Experimental and Computational Assessment of the Strength Properties of Mont Wright Tailings Matrices for Use as Road Materials

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Abstract. Mont Wright Mine tailings matrices were subjected to freezing/thawing and wetting/drying cyclic weathering tests before being tested in the unconfined compression chamber. These experimental results were subsequently compared to computational values found using the program Tailings-DEM™. Results showed that Tailings-DEM™ was capable of simulating, with reasonable accuracy, the UCS strength values of the tailings matrices tested.

1. Introduction

Mine tailings are the waste materials left after the extraction of the ore mineral. They are traditionally stored in tailing ponds adjacent to the mine opening [1]. This method of storage has created several environmental issues in the past and has prevented the use of a widely available resource.

In order to make use of mine tailings and reduce their bulky method of storage, Robinsky [2] proposed the thickened tailings disposal (TTD) system for the management of mine tailings. He showed that through the process of thickening the tailings to heavy slurry before disposal, it is possible to create a self-supporting deposit of tailings and to eliminate the traditionally used settling pond.

Robinsky [2] stated that since the conventional tailings pond has been eliminated, and without water to flow and wash out the tailings, a dam collapse becomes only a local problem and not an ecological disaster. Another advantage of the TTD system is that the system is capable of inhibiting the drainage of acid. The environmentally undesirable product is sulphuric acid. It is produced when air and water come into contact with sulphur-containing mine tailings. Once formed, it is capable of infiltrating the tailings and dissolving other undesirable metallic elements that eventually may seep through and contaminate the living environment [3].

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The thickened surface tailings disposal concept has been applied at various mining facilities for several decades, including the Kidd Creek Mine in the northern region of Ontario (Canada) and for managing the disposal of red muds produced by the alumina industry [3].

Success in the process of mine tailings hardening has led researchers to further think the possibility of using these hardened tailings in the construction industry. This would thereby utilize a vastly available untapped resource and hinder, albeit to a certain extent, the harmful effects of unprocessed tailings on the surrounding environment. This success coupled with historical evidence of using tailings in the mine backfilling industry further strengthened this new approach.

The earliest reported use of mine tailings as a construction material was its use as a mine backfilling material. Use of mine tailings for backfilling started in the early days of the potash industry by using dry and wet residues [4]. Different technologies were introduced in the last 80 years. One of these, the slurry backfill technology is considered an efficient backfill method, because of its combination of tailings and brine disposal. Since 1908, the slurry backfill technology has been successfully employed in the German potash industry, especially in the flat-lying deposits of the South Harz potash district [4].

Success with these early attempts led researchers to attempt a thorough investigation of mine backfilling using more advanced technologies and procedures. Garand et al. [5] discussed the effect of flocculent deposition of tailings sludge in the Bouchard-Hebert mine in northern Quebec. ASTM standard tests were performed on the tailings to determine their particle size, specific gravity and Atterberg limits. Then a flocculent (PERCOL E-10) was added to the tailings sludge before it was mechanically thickened in the paste backfill plant. These flocs had grain size distribution larger than or similar to coarse silt. It was stated that the beaches formed with these flocs could be used as competent foundation material for upstream raises [5]. This study presented a modification to Robinsky’s [2] thickening principle by adding a flocculent to the tailings to enhance thickening and increase stability.

Another study by Benzaazoua et al. [6] investigated in certain detail the influence of several chemical factors on the performance of mine sulphidic paste backfill. They used four samples from three different mines located in Canada, which were mixed with four types of binders and mixing water with six different chemical characteristics. This was done in an attempt to simulate field conditions. It was found that the paste backfill matrix texture was directly related to its strength development. Also it was found that the mixing water was an important parameter that affected the quality of the paste backfill mass and that, in contrast to the Portland cement based binder, slag-based binder hydration seemed to be inhibited by the presence of soluble sulphates [6]. The results of this study clearly demonstrated the inefficiency of choosing paste backfill mixtures without first testing the tailings and mixing water characteristics.

Theriault et al. [7] studied the surface disposal of paste tailings at the Bulyanhulu Gold mine in Tanzania. The goals of this process were, to conserve water, manage runoff, reduce risk and minimize containment dyke construction. The tailings slurry was dewatered before transportation to the paste plant where process water was added in the paste conditioner to produce a paste of desired consistency. The authors affirmed that the cycling of tailings deposition in thin layers has been successful in generating a stable paste stack. It was concluded that the paste stacks can be engineered to meet the required geotechnical and environmental objectives.

These earlier studies ascertained the applicability of using mine tailings as backfill materials and encouraged investigation of the use of mine tailings in other construction disciplines. One such discipline is exemplified by the work of Demers and Haile [8] who described the stabilization of zinc tailings (named Jarosite). Jarosite had been deposited in ponds sustained by clay dykes until 1998. Since then, Jarosite was thickened first using vacuum filters. Then lime, cement and water were added to the thickened Jarosite to make a product that was termed Jarofix. Laboratory tests and stack modeling were performed to determine the feasibility of using the cured Jarofix to build containment dykes and service roads. Field tests were performed, as well, after which the authors concluded that Jarofix was chemically inert. It was observed that cured Jarofix was an excellent fill material for raising containment dykes. This research was carried out inside the tailings storage facility and hence limited testing was done in this case.

Another example is the work of Zou and Sahito [9] who studied the applicability of using a new type of binder termed HiFa Bond for shotcreting underground support. The authors used mine tailings as
aggregates in shotcrete. The tailings were mixed with sand, polymer and steel fibers. Test results showed that mine tailings had potential for shotcreting for underground support.

Meanwhile, Celik et al. [10] investigated the effects of the mineralogical composition and chemical properties of gold tailings on the compressive strength of Ordinary Portland Cement (OPC). The authors used silica fume and 2 types of fly ash, with the tailings as OPC additives. It was shown that the compressive strength values of mortars prepared by these additives were acceptable as they were within the range accepted in European standards. The authors presented the conclusion that the gold tailings could be used as an additive in OPC production. No weathering resistance or leaching testing had been done in this study.

Another study by Roy et al. [11] investigated the use of gold tailings in the making of bricks. The authors mixed the tailings with 4 types of soils and Portland cement. The quality of bricks was measured in terms of compressive strength, linear shrinkage and water absorption tests. The authors performed cost analysis, as well. They showed that the quality of these bricks was improved when mill tailings were mixed with these soils. The study showed that soil-tailings bricks passed the required criteria defined in terms of compressive strength, linear shrinkage and water absorption. The cost of producing the tailings-soil bricks was shown to be less than that of traditional clay bricks. However, there were no leaching or weathering environmental tests performed.

Swami et al. [12] investigated the use of Kimberlite diamond mine tailings in the construction of road layers. For this purpose, the authors performed a field and laboratory testing program. Physical tests including Proctor, California Bearing Ratio (CBR) and unconfined compression were executed before and after stabilization with cement and bitumen. Chemical properties of the tailings were also determined before performing laboratory and field experiments. The field experiments consisted of constructing a test road section using these tailings, which were evaluated for use in sub-base, base and wearing courses. It was shown that Kimberlite tailings could be used in cement bound sub-base layers. The study did present a new approach in the area of road construction. However, the testing regime implemented was not comprehensive and there were no weathering or leaching tests conducted. These tests are considered pivotal in cold environments such as that of Canada. Also the experimental program lacked correlation with numerical analysis methods.

Other researchers such as Fall et al. [13], Fall et al. [14], Benzaazoua et al. [15], Ercikdi et al.[16], Fall and Pokharel [17], Ercikdi et al. [18] and Helinski et al. [19] investigated the use of mine tailings in the most traditional manner by using them as cemented paste backfill. While, the research group of Yang et al. [20] investigated the use of mine tailings in the glass-ceramic/ceramic tile industry.

It appears from the above that although several research studies discussed the applicability of using mine tailings in several types of construction applications, none had comprehensively addressed the issue of using mine tailings as construction materials for temporary roads in cold climates. Simulation of the strength properties of these mine tailings using a powerful numerical technique was lacking in these studies, as well. The objective of this study is the development of a new sustainable approach to road construction using mining waste in cold climate by formulation of tailings binder matrices and investigating the simulation of their unconfined compressive strength properties. This will be done after exposing them to freezing/thawing and wetting/drying cycles to simulate environmental conditions. Their strength properties will further be analyzed using the Discrete Element Method program: Tailings-DEM™. Conclusions will be drawn from the comparison of the numerical and mechanical strength properties.

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, [21]. 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 [22]. 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 [23].

Calsifrit™ is a totally amorphous siliceous material, a matrix of calcium and sodium fluoro-aluminosilicate. 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% [24].

3. The tailings

Bench scale and pilot tests carried out by Alcan International Ltd. on copper and gold tailings had shown the applicability of the thickening technology to a variety of tailings [25]. Also, Alumina tailings were investigated by the latter authors. Therefore in this study, another type of mine tailings was selected and obtained for evaluation; Mont Wright tailings from Quebec Cartier mineral company, from Mont-Wright (iron) mine, in Quebec. This type of tailings was chosen because of its proximity to 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 living environment warrant a detailed investigation into the potential of reusing them sustainably in construction. Table 1 shows the physical properties of Mont Wright tailings.

Table 1. Physical properties for Mont Wright tailings

| Type of Tailings | Mont Wright |
|-----------------|-------------|
| D_{10} (mm)     | 0.147       |
| D_{50} (mm)     | 0.255       |
| D_{60} (mm)     | 0.3         |
| D_{30} (mm)     | 0.2         |
| Cu              | 2.04        |
| Cz              | 0.91        |
| P_{4.75mm} (%)  | 100         |
| P_{0.075mm} (%) | 2.05        |
| Initial moisture content (%) | 4.27 |
| USCS            | SP          |
Where: $D_{10} =$ diameter corresponding to 10% finer, $D_{50} =$ diameter corresponding to 50% finer, $D_{60} =$ diameter corresponding to 60% finer, $C_u =$ uniformity coefficient $= D_{60} / D_{10}$, $C_z =$ coefficient of gradation $= D_{30}^2 / (D_{10} D_{60})$, $P_{4.75mm} (%) =$ 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 $=$ unified soil classification system, USCS [26].

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.

Atomic absorption analysis performed on the tailings revealed that the tailings contained Fe 3660 mg/kg, whilst the other heavy metals (Cu, Cr, Zn, Pb, Ni) where no detected.

4. Preparation of cylindrical specimens

Cylindrical specimens of Mont Wright tailings matrices measuring (44 diameter x 74 height) mm were molded for this purpose in accordance with ASTM D 4842 [27]. These cylindrical specimens were, then, cured in a moisture chamber for 28 days in the case of the wetting and drying samples, and for 43 days for the freezing and thawing samples. Unconfined compression tests were conducted on these tailings matrices after exposing them to 12 cycles of drying at 60 °C and wetting by being submerged in room temperature distilled water. The remaining samples were compressed after undergoing 12 cycles of freezing at -20 °C in a freezing cabinet and thawing in distilled water at room temperature (22 °C). Table 2 shows the codes implemented for the cylindrical specimens of the tailings matrices.

| 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             | 10                  | 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             |
| Mont Wright   | Freezing/Thawing | MC'1 | 1, 2, 3, 4, 5, 6 | 0.5                | 100            | 0                   | 0               | 0             |
|               |                 | MC'3 | 1, 2, 3, 4, 5, 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             |
5. Unconfined compression testing after weathering

It is known, that, solidified waste in the field is under continuous weathering cycles. Therefore, strength testing will not be complete without investigating the effect of weathering cycles on compression strength.

After undergoing the weathering tests, the specimens of the tailings matrices were tested under uniform conditions to find their strength in the UCS apparatus. In this test, speed of descent of the platen was kept constant at 70 mm/min, with the exception of a few samples where it had to be changed to 50 mm/min, in order to increase the maximum load the machine can apply, since these latter samples had higher compression strengths than the others. Experimental results of this test are discussed elsewhere [28].

6. Computational and experimental results

It is necessary to verify the accuracy and reliability of the proposed computational model (Tailings-DEM™) using laboratory-approved experimental results. Therefore the UCS experimental results [28] were used in the verification and analysis of this program.

Figures 1 to 6 show the UCS experimental and computational results comparison for Mont Wright tailings matrices for the matrix binder combinations shown in Table 2. The following shows these matrix binder combinations in groups of figures:

1) Figure 1 shows the 100% OPC,
2) Figure 2 shows the 90% OPC, 10% Calsifrit,
3) Figure 3 shows the 75% OPC with 25% Calsifrit,
4) Figure 4 shows the 75% OPC with 25% fly ash,
5) Figure 5 shows the 75% OPC, 15% fly ash and 10% Calsifrit,
6) Figure 6 shows the 75% OPC and 25% slag,
Figure 1. Computational and experimental UCS values for Mont Wright samples MC’11(a)-MC’16(b) after freezing/thawing.
Figure 2. Computational and experimental UCS values for Mont Wright samples MC’31(a)-MC’36(b) after freezing/thawing
Figure 3. Computational and experimental UCS values for Mont Wright samples MC’61(a)-MC’66(b) after freezing/thawing
Figure 4. Computational and experimental UCS values for Mont Wright samples MCF’31(a)-MCF’36(b) after freezing/thawing.
Figure 5. Computational and experimental UCS values for Mont Wright samples MCF’51(a)-MCF’56(b) after freezing/thawing.
Figure 6. Computational and experimental UCS values for Mont Wright samples MCS’11(a)-MCS’16(b) after freezing/thawing.
7. Discussion of Tailings-DEM™ strength modeling

Experimental and computational UCS values for the Mont Wright tailings matrices, for the cases shown, have similar types of curves indicating that computational modeling of this test was to a large extent accurate. Maximum values and slopes for the experimental and computational results followed closely. Marginal differences between the experimental and computational values could be attributed to several factors.

The marginal differences between the computational and experimental UCS results could be attributed, partially, to the experimental errors in the preparation of the specimens tested. It is known that soil-cement matrices suffer from result variability [28]. Furthermore, the presence of iron (Fe) has further complicated the outcome of the UCS experiments [28].

Another reason could be the assumptions used in defining the computational program Tailings-DEM™. The assumptions were based on modelling the particles as right-isosceles triangles. This assumption had affected the other assumption of contact mechanism. In reality, however, soil particles have varied shapes and smaller sizes and their contact mechanism is much more complicated. In addition, most soils contain different amounts of water, an effect that was not modeled in Tailings-DEM™.

It is thought that the main difference between the computational and the experimental results is the approximation to 2D modeling when writing the program. Also, binder constituents were not modeled in Tailings-DEM™, but were largely modeled through the UCS that was derived statistically [28]. In addition, the platen speed in the experimental tests was not modeled in the computational program.

Since Mont Wright tailings were predominantly sandy, it is thought that the program can be incorporated to model other types of aggregates, such as sands and gravely sands, with a particle size distribution close to Mont Wright tailings.

8. Conclusion

The DEM tool developed (Tailings-DEM™) is capable of simulating, with reasonable accuracy, the UCS strength values of Mont Wright tailings matrices. However, more physical and chemical characteristics, such as the binders’ constituents and the loading platen speed need to be modeled to make the simulation more accurate.

It is thought that Tailings-DEM™ can be incorporated to model other types of aggregates with similar particle sizes, such as sands and gravely sands.

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