Proceedings of the Annual International Conference on Soils, Sediments, Water and Energy

Volume 12 | Article 11

January 2010

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Chapter 10

INVESTIGATION OF THE USE OF MINE TAILINGS FOR UNPAVED ROAD BASE CONSTRUCTION

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Abstract: Tailings have been traditionally stored in ponds surrounded by tailings dams for many years but since many accidents, including fatal ones, took place that involved tailings dams, a new approach has become necessary for their storage. An approach devised by Robinsky in the early 1970s for the storage and disposal of mine tailings suggests that it is more advantageous environmentally to strengthen the tailings before disposal. This work attempts to emphasize this point by seeking to explore the possibility of using these hardened tailings as base materials for the construction of unpaved (temporary access) roads. Six different types of tailings that represent a cross section from several mines in eastern Canada are used and preliminary physical characteristics tests were performed followed by unconfined compressive testing. Initial results indicate that the tailings sustained more than the minimum amount of stress normally required for filling stopes and the layer coefficients determined for five of the tailings used match reasonably well with values from ten United States state departments of transportation.

Key words: tailings, Portland cement, heavy metals, unconfined compression.

1. INTRODUCTION

Tailings are the waste materials (byproducts) of the mining industry. Tailings contain all other constituents of the ore but the extracted metal, among them heavy metals and other toxic substances that are either added to the tailings in the milling process or available with the ore before that (ICOLD 2003).

Most mill tailings mass-produced worldwide are dumped in large surface impoundments (tailings dams). The embankments forming these impoundments are earth fill dams. Over the years these earth fill dams have had several serious spilling problems, some even fatal. Two recent examples of the disasters originating from tailings dams spilling are one, the Merriespruit dam tailings failure that resulted in the killing of 17 people and caused extensive damage to a residential township in South Africa in 1994 (Fourie and Papageorgiou 2001 and Fourie et al. 2001**)**. Another disaster occurred in the Philippines in 2002 where tailings spilled into Mapanuepe Lake and eventually into the Saint Tomas River. Low lying villages were flooded with mine waste. At least 250 families were evacuated from that area, (Fahey et al. 2002).

Hence it was necessary to devise another approach for the storage and disposal of mine tailings with the aim of eliminating the hazards and risks associated with mine tailings dams. Research on mine tailings stems from the necessity to prevent the danger posed by mine tailings to the environment. This danger is characterized by the tendency of mine tailings to release acids and heavy metals once in contact with oxygen and water, (Gautam et al. 2000). In 1978 Robinsky published what was probably the first detailed paper suggesting that tailings could be economically disposed of after being extensively dewatered (Robinsky 1978). He suggested the word 'thickened tailings' and even produced a schematic showing the development of a conical deposit of high-density tailings (Fourie 2002).

2. PREVIOUS RESEARCH

2.1 Tailings Thickening

Robinsky proposed the thickened tailings disposal system for the disposal of mine tailings (Robinsky 1978). He showed that by the process of thickening the tailings to heavy slurry prior to disposal, it is possible to create a self supporting deposit of tailings and to eliminate the typical superimposed settling pond.

Robinsky (1978) stated that the inherent problems associated with the operation of conventional tailings disposal schemes are eliminated using this new technique. Some of the obvious problems that are eliminated or at least much reduced are:

- Danger of failure of steep-sided tailings dams caused by earth tremors, blasting vibrations, or movement of heavy machinery;
- Erosion and undermining of the dams by seepage from the raised slimes pond in the center of the tailings deposit;
- Infiltration of undesirable tailings fluid into the underlying natural soil deposits from the liquid pond on top of the tailings; and commencement of reclamation only after mine closure.

The elimination of the conventional pond on top of the deposit also provides a major environmental advantage; the hydrostatic head that causes seepage of process and rainwater to occur through conventionally deposited tailings is eliminated. Another very important environmental advantage is that the confining dam(s) are eliminated, or, at least, reduced substantially in height which will also reduce or eliminate the problems of aging of tailings dams (Murray et al. 2000 and Vanicek 2002). Finally, the adoption of the system may permit progressive reclamation in some topographical settings.

Several research attempts followed the first mine tailings thickening paper of Robinsky with the aim of enhancing this new idea by adding a binder or other agents to the thickened tailings. An example is the work by Zou and Li (1999) who investigated direct solidification and strengthening of dilute tailings slurry. Two types of tailings were tested at water/binder ratios of up to 4.5 using special high-water binder. The main objective of their research was to develop a backfill technology that can use the total tailings and will be applicable to all types of tailings without the expensive dewatering process. These results proved that the high water tailings slurry could be solidified directly and was able to develop sufficiently high early strength and that it is possible to use the dilute total tailings slurry without the dewatering process in backfill.

The thickened surface tailings disposal concept has been applied at various mining operations for several decades, including the Kidd Creek Mine in northern Ontario and for managing the disposal of red muds produced by the alumina industry (Robinsky 1999).

Although the concept of tailings thickening is relatively new, soil stabilization techniques using cement and lime have been applied for many years now. Hilt and Davidson (1960) discussed lime fixation in clays heralding a decade of advancing technology in lime and Portland cement stabilization of clay soils (Petry and Little 2002). Prusinski (Little et al. 2000) states that since 1915 more than 140,000 km of equivalent 7.5 m wide pavement bases had been constructed from cement-stabilized soils. Cement has been found effective in stabilizing a wide variety of soils, including granular materials, silts and clays (Petry and Little 2002). The following works represent examples of using this concept in the mining industry and research:

Garand et al. (2000) described the effects of flocculent deposition of tailings sludge in the Bouchard-Hebert mine in northern Quebec. ASTM standard tests were performed on the tailings to characterize particle size, specific gravity and Atterberg limits. Then the tailings sludge was mechanically thickened in the paste backfill plant and a flocculent PERCOL E-10 is added to the sludge before it is processed in the thickener. These flocs presented uniform apparent grain-size distribution larger than or similar to coarse silt. The authors concluded that the beaches formed with these flocs can be used as competent foundation material for upstream raises. Their study presented a modification on Robinsky's thickening principle by adding a flocculent to the tailings to enhance thickening and increase stability.

Demers and Haile (2003) described the stabilization of zinc tailings, called Jarosite. The Jarosite was thickened first using vacuum filters and then lime cement and water were added to the thickened Jarosite to make a product that was named Jarofix. Field tests were performed after the commissioning of the Jarofix process in October 1998, after which the authors concluded that Jarofix is chemically inert thus eliminating all short and long term environmental risks during and after its disposal and that it was a physically stable mass. It was also found that cured Jarofix was an excellent fill material for construction of dykes and roads (Demers and Haile 2003).

Benzaazoua et al. (2002) discussed in some detail the influence that several chemical factors have on the performance of mine sulphidic paste backfill. The authors attempted to investigate the effect of the chemical characteristics on the uniaxial compressive strength on these tailings backfill. It was found that the mixing water is an important parameter that affects the quality of the paste backfill and that slag based binder hydration seems to be inhibited by the presence of soluble sulphates in contrast to the Portland cement based binder. The results of this study clearly demonstrate the inefficiency of choosing paste backfill mixtures without testing first the tailings and mixing water characteristics (Benzaazoua et al. 2002).

2.2 Tailings Management

Nguyen and Boger (1998) described two case studies where the measurement and use of rheological properties have assisted in solving large-scale tailings disposal problems in the Australian mining and mineral industry. The results have been used to develop a new waste disposal strategy whereby many technical, economical and environmental problems associated with the current disposal technology can be minimized.

Another study was detailed by Theriault et al. (2003) describing the surface disposal of paste tailings at the Bulyanhulu Gold mine in Tanzania managed by a subsidiary of Barrick Gold Corporation. Some clear goals of this process were, as stated by the authors, to conserve water, manage runoff reduce risk and minimize containment dyke construction. The tailings slurry was thus dewatered and then transported to the paste plant were process water is added in the paste conditioner to produce a paste of the desired consistency. The authors ascertained that the cycling of the tailings deposition in thin layers has been successful in generating a stable paste stack. It was concluded that paste stack can be engineered to meet the required geotechnical and environmental objectives (Theriault et al. 2003).

Results presented herein are part of an ongoing research program into the behavior of solidified mine tailings with the aim of determining the applicability of the use of tailings as base materials for temporary access roads. This will be approached by determining the unconfined compressive strength of several mine tailings-binder combinations.

3. EXPERIMENTAL PROCEDURE

3.1 Tailings Characteristics

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 (Haile et al. 2000) in addition to the alumina tailings that were investigated by the latter authors. Therefore in this study, six different mine tailings(Mussel white tailings: Placer Dome mine: Musselwhite, Ontario, Noranda Tailings: Noranda Inc.: Brunswick mine, Bathurst, NB, Louvicourt tailings: Louvicourt Mine, Val. d'Or, Quebec, Golden Giant tailings: Newmont Canada Limited, Golden Giant Mine, Marathon

(Ontario), Mont Wright tailings: Quebec Cartier mineral company, Mont-Wright, Quebec and Copper tailings: Murdochville, Quebec) were selected and obtained to evaluate a wide range of tailings from different types of mines. Laboratory tests on these tailings were carried out and the measured properties of the tailings are presented below.

3.2 Particle Size Analysis

Representative samples from each tailings type were chosen after removing any unusually big chunks of tailings. Dry sieving was performed according to ASTM D 422 (1998) after oven drying these tailings specimens in an electric oven at 105°C for 24 hours.

Hydrometer analysis was performed in accordance with ASTM D422 (1998): 4% $NaPO_3$ (sodium hexametaphosphate) solution was made by mixing 20 g of the $NaPO_3$ powder with enough water to make 500 milliliters.

Initial moisture content for each type of tailings was determined as defined by ASTM D 2216 (1998) by taking representative samples from each tailings container. After determining their wet weight, these samples were placed in an oven at 105 ^{o}C for 24 hours, after which another weight measurement was taken. This procedure was continued until constant weight was achieved. Table 1 outlines the physical characteristics of these tailings where it can be seen that according to the Unified Soil Classification System (Das, 2000), Musslewhite, Louvicourt, Golden Giant and Copper tailings are classified as silty sands whereas Noranda tailings are considered well-graded sand with silt and Mont Wright tailings are poorly-graded sand.

3.3 Specific Gravity

Representative samples were obtained from each of the six tailings types. Then they were oven dried for 24 hours at 105°C prior to determining the specific gravity. Subsequently specific gravity tests were performed according to ASTM D 854 (1998). Distilled water was used for these tests and by gently rotating and agitating the flasks, it was assured that all air bubbles were eliminated from within these samples before taking the weight measurements. Weight determinations were made using an electronic balance sensitive to 0.01 g.

Table 2 details the specific gravities of the tailings samples considered at 20 °C and the standard deviations of the samples selected for all tailings with the exception of Mont Wright and Golden Giant. Bowles (1986) states that for specific gravities measuring between 2.4-3, another procedure for determining the acceptable accuracy of the measurements was to have two readings differ by no more than 2 percent. Both Mont Wright and Golden Giant fall into this criterion as shown in Table 2. All other tailings samples satisfy the criteria of having a maximum standard deviation of 0.021 according to ASTM D854 (1998). Specific gravity results were within the range presented by other researches; (Mittal and Morgenstern, 1975; Qiu and Sego, 2001; Garand et al., 2000; Haile et al., 2000; Demers and Haile, 2003; and Crowder et al., 2000).

Table 1. Physical properties of the tailings used.

Type of tailings	**Nor-anda**	**Mussle-white**	**Golden Giant**	**Louvi-court**	**Copper**	**Mont Wright**
D_{10} (mm)	0.063	0.0045	0.004	0.005	0.02	0.147
D_{50} (mm)	0.81	0.016	0.039	0.0464	0.0622	0.255
D_{60} (mm)	1.19	0.023	0.055	0.0697	0.0844	0.3
D_{30} (mm)	0.398	0.012	0.0178	0.018	0.04	0.2
C_u	18.89	5	13.75	13.94	4.22	2.04
C_z	2.11	1.39	1.44	0.93	0.948	0.91
$P_{4.75mm}$ (%)	92	100	100	100	100	100
$P_{0.075mm}$ (%)	8.59	74.9	69.69	62.05	56.9	2.05
Initial moisture content (%)	17.04	30.15	19.71	28.1	22.33	4.27
USCS	SW-SM	SM	SM	SM	SM	SP

D_{10} = diameter corresponding to 10% finer, D_{50} = 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_z = coefficient of gradation = $D_{30}{}^2$ /(D_{10} D_{60}), $P_{4.75mm}$(%) = percentage passing sieve no. 4, $P_{0.075mm}$ (%) = percentage passing sieve no. 200.

Table 2. Specific Gravities of the tailings used.

Tailings type	Specific Gravity	Standard Deviation
Copper	3.4	0.021
Mont Wright	2.76	1.004*
Noranda	3.68	0.014
Golden Giant	2.97	1.01*
Mussle white	3.26	0.0071
Louvi court	3.33	0.0071

3.4 Unconfined Compressive Testing

Determining the strength of the tailings block is the first part to ensuring that they are suitable environmentally for disposal and for construction of service roads and containment dykes thereafter.

Type I Ordinary Portland cement was mixed with each type of tailings using a mechanical mixer. This type of cement is usually the least expensive and the most commonly used in chemical fixation and solidification applications, (Conner, 1990). In general, Portland cement systems produce stronger matrices than other inorganic binder systems, and they do it at lower mix ratios, which results in a smaller volume of waste requiring ultimate disposal, (Weitzman et al., 1988). In these tests it was desired to determine the effect of the change in water content on the compressive strength. Cement content was maintained constant during these tests. Each mix was poured subsequently in three different wooden molds with dimensions of (2.5 X 2.5 X 2.5) centimeters. These mixes were then left to cure at room temperature for 24 hours before placing them in the moisture chamber.

A moisture chamber placed inside an incubator was utilized for the storage of the cured specimens. Temperature inside the chamber was maintained at 23.5°C and the humidity at 98% (Wang and Vipulanandan, 1996; Diez et al., 1997; Zamorani et al., 1989). Having a pool of water at the bottom of the chamber ensured that humidity was maintained at this prescribed level. Figure 1 shows the tailings specimens inside the moisture chamber. For each type of tailings, density was maintained uniform since this parameter had to be constant during compression testing.

Figure 1. Tailings specimens inside the moisture chamber

Unconfined compression testing was performed by subjecting the cubes to one dimensional compression from a Com-Ten Industries™ uniaxial machine with a peak compression force of 8.896 kN applying a constant speed of descent. The peak force and peak deflection maintained during each test were recorded and used subsequently in calculations.

The speed of descent of the platen was kept constant at an average of 70 mm/minute and the test was continued until visual observation of failure of the cube. After which the machine was cleaned and made ready for another test. A total of 180 compression tests were performed in the prescribed manner.

4. RESULTS AND DISCUSSION

Figure 2 shows the results of the tests performed. Stress measured in mega Pascals is plotted in this figure against water/cement ratios. The uniaxial (unconfined) compressive strength corresponds to the maximum stress value observed during the compression test.

When varying water/cement ratio it is seen through Figure 2 that all the tailings tested experienced a drastic decrease in stress with increasing water content. It can also be seen that when increasing the water content Louvicourt had the highest stress while Noranda sustained the lowest recorded stresses and all other tailings had intermediate stress values between these two.

4.1 Effect of Water Content

It is well known that strength decreases as matrix porosity increases, and that porosity increases as the water to cement ratio increases above an optimal value (Lea, 1971 and Neville, 1995). Figure 2 illustrates that strength decreases with increasing water content for Portland cement products containing metal contaminants. The same conclusion was reached by Stegemann (2001). The correlation coefficient of these plots is not high and the scatter is obvious indicating that they are nonlinear.

4.2 Estimation of Interlaboratory Error

A quality program conducted by Stegemann et al. (2001) in which the products prepared by the University of Rome (Dall'Aglio et al., 2001), the University of Cantabria (Fernandez Olmo et al., 2001) and the University of Surrey (Gervais and Ouki, 2001 and Hills and Ouki, 1999) were each tested in all three laboratories. The unconfined compression strength results from the quality control program have been used to calculate a pooled variance, which corresponds to an interlaboratory standard deviation of 3430 kPa; measuring the UCS of separately prepared batches increased the interlaboratory standard deviation to 4120 kPa (Stegemann, 2001).

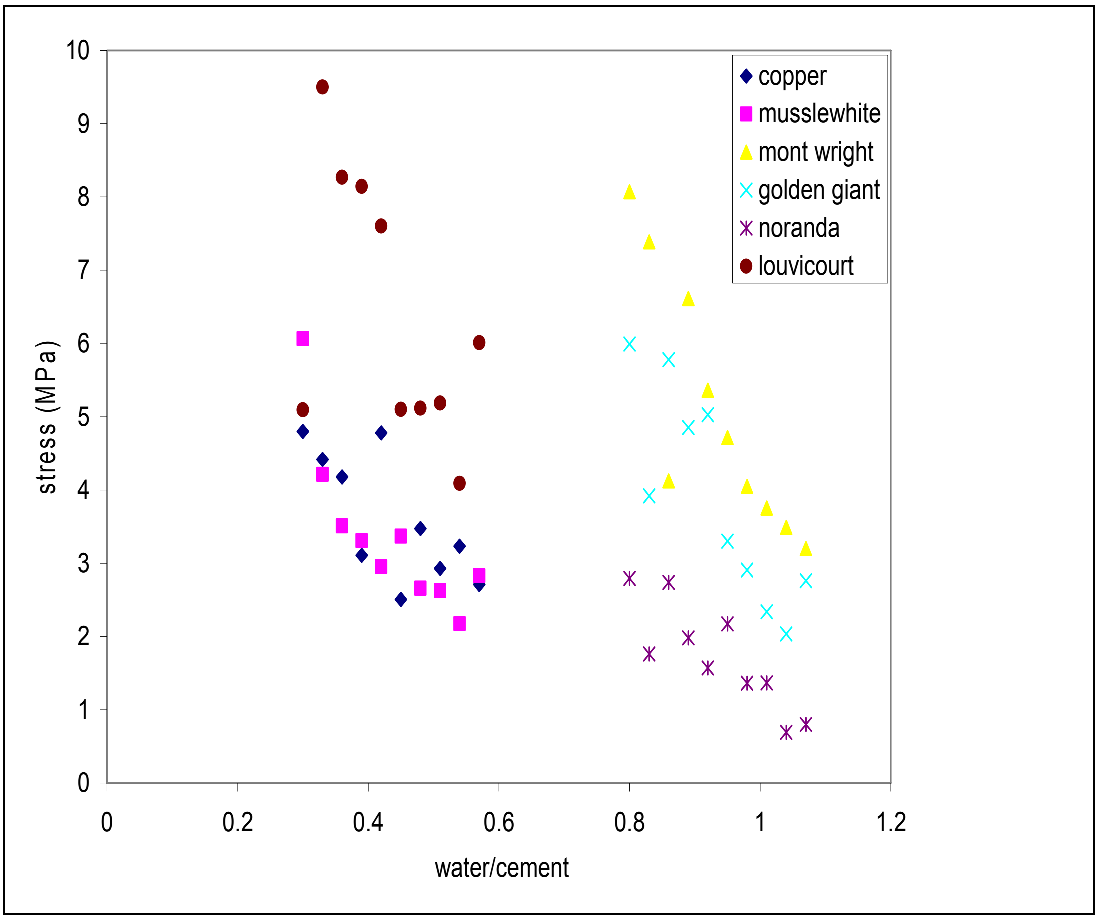

Figure 2. Stress versus water/cement ratio for all tailings

Neville (1995) also reports that for high strength concrete a typical intralaboratory standard deviation is in the range of 3500 to 5500 kPa. Table 3 shows the standard deviation range and variance for the unconfined compressive testing for the tailings considered in this study.

A comparison between the values of standard deviation reported in the literature and cited above and the values found in this work indicates that compression values for this study have much less variability and the scatter is typical for cement paste mortars and therefore could be considered accurate and applicable for design and calculation purposes.

4.3 Layer Coefficients

AASHTO highway design method requires knowledge of a structural number (SN), which is a function of several parameters including design traffic level, subgrade support, desired reliability and desired terminal serviceability, (AASHTO, 1986). The equation relating the structural number to the layer coefficients is the following:

$$SN = a_1 D_1 + m_2 a_2 D_2 + m_3 a_3 D_3$$

Where: SN = structural number; a_1, a_2, a_3 = layer coefficients for the surface, base and subbase, respectively; m_2, m_3 =drainage coefficients of the base and subbase, respectively; D_1, D_2, D_3 = thickness of the surface, base and subbase layers, respectively.

Hence it appears from the equation above that the thickness of any particular layer depends to a significant level on the layer coefficients. Thus in order to assess the suitability of the tailings for use in temporary access roads, an analysis was made to determine the layer coefficient for use when designing an access road with tailings as the base layer. Two different equations were used in this analysis; the first was developed by the University of Missouri-Rolla (Richardson, 1996):

$$E_c = 915.48 + 1314.9\, q_u \qquad (1)$$

Where E_c = Chord modulus of elasticity (MPa),
q_u = the unconfined compressive strength (MPa).

And the second equation used was developed from data supplied by work performed by Felt and Abrams (1957), Reinhold (1955) and University of Missouri-Rolla (Richardson 1996);

$$E_c = -34.367 + 2006.8\,(q_u)^{0.7784} \qquad (2)$$

Then layer coefficients are computed by using the AASHTO nomograph. The equation for the relationship of layer coefficients and modulus was derived from the nomograph and is the following (Richardson, 1996):

$$a_2 = -2.7170 + 0.49711 \log E_c \qquad (3)$$

Where a_2 = layer coefficient.

Figure 3 shows the layer coefficients for all tailings used. The coefficients for all tailings with the exception of Noranda at higher water contents, match reasonably well with values from 10 state departments of transportation reported in the literature, which range from 0.12 to 0.3 (ACI Committee, 1990), thus indicating that these mine tailings are suitable structurally for unpaved road construction. Layer coefficients for Noranda tailings with water contents more than 80% were lower than 0.12. These cubes had lower cohesion and faster disintegration when tested in compression. This could be due to higher sulphur content as indicated by the yellowish color of these hardened cubes.

Table 3. standard deviation range and variance for the unconfined compressive tests for all tailings used.

Tailings type	**Standard Deviation Range (kPa)**	**Variance**
Copper	403-1461	162409-2134521
Mont Wright	247-1419	61009-2013561
Noranda	69.9-1289.7	4886.01-1663326.09
Golden Giant	187.9-1724.9	35306.41-2975280.01
Musslewhite	216.1-1795.1	46699.21-3222384.01
Louvicourt	445.6-3529.5	198559.36-12457370.25

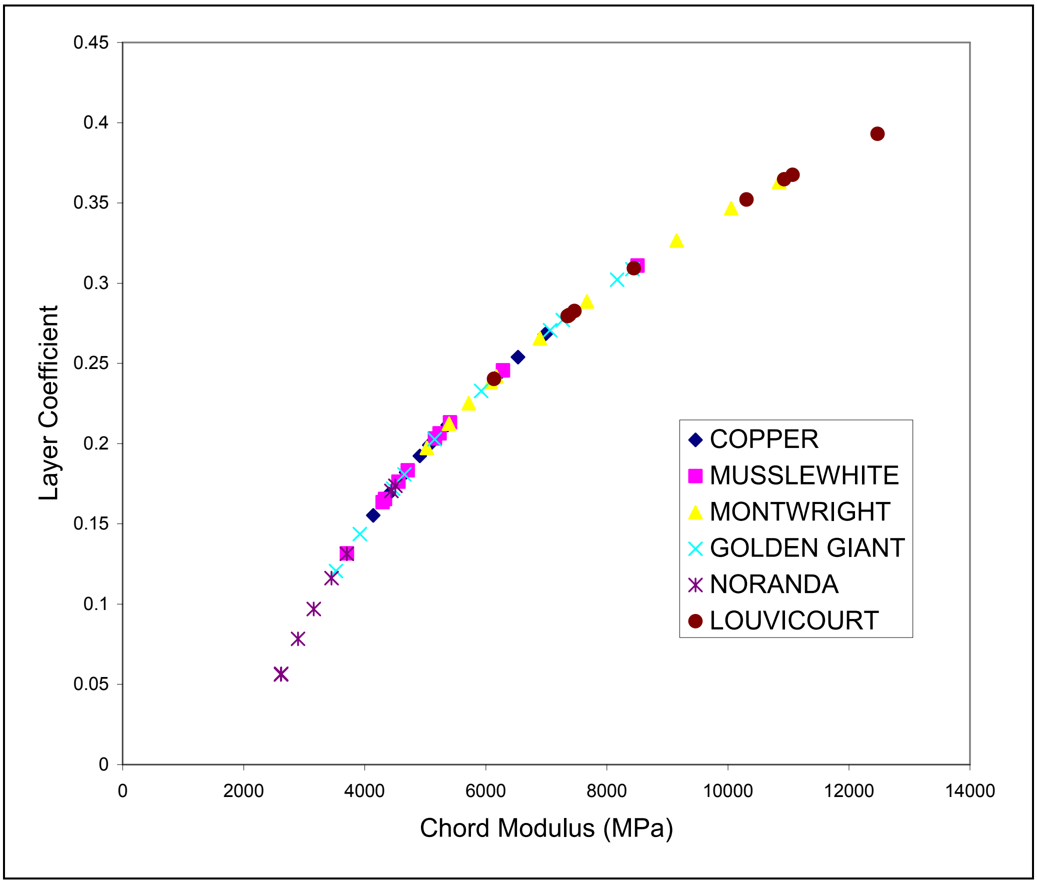

Figure 3. Layer Coefficients versus Chord Modulus for all tailings.

5. CONCLUSIONS

1. The values of the specific gravity of the tailings under study are within the typical ranges published for similar types of tailings.
2. All tailings considered exceeded the minimum limit required in strength for filling underground stopes.
3. Strength decreased as water/cement content increased for all tailings.
4. Unconfined compressive strength standard deviations for tailings specimens were lower than expected for cement paste mortars.
5. Layer coefficients determined suggest that all these tailings with the exception of Noranda can be suitable base materials structurally for building unpaved temporary access roads.

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