Solidification-Stabilisation (S/S) of Densified Mine Tailing Containing Phyllosilicates for Surface Storage under Natural Climatic Conditions

Marie Zogbili Teoro[1], Abdelkabir Maqsoud[1], Tikou Belem[1], Mamert Mbonimpa[1]

1Université du Québec en Abitibi-Témiscamingue, Rouyn-Noranda, PQ, Canada, MarieZogbili.Teoro@uqat.ca, abdelkabir.maqsoud@uqat.ca, tikou.belem@uqat.ca, mamert.mbonimpa@uqat.ca

Abstract

Mine tailings are filtered and stored on the surface in tailings storage facilities to create self-supporting tailings. However, tailings containing phyllosilicates (such as muscovite-fine tailings) may be susceptible to long-term freeze-thaw and wet-dry cycles. These environmental conditions can adversely affect hydrogeochemical stability, including the modification of saturated hydraulic conductivity (k_{sat}), water retention curve (CRE), and mobility of chemical elements, especially in the case of sulfide deposits. Additionally, these conditions impact the physical stability, including mechanical strength and bearing capacity of these tailings.

To mitigate these potential impacts, the use of hydraulic binders to solidify and stabilize these tailings is becoming increasingly a necessity. In these tests, small quantities of HE cements (0.5, 1.5, and 2%) were added to the filtered tailings, incorporating different proportions of muscovite (9.5, 12.5, and 15.5%) to form mix recipes. These blends were subjected to several tests after 28 days of curing at a controlled temperature of 18°C. Test results showed significant improvements in uniaxial compressive strength (UCS), k_{satt}, pH, Eh, and electrical conductivity (EC); all parameters improved with the addition of 2% HE cements to muscovite-bearing mine tailings of up to 15%. UCS increased from 61 kPa for unamended tailings to 493 kPa for tailings amended with 2% HE cements, k_{sat} decreased from 10^{-7} m/s to 10^{-9} m/s, and pH increased from 7 to 8.6.

The results of this study highlight the positive impact of incorporating cementitious amendment to phyllosilicate-bearing mine tailings stored on the surface under northern conditions. This finding presents an opportunity for mining companies to establish a more responsible, safe, and sustainable management system for the mining environment, all at a lower cost.

Key words: mine tailings, hydraulic properties, geochemical stability, mechanical strength, binder, climate, permafrost

Introduction

The extraction of ores during mining operation requires a treatment process at the mill to obtain an economically valuable concentrate. This process generates a large quantity of mine tailings that must be managed by the operators. Approximately 60% of these tailings are returned underground as backfill to ensure the stability of the underground mine site (Belem and Benzaazoua, 2008b; Benzaazoua et al., 2003; Benzaazoua et al., 2004a; Newman et al., 2001; Ouellet et al., 2006). The remaining portion is typically deposited on the surface in tailings storage facilities surrounded by retaining dikes. However, the mineralogical composition and granulometry of these tailings mean that their long-term management remains a real source of chemical instability such as acid mine drainage (AMD) generation by sulfide minerals oxidation, and physical instability including dike failures (Aubertin et al., 2002b; Bussière, 2007; Marques et al., 2020).

Another issue related to surface tailings management is the presence of phyllosilicates and the effect of climatic stresses such as freeze-thaw and wet-dry cycles, especially in cold regions (Létourneau, 2012; Ma et al., 2022; Ren et al., 2019). These climatic conditions can adversely affect the physical integrity of filtered tailings, including negative impacts on hydrogeochemical, geotechnical and mechanical properties. Freeze-thaw and wet-dry cycles can induce a sharp increase of water content in phyllosilicate-bearing tailings during the spring seasons. This increases in water content causes deterioration of the structure of densified mine tailings leading to the formation cracks. These changes results in increased hydraulic conductivity and progressive weakening of mechanical performance of the tailings. These phenomena promote the release, solubility, and mobility of contaminants into the environment, especially in the case of sulfurous deposits. Consequently, they create chemical instability and pose risks to surface water, groundwater, plants, and other living organisms. In such cases, the application of the solidification and stabilization method using cement becomes an effective alternative in order to increase the mechanical performance, durability and hydrogeochemical stability of mine tailings (Benzaazoua et al., 2004c; Chen et al., 2019; Hadimi, 2014; Hadimi et al., 2016; Kumpiene et al., 2008; Lwin et al., 2018; Segui et al., 2023; Tyagi and Annachhatre, 2023).

The addition of cement to tailings reduces their porosity and permeability, and increases their water-retention capacity (and air entry value) and their mechanical performance (Chen et al., 2019; Peyronnard and Benzaazoua, 2012; Shi and Spence, 2004; Wang et al., 2023). This overview shows that the solidification/stabilization method based on hydraulic binder is widely recognized and successfully utilized in several engineering fields. However, its application poses an important challenge in the mining field due to unique characteristics of each tailings, including mineralogical composition, grain size distribution, and climatic conditions to which tailings are exposed (Eagle, 2021). In light of these considerations, his study was undertaken with the objective to assess the hydrogeochemical behavior of densified, solidified, and stabilized tailings from the Meliadine mine; tailings from this mine contain phyllosilicates and are stored on the surface under natural northern climatic conditions.

This study investigated the influence of phyllosilicate amendment on various aspects of phyllosilicate-bearing tailings, including mechanical strength, water retention curve, permeability, freeze-thaw effect, and leachate water qualities. The beneficial effects of employing cement-based solidification and stabilization techniques to enhance the mechanical and hydrogeochemical properties of densified mine tailings are discussed.

Materials and Methods

In this project, materials utilized included Meliadine mine tailings, high early strength (HE) Portland cement and muscovite. The muscovite was sampled in its natural state at the Aldovs site in Preissac located in the Abitibi-Témiscamingue region of Quebec, Canada. Subsequently, it underwent protocol treatment and analysis by combined X-ray diffraction (XRD) in order to determine the content (%) of muscovite used in the mixtures.

Material properties

The filtered tailings and muscovite underwent physical characterization to determine their relative density, particle size distribution, specific surface area. Additionally, mineralogical characterized using X-ray diffraction (XRD) was conducted to determine the initial muscovite content in the tailings before doping and blending. The result of the grain size distribution are in Figure 1. This graine size distribution was used to determine specific parameters such as D_{10}, D_{60} and Cu, as well as mineralogical characterization and their proportion (Table 1).

Table 1. Physical and mineralogical properties of Meliadine mine tailings

Parameter	Value	Mineral	Proportion (Wt%)
D_R	2.9	Quartz	42.7
D_{10} (μm)	3.8	Chlorite	21.2
D_{50} (μm)	22.5	Albite	15.5
D_{60} (μm)	30.3	Muscovite	9.5
C_U	7.9	Dolomite	8.4
C_C	1.2	Magnetite	1.9
$P_{80μm}$ (%)	85		
S_s (m^2/kg)	1818.4		

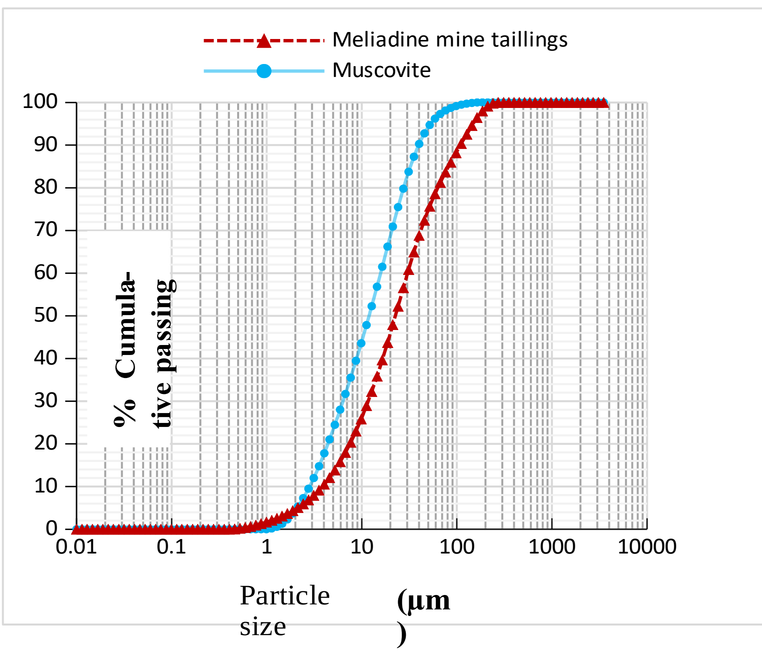

Figure 1 Particle size distribution of Meliadine mine tailings and muscovite.

Results of physical characterization indicate that Meliadine mine tailings are dense; with a density of Dr = 2.9, the amount passing through particle smaller than 80 μm is approximately 85%. The particle diameter corresponding to D_{10} (10%) is 3.8 μm. Uniformity and curvature coefficients correspond to 7.9, and 1.2 respectively. The particle size distribution of Meliadine mine tailings is typical of hard rock mines

(Aubertin et al., 2002), with a measured specific surface area of 1818.4 m^2 kg. XRD analysis of the tailings revealed quartz as the most abundant mineral at 42.7%, followed by chlorite (21.2%), albite (15.5%), muscovite (9.5%), dolomite (8.4%), and finally magnetite (1.9%).

Mix preparation and placement of cemented (CC) and uncemented (UC) layers

Various mixture of tailings and cement were employed to simulate two surface tailing storage scenarios. The mixtures were prepared with three levels of muscovite content (9.5, 12.5 and 15.5%). For each level, three proportions of Portland HE cements were added (0, 0.5, and 2% by mass) for the first scenario. Additionally, another cement (1.5% HE) was added to the 12.5% muscovite content to test a second configuration scenario involving intercalation of UC and CC column layers. This second configuration aimed to simulate continuous tailings storage in a pre-existing facility. All mixtures were prepared to a uniform consistency of 2–3.5 in (~ 5–9 cm) and a fixed solid percentage of 83.5%. The mixtures underwent a 28 day curing period at controlled temperature of 18°C in a humid chamber before further testing. All experiments were conducted in accordance with ASTM standards.

UCS

Mechanical properties were assessed in the laboratory through UCS testing. Ten cylindrical specimens, each with 7.24 cm height and 15.62 cm diameter, were prepared from different mixtures and tested after 28 days. Each sample was placed between two parallel platens of a mechanical press and compressed to measure its compressive strength. This allowed for an evaluation of the effect of the amendment on the physical integrity of the cement-based stabilized and solidified tailings.

Wetting-drying column tests

Experimental columns with 40 cm height and 15 cm diameter were used to test the hydrochemical behavior of the mixtures. All columns were subjected to experimental wet-dry cycles, where each cycle began with water saturation (volumes of 2425–3137 mL), followed by a drainage period lasting four weeks. After each cycle, leachate was collected near the bottom of the column and analyzed for physical and chemical parameters including pH, Eh, and EC.

Water retention curve

Water retention curves (WRC) were determined using the Tempe cells test (Figure 2). After the 28 day curing period, mixtures were prepared in molds of 6 cm height and 8.5 cm diameter, equivalent to the dimensions of the pressure cell. The samples were saturated and then placed between two saturated porous ceramic plates for testing. The water retention curve was obtained by plotting the various volumetric water contents (θ) as a function of suction (ψ) during the test.

Figure 2. Pressure cells (Tempe cells) used to determine the CRE of tailing mixtures.

Permeability and freeze-thaw tests

The saturated hydraulic conductivity (k_{sat}) of both amended and unamended tailings was determined using the variable-load flexible-wall permeability test in accordance with ASTM D5084-16a. The mixture sample used for the permeability and freeze-thaw tests was prepared for curing in PVC molds (10.3 cm height and 20.5 cm diameter) before placed in the permeameter with a porous stone and geotextile at the ends. The sample was saturated with deionized and deaerated water. Containment and saturation pressures were 30 and 20 kPa, respectively. The saturated hydraulic conductivity k_{sat} (cm/s) was calculated using the formula:

$$k_{sat} = \frac{(a \in X\, a\, out)\, X\, L}{(a \in + a\, out)\, X\, A\, X\, (t2 - t1)}\, X \ln\left(\frac{h2 - h1}{h2 - h1}\right) \qquad \text{Equation 1}$$

where, a_{in} = area of the transverse session of the water inlet burette; a_{out} = water outlet burette area; L = sample height in cm; A = sample session area; and h_2 = pressure losses across the sample at times t_1 and t_2. Twelve cycles of freeze-thaw tests were conducted on solidified and stabilized samples to assess the effects of freeze-thaw on the hydraulic conductivity of amended tailings. The samples, surrounded by membranes and isolated in a cell, were moved to a freezer with an average temperature of -26°C during 24 hrs during for the freezing phase. Subsequently, samples were thawed at an ambient temperature of 20°C.

Results and discussion

UCS

Results of UCS tests on the various mixtures are depicted in Figure 3. Its evident that the increase in the UCS of the mixtures correlates with the increase in the proportion of cement. Over mixtures of all cement contents (0.0, 0.5, 1.5, and 2%) the UCS increased from 61.4 kPa (0.0% cement) to 493.4 kPa (2% HE cements). These finding are consistent with previous studies from other authors (Belem et al., 2000; Fall et al., 2008; Hamberg et al., 2015). However, for the same mixtures and cement proportions, the compressive strength decreased with increasing muscovite percentage (9.5,12.5, and 15.5%). This demonstrates the negative impact of phyllosilicates on the development of UCS in cement-based mixes. Similar adverse effects of muscovite have been observed by other authors (Benzaazoua et al., 2010; Cepuritis et al., 2014; Loorents et al., 2007; Miskovsky, 2004).

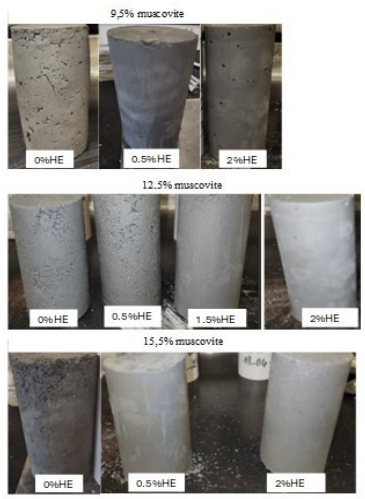

Figure 3. Effect of cement and muscovite on UCS development.

Physical and chemical properties of leachate

Analytica results of physical and chemical parameters (pH, Eh, EC) are presented in Figure 4. Results show that parameters (pH, Eh, EC) improved gradually after each wet-dry cycle, especially after the addition of 2% cement. This behaviour was observed by other authors (Deschamps et al., 2009b; Hadimi et al., 2016). The pH values increased from 6.3 to 7.8 for unamended tailings and from 7.40 to 8.6 for tailings amended with 2% HE cements for all mixes (9.5, 12.5 and 15.5% muscovite). The variation in pH values observed with 0.5% cement proportions could be attributed to the rapid desaturation of the amended tailings, potentially leading to oxidation of the tailings and subsequent generation of acidity. This highlights the importance of cement content in achieving predictable and consistent results in tailings stabilization.

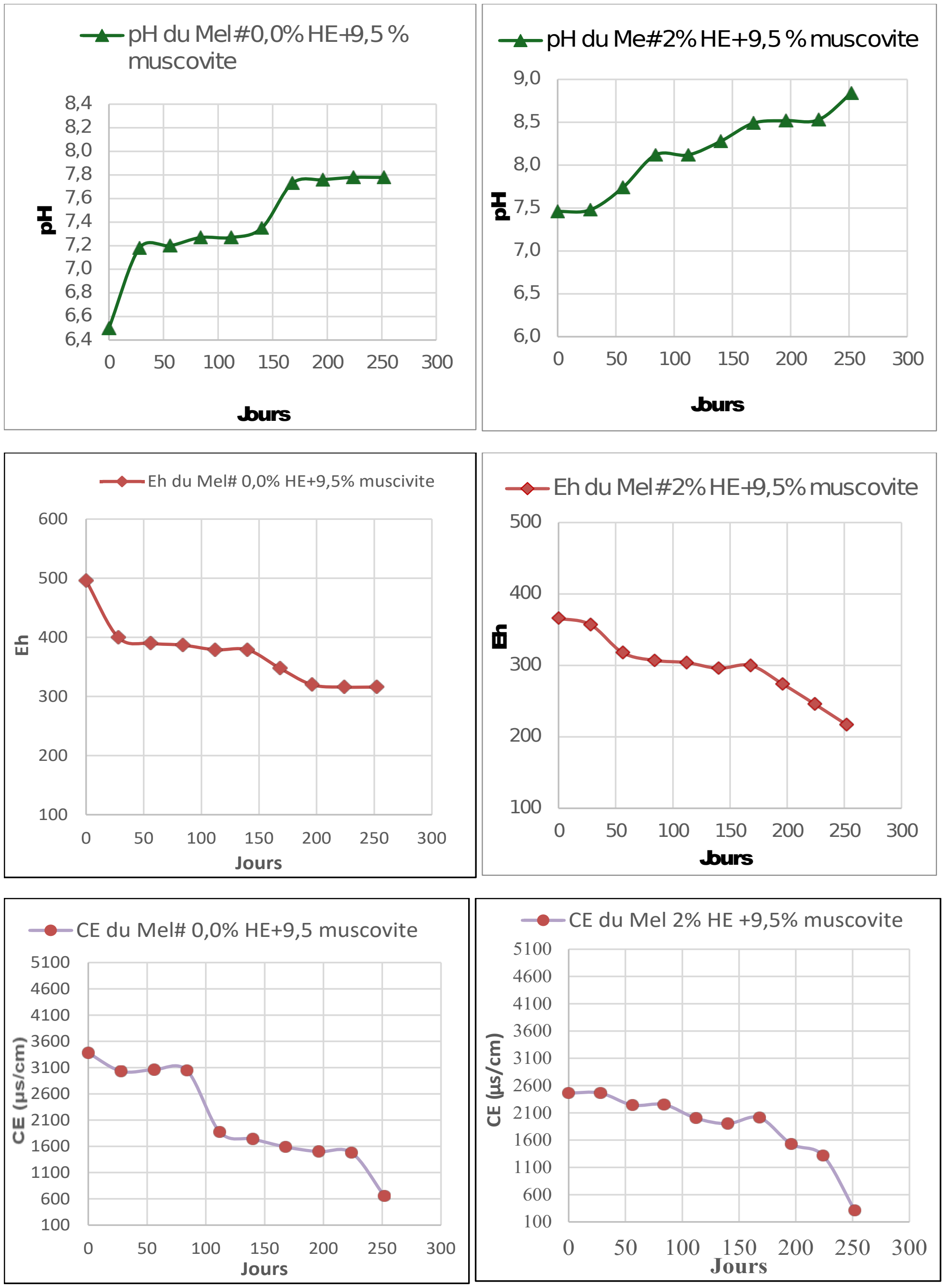

Figure 4. Evolution of physical and chemical parameters (pH, Eh, CE) as a function of % cement and number of wet-dry cycles.

Evolution of water retention properties

The Air Entry Value (AEV) of all mixtures was determined on the water retention curves (CRE), using the tangent method (Fredlund et al., 2012) (Figure 5). Values obtained are shown in Table 2.

Table 2 Air Entry Value (AEV) for the amended tailings

Mix		AEV(Kpa)
% cement HE	% muscovite	
0	9.5	10.2
2		11.3
0	12.5	10.5
1.5		10.3
2		10.8
0	15.5	10.8
2		10.7

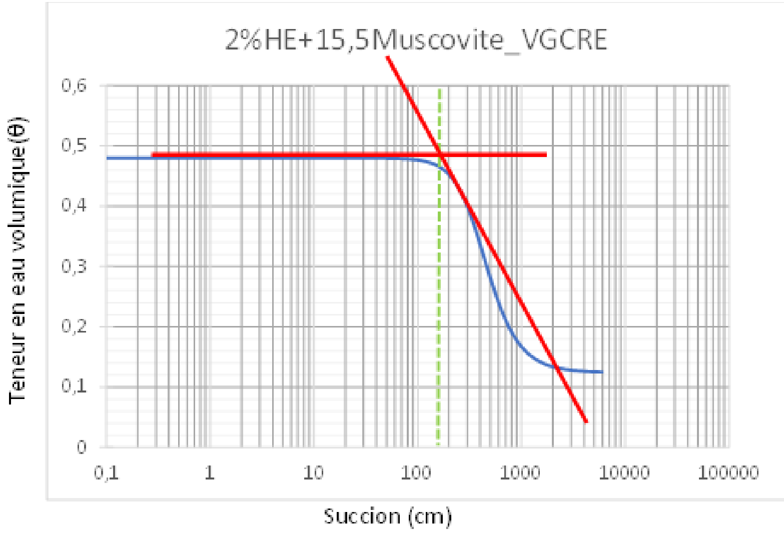

Figure 5. Retention curve measured and fitted using van Genuchten's RETC model.

Results in Table 2 demonstrate that the incorporation of muscovite led to a marginal increase in AEV, with an increase of 3 kPa observed (30 kPa to 33 kPa rise). This increment could be deemed negligible considering potential evaluation method errors. However, the addition of cement resulted in a notable rise in AEV. Specifically, for muscovite proportions of 9.5, 12.5, and 15.5%, the AEV increased from 30 kPa to 56 kPa, from 31.5 kPa to 40 kPa, and from 33 kPa to 48 kPa, respectively.

Assessment of freeze-thaw effects on saturated hydraulic conductivity of CC and UC tailings containing phyllosilicates (muscovite)

Results of the saturated hydraulic conductivity measurements (k_{sat}) are presented in Table 3.

Table 3. Permeability and freeze-thaw test results.

Mel# (%)		Evolution of k_{sat} as a function of the number of freeze-thaw cycles						
Ciment (HE)	Muscovite	Cycle 0	Cycle 2	Cycle 4	Cycle 6	Cycle 8	Cycle 10	Cycle 12
		k_{sat} (m/s)						
0.0	9.5	8,33E-08	1,10E-07	1,39E-07	1,58E-07	1,73E-07	1,94E-07	1,98E-07
0.5		3,41E-08	7,53E-08	9,49E-08	1,09E-07	1,16E-07	1,23E-07	1,27E-07
2		2,33E-08	4,93E-08	7,28E-08	7,75E-08	7,86E-08	8,20E-08	8,74E-08
0	12.5	8,22E-08	9,98E-08	2,03E-07	2,39E-07	3,00E-07	3,45E-07	3,94E-07
0.5		8,24E-08	9,99E-08	1,45E-07	1,77E-07	1,89E-07	2,21E-07	2,44E-07
1.5		1,57E-07	2,22E-07	2,84E-07	2,91E-07	3,05E-07	3,53E-07	3,84E-07
2		2,21E-08	5,97E-08	8,93E-08	9,43E-08	1,34E-07	1,53E-07	1,57E-07
0	15.5	8,13E-08	9,95E-08	2,14E-07	2,84E-07	3,06E-07	3,72E-07	4,03E-07
0.5		5,56E-08	7,87E-08	1,33E-07	2,41E-07	2,62E-07	3,26E-07	3,52E-07
2		3,24E-08	5,76E-08	9,98E-08	2,02E-07	2,12E-07	2,98E-07	3,02E-07

Freeze-thaw results show an increase in k_{sat} (m/s) of an order of magnitude ($8,33 \times 10^{-8}$ to 1.03×10^{-7} and 8.24×10^{-8} to $1,12 \times 10^{-7}$) respectively in Cycle 2 for the 0.0% HE + 9.5% muscovite and 0.5% HE + 12.5% muscovite mixtures. A slight increase of k_{sat} was observed (2.33×10^{-8} to $8,74 \times 10^{-8}$) throughout the test period (Cycle 12) for the 2% HE+9.5% muscovite. It should be noted that the 1.5% HE + 12.5% muscovite-bearing mixture was the only one to start with a higher k_{sat} (1.57×10^{-7} to $3.64\ 10^{-7}$), but it did not show any major variation. The high k_{sat} of the 0.0% HE+15.5% muscovite could be attributed to its particle size, as finer materials tend to be less permeable (Fall et al., 2009).

Conclusion

The findings of this study highlight the influence of phyllosilicates, specifically muscovite, on the mechanical and hydrogeochemical properties of solidified and stabilized tailings. Phyllosilicates were found to diminish UCS of the tailings. Freeze-thaw cycles led to a notable increase in the k_{sat} of cemented tailings containing < 2% cement. However, the addition of 2% HE cements greatly enhanced both mechanical (UCS increased from 61 Kpa to 493 kPa) and hydrogeochemical properties (k_{sat} decreased by an order of magnitude). As well, pH, Eh, and electrical conductivity (CE) exhibited considerable improvement. Indeed, the addition of the binder increased AEV, indicating an enhancement in the retention capacity of the mixes. This improvement suggests that the binder contributes to better water retention properties, which can be crucial for the overall performance and stability of the solidified and stabilized tailings. UCS measurements provided insights into the physical integrity of the various mixtures used in the study.

Overall, the study underscores the potential of solidification and stabilization techniques for tailings containing phyllosilicates. However, careful consideration of the cement percentage in relation to the proportion of phyllosilicates is essential for the effective application of this technique.

References

Aubertin, M. (2003). Sulphide reactivity within cemented paste bakfill: Oxygen consumption test results.

Aubertin, M., Mbonimpa, M., Jolette, D., Bussière, B., Chapuis, R., James, M. et Riffon, O. (2002b). Stabilité géotechnique des ouvrages de retenue pour les résidus miniers: problèmes persistants et méthodes de contrôle. Dans. Défis & Perspectives: Symposium.

Barast, G., Benzaazoua, M., Maqsoud, A., Bussière, B. (2014). Long term hydro-geochemical behaviour of surface paste disposal in field experimental cells. Dans. Proceedings of the Conference Canadienne de Ge'otechnique, GeoRegina, CD-Rom, Regina, Slovakia.

Belem, T. et Benzaazoua, M. (2008b). Design and application of underground mine paste backfill technology. Geotechnical and Geological Engineering, 26(2), 147-174.

Benzaazoua, M., Belem, T., Ouellet, S. et Fall, M. (2003). Utilisation du remblai en pâte comme support de terrain. Partie II: comportement a court, a moyen et a long terme. Proceedings of Apres-mines.

Benzaazoua, M., Fall, M. et Belem, T. (2004a). A contribution to understanding the hardening process of cemented pastefill. Minerals engineering, 17(2), 141-152.

Benzaazoua, M., Marion, P., Picquet, I. et Bussière, B. (2004c). The use of pastefill as a solidification and stabilization process for the control of acid mine drainage. Minerals engineering, 17(2), 233-243.

Bussière, B. (2007). Colloquium 2004: Hydrogeotechnical properties of hard rock tailings from metal mines and emerging geoenvironmental disposal approaches. Canadian Geotechnical Journal, 44(9), 1019-1052.

Bussière, B., Aubertin, M., Zagury, G. J., Potvin, R. et Benzaazoua, M. (2005). Principaux défis et pistes de solution pour la restauration des aires d'entreposage de rejets miniers abandonnées. Dans. Proceedings of the Symposium.

Chen, G., Shah, K. J., Shi, L., Chiang, P.-C. et You, Z. (2019). Red soil amelioration and heavy metal immobilization by a multi-element mineral amendment: performance and mechanisms. Environmental Pollution, 254, 112964.

Eagle, A. (2021). Rapport sommaire de 2021 sur la gestion des residus.

Fall, M., Adrien, D., Célestin, J., Pokharel, M. et Touré, M. (2009). Saturated hydraulic conductivity of cemented paste backfill. Minerals engineering, 22(15), 1307-1317.

Godbout, J., Bussière, B., Aubertin, M., Belem, T. et Benzaazoua, M. (2004). Évolution des propriétés de rétention d'eau des remblais miniers cimentés en pâte durant le curage. Dans. Proceedings of the 57th Canadian Geotechnical Conference and the 5th joint CGS-IAH Conference.

Hadimi.I. (2014). Étude du comportement hydrogéochimique à long terme d'un dépôt de rejets miniers sulfureux et des effets d'amendements cimentaires: simulations expérimentales au laboratoire [École Polytechnique de Montréal].

Hadimi, I., Mostafa, B., Maqsoud, A., Bussière, B. (2016). Effect of cementitious amendment on the hydrogeological behavior of a surface paste tailings' disposal. Innovative Infrastructure Solutions, 1(1), 1-15.

Kumpiene, J., Lagerkvist, A. et Maurice, C. (2008). Stabilization of As, Cr, Cu, Pb and Zn in soil using amendments–a review. Waste management, 28(1), 215-225.

Létourneau, M. (2012). Effet du gel et du dégel sur les propriétés mécaniques et physiques des sols argileux.

Lwin, C. S., Seo, B.-H., Kim, H.-U., Owens, G. et Kim, K.-R. (2018). Application of soil amendments to contaminated soils for heavy metal immobilization and improved soil quality—A critical review. Soil science and plant nutrition, 64(2), 156-167.

Ma, L.-H., Chen, J., Zhao, Y.-F., Zhang, C., Liu, R. et Ren, S. (2022). Water Content and Bedding Angle Effects on the Mechanical Properties and Micro-/Macro-Failure Mechanism of Phyllite. Arabian Journal for Science and Engineering, 1-19.

Maqsoud, A., Bussière, B., Aubertin, M. et Mbonimpa, M. (2012). Predicting hysteresis of the water retention curve from basic properties of granular soils. Geotechnical and Geological Engineering, 30(5), 1147-1159.

Marques, A., Oliveira, S., Paes, B., Paes, I. et Coelho, A. (2020). Evaluation of the Liquefaction Susceptibility of Filtered Iron Ore Tailings from the Iron Quadrangle (Brazil). Dans. Paste 2020: 23rd International Conference on Paste, Thickened and Filtered Tailings.

Newman, P., White, R. et Cadden, A. (2001). Paste, the future of tailings disposal. Dans. Proceedings of the 2nd International Conference on Mining and the Environment, Skelleftea, Sweden.

Ouellet, S., Bussière, B., Mbonimpa, M., Benzaazoua, M. et Aubertin, M. (2006). Reactivity and mineralogical evolution of an underground mine sulphidic cemented paste backfill. Minerals engineering, 19(5), 407-419.

Ren, J., Vanapalli, S. K., Han, Z., Omenogor, K. O. et Bai, Y. (2019). The resilient moduli of five Canadian soils under wetting and freeze-thaw conditions and their estimation by using an artificial neural network model. Cold Regions Science and Technology, 168, 102894.

Segui, P., Safhi, A. e. M., Amrani, M. et Benzaazoua, M. (2023). Mining Wastes as Road Construction Material: A Review. Minerals, 13(1), 90.

Tyagi, S. et Annachhatre, A. P. (2023). A review on recent trends in solidification and stabilization techniques for heavy metal immobilization. Journal of Material Cycles and Waste Management, 1-25.