterwards each specimen was transferred to another dry beaker prepared as before, taking into account that all loosely attached particulates were removed by spraying with distilled water from a wash bottle to the surface of the specimen. Water was left to drain into the original beaker [19]. Then the specimens’ weight loss was determined by measuring the amount of the solid residue in these beakers by evaporating water in the oven. A total of 12 cycles was performed in the prescribed manner. Figures 1, 2, 3, 4 show the experimental results of these tests.

3. Results and Discussion

![Figure 1](image_url)

**Figure 1.** Weight loss after freezing and thawing test for Musselwhite test matrices
Figure 2. Weight loss after freezing and thawing test for Musselwhite control matrices

Figure 3. Weight loss after freezing and thawing test for Mont Wright control matrices
ASTM stipulates that for a sample to fail the freezing and thawing test it has to lose 30% of its weight during or after the completion of this test [19]. Accordingly, it can be seen from Figures 1 to 4 that all matrices tested for both Mont Wright and Musselwhite tailings fared well in this test as the maximum cumulative weight loss did not exceed 0.8% during the 12 cycles of freezing and thawing.

Figures 1–4 show that test and control specimens had similar weight loss values and characteristics, which is clear proof of rigidity of the mixtures and samples. They also show that adding Calsifrit to the cement-only specimens had a positive effect on durability for the Mont Wright specimens (testing and control) with weight loss decreasing with the addition of 10% and 20% Calsifrit to the cement-only mixtures. The same mixtures had less effect on the Musselwhite specimens. On the other hand slag-OPC matrices fared the best with the least weight loss out of all tailings matrices tested. The 5% Fly ash -20% Calsifrit -75% OPC matrix had less weight loss than the same matrix with slag for Mont Wright tailings. These mixtures showed an opposite effect on Musselwhite matrix specimens.

The increase in durability of Mont Wright specimens with addition of Calsifrit could be attributed to the improvement in the bond between the hydrated cement matrix and the tailings particles. This is due to the conversion of calcium hydroxide, which tends to form on the surface of the aggregate particles, to calcium silicate hydrate [20]. Musselwhite tailings on the other hand had an amount of Zn and Pb that retarded hydration as previously discussed, preventing the creation of a stronger bond between the aggregate particles and the hydrated cement matrix. This could be the reason that Musselwhite tailings matrices, generally, showed more weight loss than Mont Wright matrices.

4. Numerical modeling of particulate media
Traditionally, continuum based numerical analysis methods have been used qualitatively and quantitatively to analyze particulate and granular media. The most notable example in soil mechanics is the Finite Element Method and its various hybrids.
Although the finite element method was used to study discontinuous problems, it has several disadvantages. For example this method is continuous in nature, which means that it cannot efficiently model the discontinuity property. Also, as the accuracy of the model is as good as the assumptions used, reproducing complex behavior with continuous methods requires complex constitutive models, containing sometimes dozens of parameters and internal variables in order to capture discontinuous behavior. This can improve results but on the other hand they are computationally intensive and time consuming [21].

Due to their particulate nature, soils can experience significant local deformations and bifurcations. Continuum based methods cannot compensate for such anomalies without incremental analysis involving nonlinear elasto-plasticity based constitutive relations. Even so this approach is lacking in adequately modeling the most rudimentary behavior of soils, including non-linear deformations and local yielding [22].

4.1 The Discrete Element Method program Tailings-DEMTM

In 1979 Cundall and Strack developed the Discrete Element Method [23]. This method models particulate media as a discrete collection of particles. This random collection of particles interacts through their contact forces. The method calculates the displaced positions and rotations of these particles at discrete time intervals. The DEM-simulation is started by first generating a model, which results in the random orientation of the particles with assigned initial velocities. Forces and moments acting on each particle are computed form the initial data and the relevant physical laws and contact models. Generally, the simulation consists of three steps: the initialization, the explicit time stepping and post processing.

In the DEM the microstructure of the system is modeled rather than using constitutive laws or complicated elements. Using DEM we can capture changes in microstructure, change in shape and deformations, dynamics and forces within the system in real time and in detail. Compared to conventional continuum methods, the DEM uses fundamental and fewer parameters when modeling discontinuous behavior [21].

Tailings-DEMTM is a Discrete Element Method computer program written for the evaluation of the strength and durability characteristics of these tailings binder matrices [12]. The program was written using the computer programming language C++ and the compiler Code Blocks. General assumptions employed when using Tailings-DEMTM are explained elsewhere [12].

Thermal stresses resulting from the change in temperatures of the freezing and thawing test [19], are calculated according to the following equation by Pytel and Singer [24]:

\[ \sigma = E \alpha \Delta t \quad (1) \]

Where:
- \( \sigma \) = thermal stress (MPa)
- \( E \) = modulus of elasticity (MPa)
- \( \alpha \) = coefficient of thermal expansion (m/m °C)

The United States Federal Highway Administration (FHWA) employs a value range of \((18-20) \times 10^{-6}/°C\) for the coefficient of thermal expansion of saturated cement pastes [25]. The average for this range, \(19 \times 10^{-6}/°C\), is used in calculating the thermal stresses in this study.

The modulus of elasticity (E) for each tailings matrix is assumed to be equal to the slope of the linear portion of the stress versus strain diagram of that matrix.

Equation (1) was used to compute the thermal stresses in the matrix resulting from the change in temperatures during its exposure to freezing/thawing cycles. Matrix weight loss was used as the indicator of matrix response to the freezing/thawing environment.

The thermal stress resulting from the change in the specimen temperature is found according to Equation (1) shown above. The coefficient of thermal expansion in this equation is a measure of the materials expansion or contraction with temperature. Due to the relatively small length changes associated with thermal expansion, it is usually expressed in terms of micro strains per unit temperature change. The United States Federal Highway Administration employs a value range of \((18-20) \times 10^{-6}/°C\) for the coefficient of
thermal expansion of saturated cement pastes [25]. The average of this range, 19 x 10^-6/°C, is used in this study for calculating the thermal stresses.

The modulus of elasticity (E) for each tailings matrix is assumed equal to the slope of the linear portion of the stress versus strain experimental diagram of that matrix. This value of E is used in Equation (1) to find the thermal stress.

Once the thermal stress is calculated according to Equation (1), it is multiplied by the cross sectional area of the cylindrical specimen to get the maximum thermal load. Dimensions of the cylindrical specimen used are: 44 mm diameter and 74 mm height. These values represent the actual dimensions used experimentally.

Subsequently, this load is used in finding the change in length (ΔL) associated with computational results, which represents the length response of the specimen to the vertical load applied to it during the UCS test. This change in length divided by the initial specimen length is assumed here to represent the weight loss from freezing and thawing thermal stresses expressed in units of MPa. The change in length (ΔL) is found by graphically reading off the displacement corresponding to the thermal load found using Equation (1) for the tailings matrix in question. The computational weight loss for the tailings matrix equals this displacement divided by the initial length of the specimen (74 mm).

Figures 5, 6, 7 show the computational percentage weight loss found using the procedure explained and its comparison with the experimental weight loss results for the freezing/thawing tests on the tailings matrices. The percent difference is found by subtracting the computational weight loss from the experimental and dividing the result by the experimental weight loss. Then, the factor of safety is found by dividing the experimental over the computational weight loss. Table 2 shows the specimen descriptions as used here.

As explained above, the matrix was previously exposed to the freezing/thawing cycles test following ASTM D 4842 [19]. Temperature range used in the computation was according to the laboratory test; i.e. from room temperature (22 °C) to the freezing temperature of-20 °C. Results show that all tailings matrices tested fared well in this test as the maximum value of the cumulative mass loss did not exceed 0.8% [12].
Figure 6. Weight loss comparison between the computational and experimental for Musselwhite matrices after freezing and thawing.

Figure 7. Compression strength for Musselwhite samples MWF’11-MWF’16 after freezing/thawing (Musselwhite tailings, Cylindrical Specimens, 75% OPC, 25% FA, Freezing/Thawing)
| Tailings Type | Weathering Type | Code | Specimen | Binder/ Tailings (%) | OPC/Binder (%) | Calsifrit/Binder (%) | Fly ash/Binder (%) | Slag/Binder (%) |
|---------------|-----------------|------|----------|----------------------|----------------|----------------------|-------------------|----------------|
| Mont Wright   | Wetting/Drying  | MC1  | 1, 2, 3, 5, 6 | 0.5 | 100 | 0 | 0 | 0 |
|               |                 | MC3  | 1, 2, 3, 4, 5, 6 | 0.5 | 90 | 0 | 0 | 0 |
|               |                 | MC6  | 1, 2, 3, 4, 5, 6 | 0.5 | 75 | 25 | 0 | 0 |
|               |                 | MCF1 | 1, 2, 3, 4, 5, 6 | 0.5 | 75 | 0 | 25 | 0 |
|               |                 | MCF3 | 1, 2, 3, 4, 5, 6 | 0.5 | 75 | 10 | 15 | 0 |
|               |                 | MCF5 | 1, 2, 3, 4, 5, 6 | 0.5 | 75 | 20 | 5 | 0 |
|               |                 | MCS1 | 1, 2, 3, 4, 5, 6 | 0.5 | 75 | 0 | 0 | 25 |
|               |                 | MCS3 | 1, 2, 3, 4, 5, 6 | 0.5 | 75 | 10 | 0 | 15 |
|               |                 | MCS5 | 1, 2, 3, 4, 5, 6 | 0.5 | 75 | 20 | 0 | 5 |
|               |                 | MW1  | 1, 2, 3, 4, 5, 6 | 0.375 | 100 | 0 | 0 | 0 |
|               |                 | MW3  | 1, 2, 3, 4, 5, 6 | 0.375 | 90 | 10 | 0 | 0 |
|               |                 | MW6  | 1, 2, 3, 4, 5, 6 | 0.375 | 75 | 25 | 0 | 0 |
|               |                 | MWF1 | 2, 3, 4, 5, 6, 6 | 0.375 | 75 | 0 | 25 | 0 |
|               |                 | MWF3 | 1, 2, 3, 4, 5, 6 | 0.375 | 75 | 10 | 15 | 0 |
|               |                 | MWF5 | 1, 2, 3, 4, 5, 6 | 0.375 | 75 | 20 | 5 | 0 |
|               |                 | MWS1 | 1, 2, 3, 4, 5, 6 | 0.375 | 75 | 0 | 0 | 25 |
|               |                 | MWS3 | 1, 2, 3, 4, 5, 6 | 0.375 | 75 | 10 | 0 | 15 |
|               |                 | MWS5 | 1, 2, 3, 4, 5, 6 | 0.375 | 75 | 20 | 0 | 5 |
| Musselwhite   | Freezing/Thawing| MC’1 | 1, 2, 3, 4, 5, 6 | 0.5 | 100 | 0 | 0 | 0 |
|               |                 | MC’3 | 1, 3, 4, 5, 6, 6 | 0.5 | 90 | 10 | 0 | 0 |
|               |                 | MC’6 | 1, 2, 3, 4, 5, 6 | 0.5 | 75 | 25 | 0 | 0 |
|               |                 | MCF’3 | 1, 2, 3, 4, 5, 6 | 0.5 | 75 | 10 | 15 | 0 |
|               |                 | MCF’5 | 1, 2, 3, 4, 5, 6 | 0.5 | 75 | 20 | 5 | 0 |
|               |                 | MCS’1 | 1, 2, 3, 4, 5, 6 | 0.5 | 75 | 0 | 0 | 25 |
|               |                 | MCS’3 | 1, 2, 3, 4, 5, 6 | 0.5 | 75 | 10 | 0 | 15 |
|               |                 | MCS’5 | 1, 2, 3, 4, 5, 6 | 0.5 | 75 | 20 | 0 | 5 |
|               |                 | MW’1 | 1, 2, 3, 4, 5, 6 | 0.375 | 100 | 0 | 0 | 0 |
|               |                 | MW’3 | 1, 2, 3, 4, 5, 6 | 0.375 | 90 | 10 | 0 | 0 |
|               |                 | MW’6 | 1, 2, 3, 4, 5, 6 | 0.375 | 75 | 25 | 0 | 0 |
|               |                 | MWF’1 | 2, 3, 4, 5, 6, 6 | 0.375 | 75 | 0 | 25 | 0 |
|               |                 | MWF’3 | 1, 2, 3, 4, 5, 6 | 0.375 | 75 | 10 | 15 | 0 |
|               |                 | MWF’5 | 1, 2, 3, 4, 5, 6 | 0.375 | 75 | 20 | 5 | 0 |
|               |                 | MWS’1 | 1, 2, 3, 4, 5, 6 | 0.375 | 75 | 0 | 0 | 25 |
|               |                 | MWS’3 | 1, 2, 3, 4, 5, 6 | 0.375 | 75 | 10 | 0 | 15 |
|               |                 | MWS’5 | 1, 2, 3, 4, 5, 6 | 0.375 | 75 | 20 | 0 | 5 |
5. Discussion of Tailings-DEM™ modeling of freezing/thawing

Based on the results shown in Figures 5, 6, 7 it is evident that differences in the freezing/thawing weathering results are within an average factor of safety of 2. The experimental values were higher than the computational for all Mont Wright and most Musselwhite matrices. The Musselwhite matrices with the following binder mixtures had higher computational weight loss values than experimental: 75% OPC and 25% slag (testing and control) and 75% OPC, 15% slag, 10% CF (control).

The reason behind this discrepancy could be attributed to the relatively high ratio of particles smaller than 75 micrometer that Musselwhite tailings contain as revealed in the physical properties shown in Table 1. Additionally, slag's average specific gravity of 2-3 may have resulted in more matrix voids filled by slag particles during the mixing stage rendering the matrix more resistant to freezing and thawing weathering effects. It is also shown that when the binder content contained 25% of slag, weight loss was lower for all Musselwhite and Mont Wright matrices, for both testing and control specimens. This is clearly evident in Figures 1, 2, 3, 4. Musselwhite tailings matrix with 25% slag had 1 mg/L Fe content according to the TCLP test [12]. Compared to this, no Fe content was detected with the equivalent Mont Wright tailings matrix. Al-Otaibi [26] who used steel mill (iron oxides) as fine aggregate in cement mortars, found that drying shrinkage was lower when using steel mill scale. He also showed that replacing 40% of sand with steel mill gave the highest increase in compressive strength and increased flexural strength. This may have contributed to Musselwhite matrices having less percent weight loss than their Mont Wright counterparts.

The US Federal Highway Administration cite research by Malhotra [27] who did freeze thaw tests on concrete incorporating 25-65% slag. Test results indicated that regardless of the water / (cement + slag) ratio, air entrained concrete slag specimens performed excellently in freeze thaw tests, with relative durability factors greater than 91% [25].

There is not much deviation between the experimental and computational results for the Musselwhite tailings matrix when the binder content is composed of 75% OPC and 25% fly ash as can be seen in Figures 5 and 6. This is explained by the fact that the weight loss was found computationally based on the experimental stiffness coefficient. It can be seen in Figure 5 that all 6 specimens of this matrix combination had very close strength and stiffness values, hence closing the gap between experimental and computational results.

Other reasons for the differences between computational and experimental results can be attributed to the triangular particle shape used in the Tailings-DEM™ program. Changing the assumed particle shape to a pentagon or a more circular shape may lead to the results being more closely related. Reducing their size and increasing their number may also enhance the results.

The above suggests that Tailings-DEM™ can be used with confidence to account for and predict freezing and thawing weathering effects, as described by the procedure in Mahmood [12]. However, it should be used with caution when the matrices contain a detectable Fe content coupled with slag binder content between 10% - 25%.

6. Conclusions

- It can be seen that Mont Wright and Musselwhite tailings matrices passed the freezing/thawing weathering tests with a maximum weight loss of 0.8%, which indicates that these matrices can be used as a construction material sustainably in cold regions,
- Adding Calsifrit to the cement-only specimens had a positive effect on durability for the Mont Wright testing and control specimens with weight loss decreasing with the addition of 10% and 20% Calsifrit to the cement-only mixtures. Although the same mixtures had less effect on the Musselwhite samples, it can be concluded that Calsifrit is a viable Portland cement replacement, within the limits shown above,
- Simulating the vulnerability of Mont Wright and Musselwhite tailings binder matrices to cold climate, through the freezing/thawing test, using the Discrete Element Method was successful,
Differences between experimental and computational freezing/thawing weathering results are within an average factor of safety of 2.

Acknowledgment
The authors would like to acknowledge with gratitude the support that Dr. Michelle Nokken and Dr. Catherine Mulligan of Concordia University (Montreal, Canada) have provided for this study.

References

[1] Fourie A B and Papageorgiou G 2001. Defining an appropriate steady state line for Merriespruit gold tailings Canadian Geotechnical Journal 38(4) 695-706.
[2] Fourie A B, Blight G E and Papageorgiou G 2001. Static liquefaction as a possible explanation for the Merriespruit tailings dam failure Canadian Geotechnical Journal 38(4) 707-719.
[3] Government of Quebec, Societe du Plan Nord 2011 https://plannord.gouv.qc.ca/en/.
[4] Garand P, Vezina S and Bocking K 2000 Effects of flocculent on deposition of tailings sludge for upstream raise of impoundment dykes In Proceedings of the 53rd Canadian Geotechnical Conference Canadian Geotechnical Society 15-18 October 2000 Montreal Quebec pp. 633-640.
[5] Benzaazoua M, Belem T and Bussiere B 2002 Chemical factors that influence the performance of mine sulphidic paste backfill Cement and Concrete Research 32(7) 1133-1144.
[6] Theriault J A, Frostitak J and Welch D 2003 Surface disposal of paste tailings at the Bulyanhulu gold mine, Tanzania In Proceedings of Sudbury 2003 Mining and the Environment 25-28 May 2003 Sudbury Ontario.
[7] Roy S, Adhikari G R and Gupta R N 2007 Use of gold mill tailings in making bricks: a feasibility study Waste Management and Research 25(5) 475–482.
[8] Helsinki M, Fahey M and Fourie A 2010 Coupled two-dimensional finite element modeling of mine backfilling with cemented tailings Canadian Geotechnical Journal 47(11) 1187-1200.
[9] Zhang L 2012 Recycling and utilization of mine tailings as construction material through Geopolymerization In Proceedings U.S. EPA Hardrock Mining Conference 2012: Advancing Solutions for a New Legacy April 3-5 2012 Denver Colorado.
[10] Ugama T I, Ejeh S P and Amartey D Y Effect of tailings on the properties of concrete 6 (10) 2014 IISTE.
[11] Sabat V, Shaikh M, Kanap M, Chaudhari M, Suryawanshi S and Knadgouda K Use of iron ore tailings as a construction material 3(2) Aug. 2015 International Journal of Conceptions on Mechanical and Civil Engineering.
[12] Mahmood Ali A 2012 Experimental and computational assessment of tailings binder matrices for construction purposes in cold regions Ph. D. thesis Concordia University Department of Building Civil and Environmental Engineering Montreal Quebec.
[13] Haile G, O’Callaghan W B, Hartney T F and Cameron W 2000. Experience with thickened red mud tailings (paste) stacking tropical and temperate climates and applicability of the technology to other tailings In Proceedings of the 53rd Canadian Geotechnical Conference Canadian Geotechnical Society 15-18 October 2000 Montreal Quebec.
[14] Das Braja M 2000 Fundamentals of geotechnical engineering. Brooks/Cole Publishing Company California.
[15] Conner J 1990. Chemical fixation and solidification of hazardous wastes Van Nostrand Reinhold New York.
[16] ASTM C 989 2006 Standard specification for ground granulated blast-furnace slag for use in concrete and mortars Annual Book of ASTM Standards American Society for Testing and Materials Philadelphia Pennsylvania Vol. 04.02.
[17] Lafarge North America 2007 12950 Worldgate Dr Ste. 500 Herndon Virginia 20170.
[18] NovaFrit International 2006 1200 Garnier Street Ville Ste-Catherine Quebec J0L 1E0.
[19] ASTM D 4842-90 1996 Standard test method for determining the resistance of solid wastes to freezing and thawing Annual Book of ASTM Standards, American Society for Testing and Materials, Philadelphia Pennsylvania. Vol. 11.04.
[20] Toutanji H, Delatte N, Aggoun S, Duval R and Danson A 2004 Effect of supplementary cementitious materials on the compressive strength and durability of short-term cured concrete Cement and Concrete Research 34(2) 311–319.
[21] Matar M I 2005 Modeling of Montmorillonite clay-water interactions with particle subdivisions using three dimensional Discrete Element Method Ph.D. thesis North Dakota State University Fargo North Dakota.
[22] Khwaja M 1996. Discrete Element Method: micro-mechanical and large scale modeling M.Sc. thesis University of Massachusetts Lowell Massachusetts.
[23] Cundall P A and Strack O D L 1979 A discrete numerical model for granular assemblies Geotechnique 29(1) 47-65.
[24] Pytel A and Singer F L 1987 Strength of materials Harper and Row Publishers Inc. New York.
[25] FHWA 2011 US Federal Highway Administration website info, http://www.fhwa.dot.gov 1200 New Jersey Ave SE Washington DC 20590.
[26] Al-Otaibi S 2008 Recycling steel mill scale as fine aggregate in cement mortars. European Journal of Scientific Research 24(3) 332-338.
[27] Malhotra V M 1983 Strength and durability characteristics of concrete incorporating a pelletized blast-furnace slag ACI special publication SP-79 The use of fly ash, silica fume, slag and other mineral by-products in concrete Editor V M Malhotra 892 - 921 and 923—31 American Concrete Institute Detroit Michigan.