



An engineered cover system for mine tailings using a hardpan layer: A solidification/stabilization method for layer and field performance evaluation

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ABSTRACT

A cover system for mine tailings with a solidified layer (called an engineered hardpan) was developed in this study to reduce water infiltration, acid generation and sulfide oxidation. Hydrated lime and water-glass were used to produce calcium silicate, which can serve as a binder when constructing a hardpan layer. The compressive strength of each solidified/stabilized material was found to be sufficient in the lab, and the amounts of heavy metals were significantly reduced in chemical leaching tests. Various characteristics of tailings may affect the layer's mechanical strength early on, but a long curing period is capable of compensating for these effects. Heavy metals were stabilized as carbonate-bound phases and sulfide minerals were surrounded by calcium silicate matrix, thereby preventing further reaction. To evaluate the field performance of the system, a hardpan layer was installed on top of tailings on a pilot scale. Leachate with high salt content was generated in the tailings layer in the early stages of monitoring, but after approximately 6 months, the objective was achieved as the hardpan layer gradually stabilized. Notably, during the heavy rainfall season of the later monitoring stage, water infiltration was continuously prevented by the system.

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1. Introduction

Mine tailings are ground rock particles from which valuable minerals or metals have been extracted, and they are considered to be one of the most severe sources of acid drainage and heavy metal pollution in soil and water [1]. The management of acid-generating tailings is a primary concern for the reclamation of closed mines. Soil covers involving single or multiple layers are generally used to rehabilitate tailings disposal areas [2,3]. Various designs of cover systems with different materials have been suggested to prevent acid mine drainage and rainwater infiltration in tailings impoundments [4–7]. A previous study described the instrumentation system and site characterization procedures used to evaluate the performance of an engineered cover system placed on mine waste [3].

On the other hand, cemented layers within or on the surface of tailings deposits (so-called hardpans) form naturally and become zones of contaminant attenuation [8–10]. Sulfates, carbonates and secondary silicate minerals formed during the weathering process are the main cementing materials, and they reduce permeability and stabilize contaminants in hardpans. However, environmental

contamination can occur because the hardpans do not form homogeneously or cover the entire surface of tailings with a uniform thickness.

In this study, we use a hardpan layer as one of the protective layers in a mine tailings cover system. For this purpose, we developed a simple solidification/stabilization (S/S) method for the construction of hardpan on the tailings surface which should be easily applicable in the field, and a tailings cover system with hardpan was installed in the field to assess its performance for a relatively long period. Developing a solidification/stabilization method for tailings with binders other than ordinary Portland cement is another purpose of this study.

2. Engineered cover system with a hardpan layer

The cover system for mine tailings impoundments suggested in this study is a model wherein a hardpan layer is constructed on top of the tailings that is homogenous both in its properties and thickness, as illustrated in Fig. 1. Also, a capillary break layer composed of a fairly coarse material, such as gravel, can be placed to prevent pore water in the tailings from moving upward until the hardpan layer is stabilized. The final top layer is covered with soil for revegetation in the model. A constructed hardpan layer can limit acid leachate, rain water infiltration and sulfide mineral oxidation, and it can also reduce the thickness of soil cover. Column

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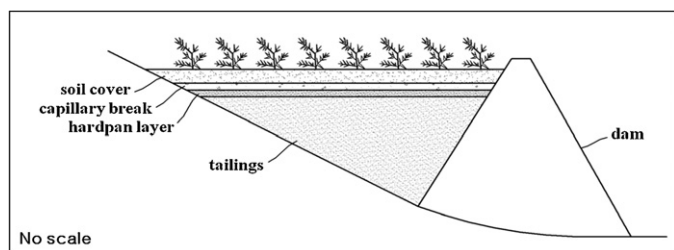
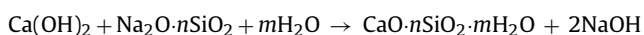


Fig. 1. Schematic diagram of the engineered cover system with a hardpan layer.

experiments have verified that hardpans that are situated between reactive tailings and cover material improve leachate water quality and reduce the rate of sulfide oxidation [11]. If a hardpan layer is sufficiently resistant to water and chemically stable, acid leachate is not generated, and a capillary break layer can be an option.

A hardpan layer can be built using a solidification/stabilization process. S/S technology often consists of incorporating industrial or mining wastes together with binding agents in a matrix with reasonably good cohesive properties, providing both encapsulation and chemical fixation of potentially mobile elements [12]. Various S/S processes for tailings have been suggested, mostly using ordinary Portland cement, and many studies have been conducted on potential reaction mechanisms and properties [12,13]. However, it is very difficult to apply any single method to different types of tailings due to their different characteristics, which include their acid generation potential, their size distribution and their mineral composition. This is why new and different methods need to be developed. Cement, even though it is the most commonly used binder, cannot be directly applied to high sulfide tailings because the resident acids and sulfate salts inhibit its chemical stabilization. Sulfate attack phenomena (precipitation of expansive hydrated sulfates) can happen leading to a deleterious effect on the strength gain and inhibition of cement hydration [14,15]. As binders for S/S processes, other inorganic binders such as pozzolans and geopolymers [16,17] are suggested as alternatives because cement manufacturing is an important CO₂-generating industry. However, these binders require a thermal treatment and a relatively long curing time. For field applications, simpler methods need to be developed.

Hydrated lime (Ca(OH)₂) is commonly used to prevent acid drainage and to stabilize contaminants [18,19]. However, heavy metals may be released during the transformation of lime to calcium carbonates by reaction with carbon dioxide [20], and the mechanical strength of the solidified tailings is not sufficient with only lime. Thus, in this study, waterglass was added as a silicate source to produce calcium silicate, which can serve as a binder. Waterglass can be reacted with hydrated lime at field temperatures to form calcium silicate gel or precipitate, as the equation below shows [21,22],



During this reaction, metals released from the tailings co-precipitate with the calcium silicate, and further sulfide mineral oxidation is inhibited by surrounding mineral particles. In field applications, the mixing ratio may need to be precise; nonetheless,

Table 1
Major chemical composition (wt.%) and mineralogy of the tailings samples.

| | SiO ₂ | Al ₂ O ₃ | Fe ₂ O ₃ | CaO | MgO | K ₂ O | Na ₂ O | TiO ₂ | MnO | S | Igloss | Mineralogy* |
|----|------------------|--------------------------------|--------------------------------|------|------|------------------|-------------------|------------------|------|------|--------|---|
| GP | 52.7 | 19.3 | 8.41 | 0.56 | 0.81 | 5.71 | 0.26 | 0.38 | 0.10 | 2.62 | 7.84 | Qtz, Mu, Kln, Py, Gp |
| JF | 43.0 | 5.20 | 19.2 | 18.2 | 1.48 | 0.63 | 0.22 | 0.35 | 4.44 | 6.31 | 3.31 | Qtz, Bt, Mag, Py, Asp, Pyr, Cal |
| JW | 40.1 | 4.42 | 22.3 | 15.8 | 1.47 | 0.47 | 0.21 | 0.32 | 4.80 | 8.50 | 7.32 | Qtz, Gp, Mag, Chl, Cal, Pyr, Py, Hed, Magne |

* Abbreviations: Asp; arsenopyrite, Bt; biotite, Cal; calcite, Chl; chlorite, Gp; gypsum, Hed; hedenbergite, Kln; kaolinite, Mag; magnetite, Magne; magnesiohornblende, Mu; muscovite, Py; pyrite, Pyr; pyrrhotite, Qtz; quartz.

Table 2
Results of de-ionizing water leaching tests (1:10, w/w) of the tailings samples (mg/L).

| | GP | JF | JW |
|----|-------|-------|-------|
| pH | 3.93 | 6.78 | 5.72 |
| Ca | 246 | 180 | 628 |
| K | 0.03 | 0.86 | 0.81 |
| Mg | 61.5 | 0.08 | 4.29 |
| Na | 5.11 | 3.99 | 4.62 |
| Si | 2.19 | 3.38 | 4.40 |
| Al | 26.9 | 0.16 | 1.63 |
| Fe | 116 | 0.61 | 10.9 |
| Mn | 53.6 | 6.58 | 161 |
| As | 0.29 | 0.17 | 0.18 |
| Cd | 6.30 | <0.01 | 0.29 |
| Co | 2.2 | <0.01 | 0.35 |
| Cr | <0.01 | <0.01 | <0.01 |
| Cu | 32.6 | <0.01 | <0.01 |
| Ni | 0.77 | 0.20 | <0.01 |
| Pb | 0.19 | 0.09 | 0.21 |
| Zn | 217 | 0.21 | 132 |

excess waterglass can form silicate gel by reacting with acid, resulting in additional binder effects, and excess hydrated lime can help to control the high pH conditions of the hardpan material for a longer period.

3. Experimental

3.1. Tailings characteristics

Tailings samples were collected from two abandoned base-metal mines (GP and JH mines) in Korea, which were chosen based on acid–base assessment test results for various tailings samples indicating high acid generation potential. At one site (JH mine), tailings samples were separated into two types, fresh (JF) and weathered (JW); thus, three kinds of samples (GP, JF, JW) in total were used in the study. From the major component analysis by XRF (Rigaku 3726A) (Table 1), the GP sample had lower sulfur content than the JF and JW samples, but it also had lower calcium content, resulting in low buffer capacity and high acidity. In de-ionized water leaching tests of the samples (Table 2), GP had the lowest pH value (3.93), and significant amounts of Fe, Al, Mn, Cd, Cu, and Zn were released into the solution. Regarding mineralogical composition (Table 1), pyrite was found in all samples, and various secondary minerals such as hedenbergite, magnesiohornblende and gypsum were found in the JW sample. For size distribution measured with a Malvern Mastersizer, the GP sample was composed primarily of silt (more than 95%; Fig. 2), and JW had finer size fractions than JF. JW showed a higher ignition loss content than JF (Table 1), another indication of the formation of finer secondary hydrate minerals in the weathered tailings.

3.2. Solidification/stabilization tests in the lab

To produce S/S specimens, well-dried tailings were mixed with hydrated lime (industrial grade, calcium hydroxide) at ratios of 5, 10, 15, and 20 wt.% using a mortar mixer, and liquid waterglass (industrial grade, SiO₂/Na₂O = 3.2) was added before mixing

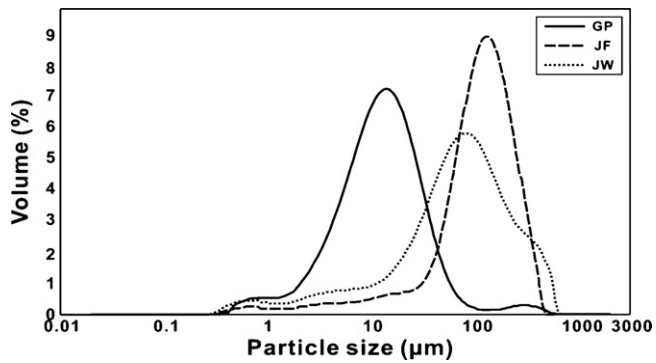


Fig. 2. Particle size distributions of the tailings samples.

again to obtain material with the appropriate plasticity. The mixture ratios of the tailings, hydrated lime and waterglass are given in Table 3, together with flow-test values for the mixed materials. The mixed materials were placed into cube moulds ($50 \times 50 \times 50$ mm) and vibrated for 30 s. After 24 h, the S/S monoliths were removed from the moulds and cured for 3, 7 and 28 days at room temperature with a cover of wet linen. For the case of GP with 5 wt.% hydrated lime, S/S monoliths were not produced due to insufficient mixing of finer fractions of the tailings. A higher portion of waterglass was used for GP, also due to the high proportion of fine fractions.

Cubic S/S specimens were used to determine the compressive strength using a universal strength tester according to the procedure of ASTM (American Society for Testing and Materials) C109. The toxicity characteristic leaching procedure (TCLP) as defined by the US EPA [23] was also applied to the original tailings and the S/S materials after the mechanical tests. All strength measurements and extraction analyses were performed in triplicate. Crushed samples of the S/S materials were used in sequential extractions and instrumental analysis to assess the stabilization of metals in the tailings. The sequential extraction procedure by Li et al. [24] was adopted to accommodate the high alkaline nature of the binders. Using a field emission-scanning electron microscope (FE-SEM, JEOL JSM-7000F) operated at an accelerating voltage of 15 kV, the microstructure and chemical compositions of reaction products in the S/S specimens were examined.

3.3. Pilot-scale field application

The JF and JW sampling site (JH mine) where reclamation work has occurred was selected for the field application of both engineered and simple soil cover systems for tailings. The tailings impoundment has been abandoned since the mine closure in 1986, and its surface was mostly dried except for sporadic rainfall

Table 3
Mixing ratios of tailings, hydrated lime and waterglass, and flow-test values.

| Tailings sample | Mixing ratio (wt.%) | | Liquid/Solid | Flow (%) |
|-----------------|---------------------|---------------|--------------|----------|
| | Tailings | Hydrated lime | | |
| GP | 90 | 10 | 0.95 | 183 |
| | 85 | 15 | 0.95 | 178 |
| | 80 | 20 | 1.00 | 187 |
| JF | 95 | 5 | 0.54 | 202 |
| | 90 | 10 | 0.65 | 206 |
| | 85 | 15 | 0.73 | 209 |
| | 80 | 20 | 0.73 | 195 |
| JW | 95 | 5 | 0.62 | 195 |
| | 90 | 10 | 0.62 | 188 |
| | 85 | 15 | 0.73 | 170 |
| | 80 | 20 | 0.77 | 176 |

events. At each cover installation, a bracket-shaped acrylic partition ($3 \times 3 \times 2.1$ (h) m) was placed into the tailings to a depth of 1.5 m to isolate the installations from each other, and the upper 60 cm section was constructed as a cover layer (Fig. 3). Other cover materials were also applied in the field application, and sites #1 and #7 are a simple soil cover and an engineered cover, respectively, in the plan view in Fig. 3. For the simple soil cover, soil was placed to a thickness of 60 cm. For the engineered cover system, a hardpan layer was installed to a thickness of 10 cm using the hydrated lime and waterglass S/S method, and the upper 50 cm was filled with soil. Tailings used for hardpan formation was collected from tailings stack set aside during surface leveling operation of the tailings impoundment before the pilot test started. Thus, the tailings were of mixed depths (less than 1–2 m) and relatively dried, which were used for hardpan formation without pre-treatment. To monitor the performance of the hardpan layer, a capillary break layer was omitted from the field application. For the hardpan layer installation, tailings were mixed with hydrated lime (10 wt.%), and waterglass was added at a L/S ratio of 0.3. Less waterglass was added than in the lab because of the higher moisture content of the field tailings. After thorough mixing, the mixture was placed on top of the tailings to a thickness of 10 cm, and it was treading using a plate vibrating compactor. At each cover system, VWC (volumetric water content)/TEMP/EC (electrical conductivity) sensors for measuring volumetric water content, temperature and electrical conductivity (ECH2O-TE, Decagon Devices) [25] were installed at depths of 50 cm below, 10 cm below and 30 cm above the boundary of the tailings and the cover layer (Fig. 3). A porous ceramic soil water sampler was installed in the middle of the soil layer to collect pore water from the surface. In addition, an automated weather station was installed to monitor climatic conditions at the field application site.

All field work was performed during 28–30 July 2009, and by early November 2010, climate and sensor data had been monitored for approximately 15 months. Periodically collected pore water samples were measured for pH and electrical conductivity in the field, and they were analyzed for relevant chemical components using an ICP-AES (Jobin Yvon 38) in the laboratory.

4. Results and discussion

4.1. Mechanical strength of S/S specimens

The compressive strength values for all the S/S specimens were greater than 0.345 MPa (50 psi), the ASTM recommendation for rigid pavement/foundation service conditions [26], and the strength values increased with increasing curing time (Fig. 4). Although the strength values showed little increase as the proportion of hydrated lime was increased, the values at 20 wt.% were particularly high for the JF and JW tailings after 7 or 28 days of curing. A maximum strength of 6.7 MPa was obtained for the JW tailings. In a comparison between samples, JW had higher strength values than JF early on (after 3 or 7 days of curing), despite little distinctive difference, and the strength values of GP were similar or slightly lower than those of JF. However, after 28 days of curing, the strengths of all the specimens had increased to about 3 MPa or their maximum value. In the case of GP, the early strength seemed to be relatively low, and it showed irregular variations during curing possibly due to poor mixing of the fine tailings fractions with the hydrated lime. By contrast, the greater strength of the JW specimen may originate from the contribution of secondary minerals and better size gradation (as shown in Fig. 2) in the weathered tailings. The universal increase in strength after 28 days of curing, however, indicates that these effects of size fractions and mineral composition were compensated for by longer

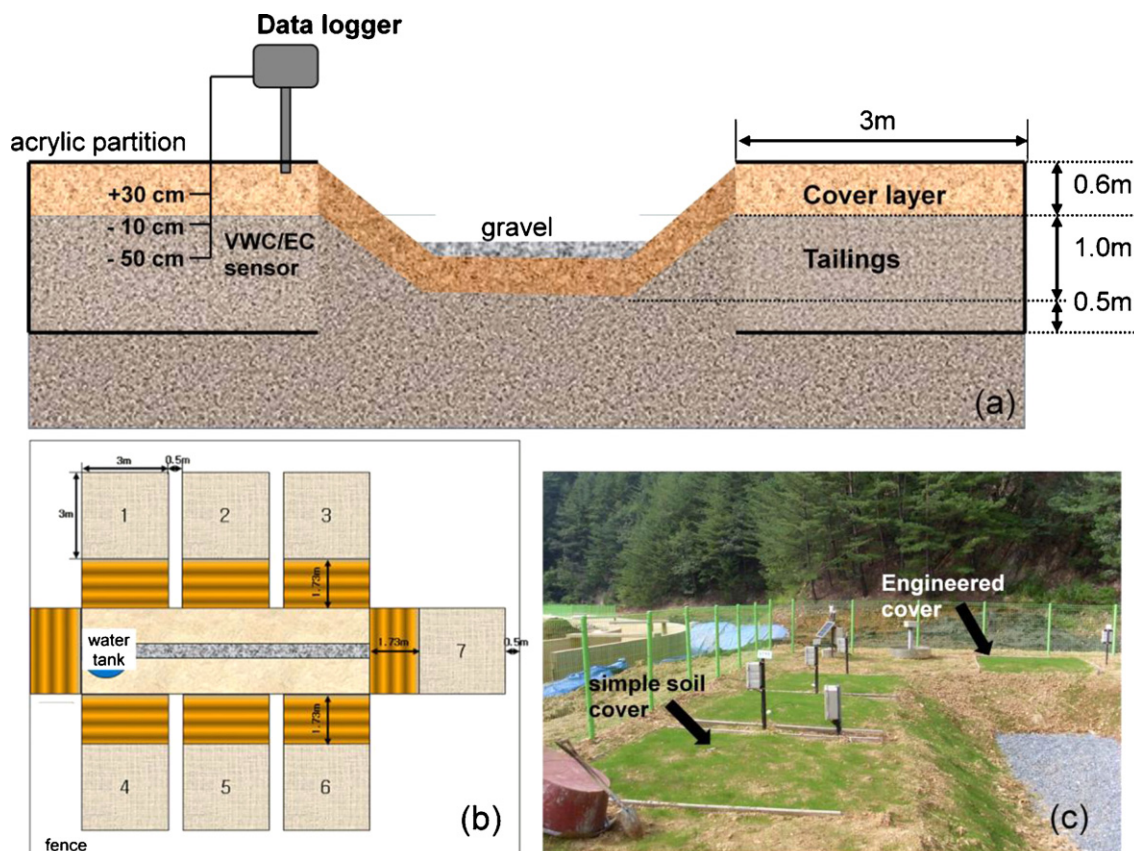


Fig. 3. Pilot-scale construction of tailings cover systems; (a) cross-section, (b) plan and (c) completed view.

curing. Accordingly, although early strength may be affected by the size distribution and the presence of secondary minerals in the tailings, the strength required for the physical performance of the hardpan layer can be obtained in field applications of the S/S method using hydrated lime and waterglass after sufficient curing time. Only in the case of very fine tailings, as shown in the GP results, should a preliminary test on the mixing with binders be necessary.

4.2. Stabilization of S/S specimens

The TCLP results indicate that the leached amounts of heavy metals, such as Cd, Cu, Pb, Zn, Fe, and Mn, were significantly lower with all the S/S materials than with the original tailings, indicating that the heavy metals were chemically stabilized. All the concentrations of Cd, Fe, Mn and Zn in the extracted solutions from S/S materials cured for 7 days are summarized in Table 4. In the case of S/S materials with 5 wt.% hydrated lime, certain quantities of Fe, Mn and Zn were found for the JF and JW tailings. However, the addition of 10 wt.% hydrated lime significantly reduced the amounts of leached metals. Based on the mechanical strength and TCLP results, 10 wt.% of hydrated lime is required to accomplish sufficient solidification/stabilization of tailings.

The chemical fractions of Cd and Zn in the original tailings and the S/S specimens with 10 wt.% hydrated lime are presented in Fig. 5. In the original GP tailings, the exchangeable fractions of Cd and Zn predominated at 56% and 68%, respectively, representing the phases most extractable by reaction of sulfide minerals under strong acidic conditions. Similarly, higher proportions of exchangeable metal fractions were found in the JW tailings than the JF. In JF tailings, which were relatively fresh, Cd and Zn were mostly present as sulfide and residual fractions, suggesting low

oxidation of the original sulfide minerals in the tailings. In the case of 10% S/S specimens, particularly for GP, the exchangeable fractions of the metals were significantly reduced, and instead, the carbonate-bound fractions were increased to 90% for Cd and 72% for Zn. In a study of the solidification/stabilization of industrial waste with Portland cement and fly ash [24], the sequential extraction

Table 4

TCLP results for tailings and solidified/stabilized (S/S) material (7 days of curing).

| Element | Sample | TCLP (mg/L) | | |
|---------|----------|-------------|-------|-------|
| | | GP | JF | JW |
| Cd | Tailings | 2.78 | <0.01 | 0.21 |
| | 5% S/S | – | <0.01 | 0.03 |
| | 10% S/S | 0.02 | <0.01 | <0.01 |
| | 15% S/S | <0.01 | <0.01 | <0.01 |
| | 20% S/S | <0.01 | <0.01 | <0.01 |
| Fe | Tailings | 2.66 | 4.58 | 25.9 |
| | 5% S/S | – | 1.50 | 2.05 |
| | 10% S/S | 0.19 | 0.27 | 0.20 |
| | 15% S/S | 0.25 | 0.07 | 0.01 |
| | 20% S/S | <0.01 | 0.37 | 0.09 |
| Mn | Tailings | 22.9 | 58.7 | 121 |
| | 5% S/S | – | 16.0 | 18.4 |
| | 10% S/S | 0.26 | 2.08 | 2.93 |
| | 15% S/S | 0.29 | 0.31 | 0.08 |
| | 20% S/S | <0.01 | 0.17 | 0.09 |
| Zn | Tailings | 95 | 6.54 | 83.2 |
| | 5% S/S | – | 2.75 | 16.0 |
| | 10% S/S | 0.26 | 0.17 | 0.95 |
| | 15% S/S | 0.20 | 0.04 | 0.04 |
| | 20% S/S | 0.02 | 0.06 | 0.03 |

–: no data.

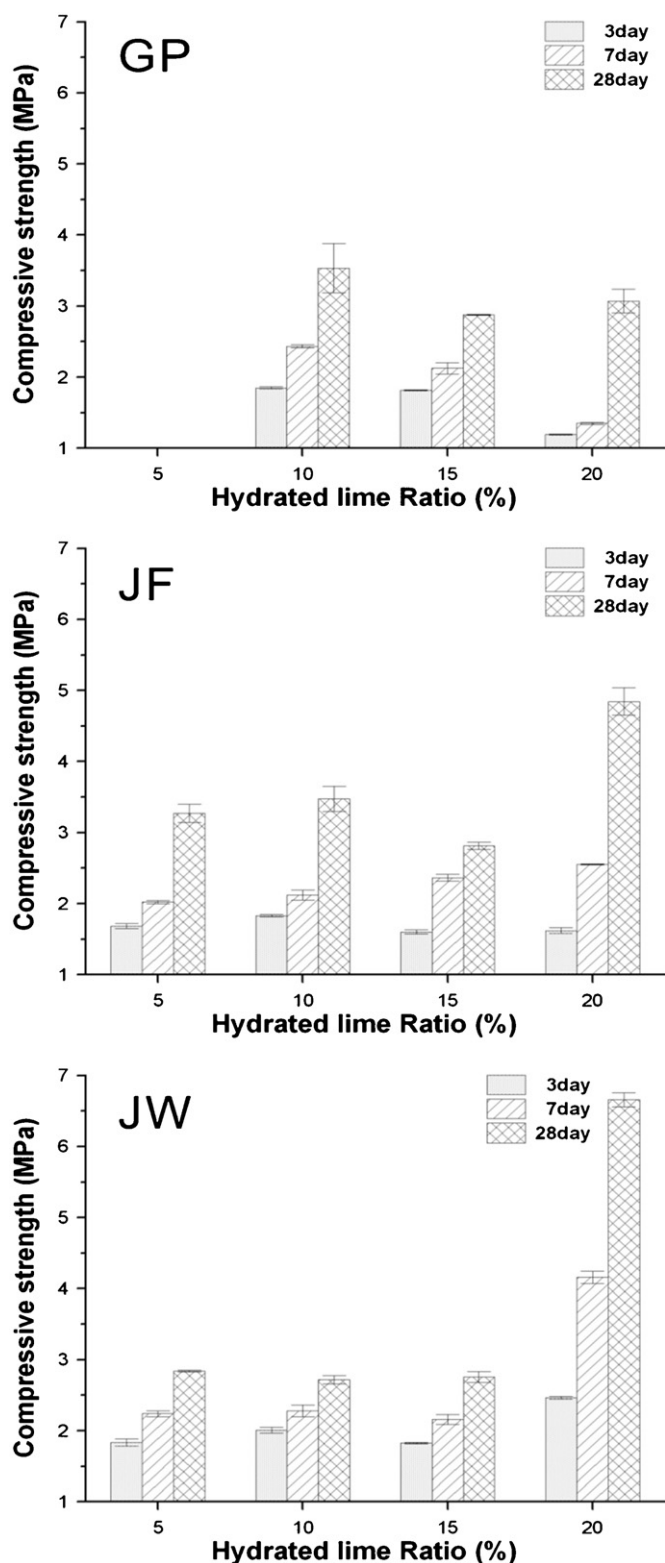


Fig. 4. Compressive strength of S/S materials according to mixture ratio and curing age.

of S/S materials showed that more than 80% of the heavy metals were associated with fraction 2 (bound to carbonates/specifically adsorbed, extracted with 1 M NaOAc at pH 5.0 with a solid to liquid ratio of 1:60), indicating that the heavy metals could exist in the S/S matrix as metal hydrated phases or metal hydroxides precipitated on the surface of calcium silicate hydrates, fly ash and

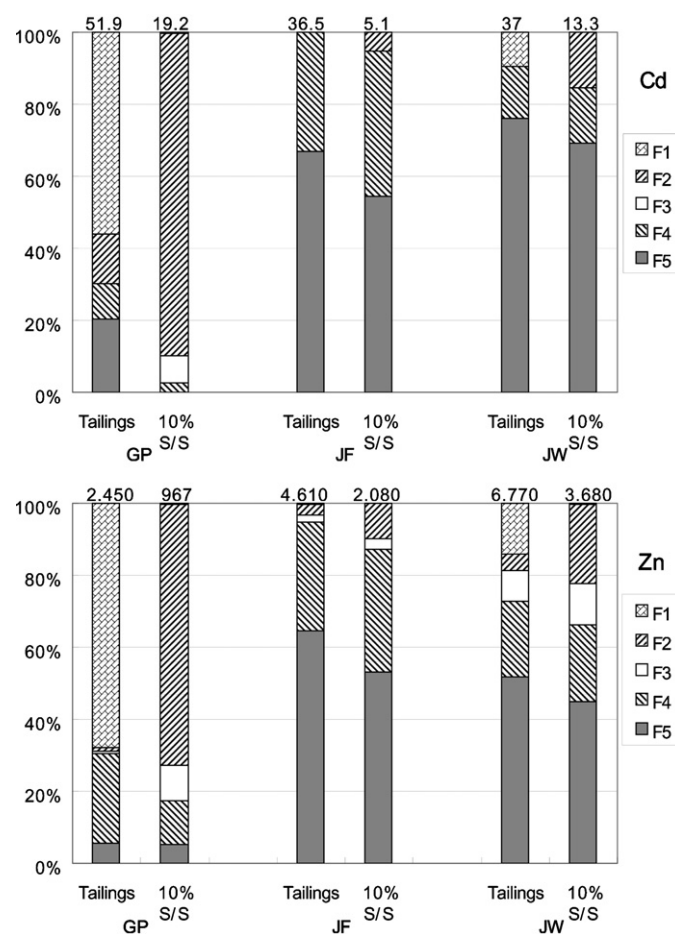


Fig. 5. Chemical fractionation of Cd and Zn in tailings and 10% S/S materials (F1: exchangeable, F2: carbonate-bound, F3: Fe/Mn oxides, F4: organic/sulfide, F5: residual. The total concentrations of Cd and Zn are given on the bars).

sludge particles. In this study, the sequential procedure of Li et al. [24] was adopted, and the exchangeable heavy metal fractions in the original tailings seemed to be transformed into metal hydrates or combined with calcium silicate hydrates under the alkaline solidification/stabilization conditions. The JW S/S materials showed similar results. However, in the case of JF, the residual fractions were about 10% lower than in the original tailings, and a slight increase in the sulfide fractions was also noted. Thus, the heavy metals in the fresh sulfide minerals in the tailings were changed into various secondary phases by reaction with the alkaline binder. Overall, the easily extractable heavy metal fractions in the tailings seemed to be stabilized as carbonate-bound phases, and their long-term stability is dependent on pH variations and solubility controlled processes.

From the FE-SEM analysis, the formation of glassy and gel-like matrix of calcium silicates was confirmed, and these played the role of binder in the S/S materials (Fig. 6a). Metal-containing sulfide minerals such as pyrrhotite and sphalerite, which appear bright in the back-scattered electron image in Fig. 6b, were surrounded by calcium silicate matrix, preventing further reaction. Some calcium silicate matrix contained small amounts of Fe and Al, indicating that the metals released during the solidification/stabilization process can combine into the binder. Virtually no isolated metal hydrate particles were found. The carbonate-bound fractions determined from the sequential extractions seemed to be combined phases with calcium silicate products.

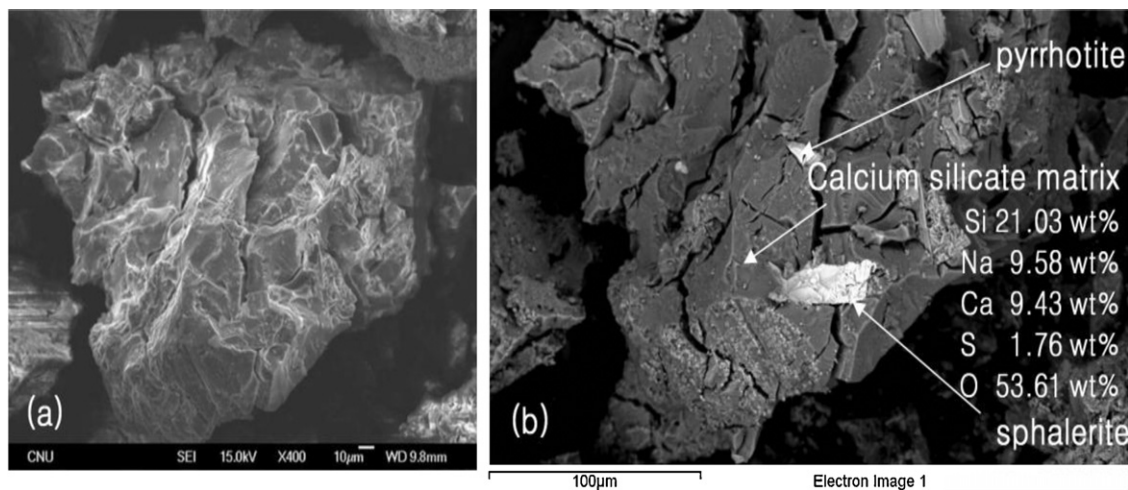


Fig. 6. SEM analysis of S/S materials: (a) secondary electron image and (b) back-scattered electron image.

4.3. Field performance of the hardpan layer

The variations of VWC by depth in the tailings and cover layers, as illustrated with daily precipitation data in Fig. 7, can be used to evaluate the infiltration of rain water into the system. Daily precipitation, which is the most important factor for the performance of a

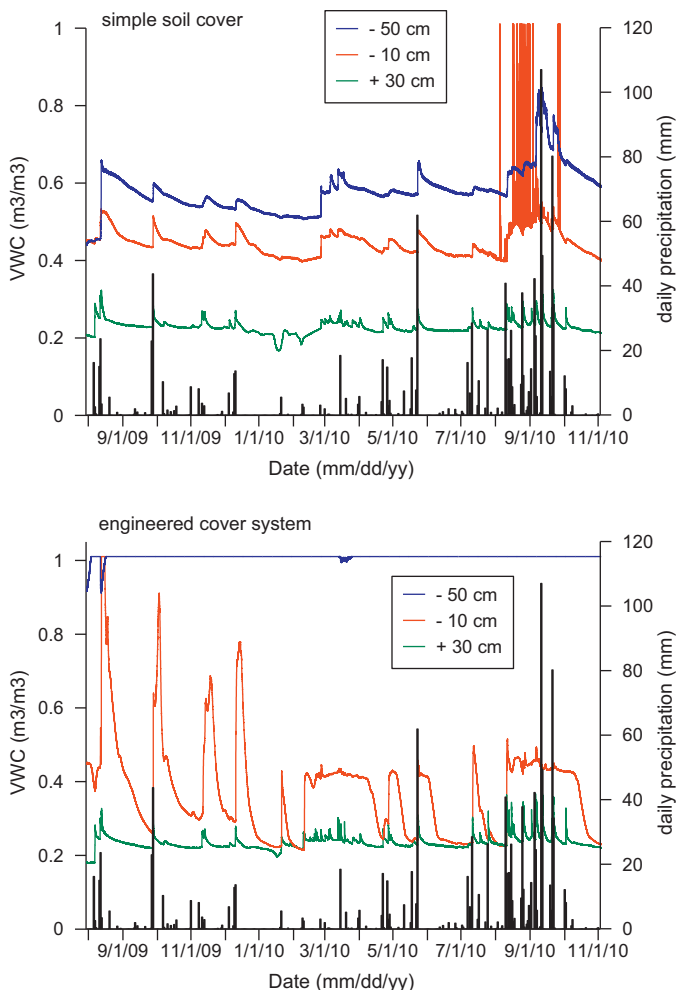


Fig. 7. Volumetric water content by depth in simple soil and engineered cover systems for mine tailings.

tailings cover system, had low values during the winter season, but events as high as 44 mm occurred at the end of September 2009 and 62 mm in mid-May 2010. During the later stage of the monitoring period (after July 2010), there were several intense rain events with a maximum value of 107 mm on 11 September 2010, and many days of more than 20 mm occurred. The monthly amounts were 96 mm for July, 193 mm for August and 378 mm for September, and the cumulative precipitation for this period (1105 mm) was 60% of the total.

With the simple soil cover system, VWC increased directly along with rainfall events and then decreased to its original level (the initial VWC value) at -10 cm and -50 cm below the tailings and soil cover boundary. These phenomena continued during the whole monitoring period, and the -10 cm depth was fully saturated during the intensive rainy season after August 2010, indicating free infiltration of rain water in the simple soil cover system. In the soil cover, the $+30$ cm depth showed similar variations. Unfortunately, the -50 cm depth in the engineered cover system was in a saturated condition with no VWC variation during the whole period. Dramatic increases in the -10 cm depth along with rainfall events and then declines to below the original level were observed in the early monitoring period. This may suggest that the hardpan was not fully hardened and condensed, resulting in the easy infiltration of rain water. Decreases of VWC to less than the original level indicate water absorption by the calcium silicate matrix in the hardpan layer. However, after approximately 6 months (February 2010), the sensitivity to rainfall events decreased, and the VWC values were around their original level, 0.4. During the intensive rainfall season, VWC did not significantly increase, indicating good water prevention performance of the hardpan layer, which was fully condensed. The $+30$ cm depth in the cover varied similarly compared to the simple soil cover.

Increases in EC in the simple soil cover system (Fig. 8) at the -10 cm depth indicate the reaction of tailings with infiltrated rain water and that leachate with high salt content moved downward, leading to the increase of EC at the -50 cm depth. The large increase of EC at the -10 cm depth after December 2009 seemed to be brought about by oxidation of the sulfide minerals in the tailings. Insignificant variations at the -50 cm depth may be due to the precipitation of secondary minerals during the downward movement of the leachate. These patterns were observed continuously with rainfall events, and in the later heavy rain season, large increases of EC were also observed at the -50 cm depth. The EC at each depth during the later stage of the monitoring period (after July 2010) was 0.64–1.59 at -50 cm, 0.36–2.02 at -10 cm, and 0.01–0.06 dS/cm at $+30$ cm. In the engineered cover system, large increases (to

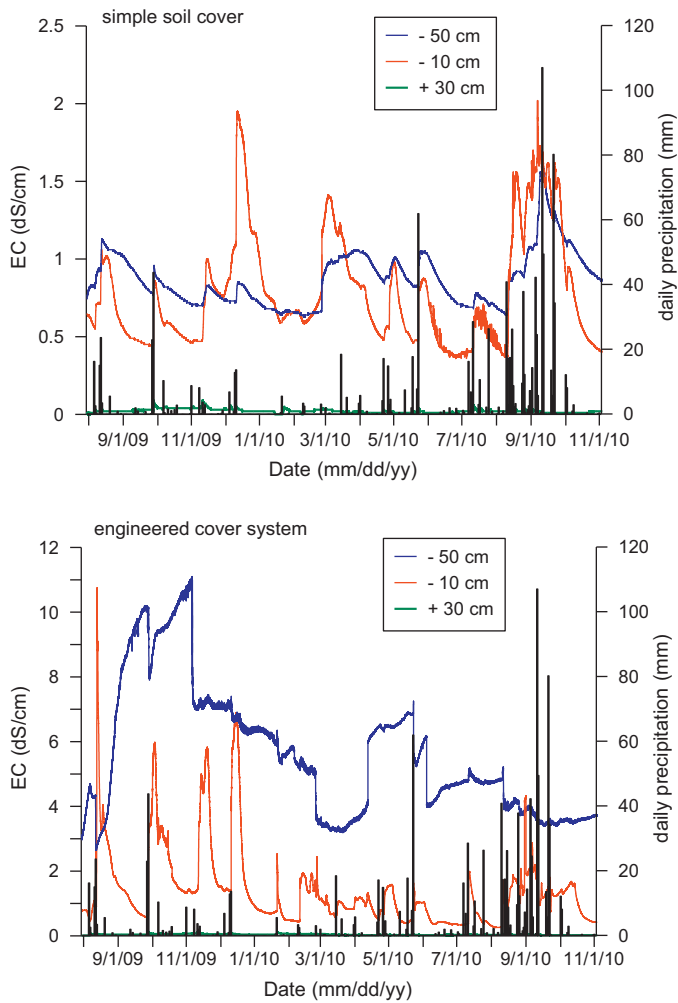


Fig. 8. Electrical conductivity by depth in simple soil and engineered cover systems for mine tailings.

10.8 dS/cm) at the –10 cm depth seemed to result from the dissolution of waterglass and/or secondarily formed Na-salts in the hardpan. At the –50 cm depth, increased EC may also come from downward movement of the leachate. Although these patterns were observed continuously, the formation of high salt leachate declined, and the influence on the lower layers was reduced after 6 months. This indicates that insoluble precipitates were formed and chemical stabilization with physical water prevention was achieved. In particular, despite the heavy rainfall during the later period, the variations of EC at the –10 cm depth were not great, and little change was observed at the –50 cm depth. The EC at each depth during the later stage of the monitoring period (after July 2010) was 3.39–5.23 at –50 cm, 0.26–4.33 at –10 cm, and 0.02–0.07 dS/cm at +30 cm, showing great reduction and stabilization compared to the early period.

Pore water samples were collected 6 times during the monitoring period, and their chemical characteristics are presented in Table 5. In the simple soil cover system, the water samples showed neutral pH (6.20–7.53) and relatively high levels of Ca (up to 316 mg/L) and Mg (up to 86.2 mg/L) with trace amounts of heavy metals. This result is due to the fact that the tailings originated from a scarn-type deposit, and therefore, the dissolution of carbonate minerals was dominant, thereby reducing the formation of acid leachate and heavy metal release. For the engineered cover system, strong alkalinity (pH 10.3–10.9) and high EC (1.86–23.5 mS/cm) were found in the pore water samples resulting

Table 5
Chemical components of pore waters periodically collected from the soil layer of each cover system.

| System | Date | pH | EC (mS/cm) | Ca (mg/L) | K (mg/L) | Mg (mg/L) | Na (mg/L) | Si (mg/L) | Al (mg/L) | As (mg/L) | Cd (mg/L) | Fe (mg/L) | Mn (mg/L) | Pb (mg/L) | Zn (mg/L) |
|-------------------|-------------------|------|------------|-----------|----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| Simple soil cover | 16 December 2009 | 6.99 | 2.39 | 316 | 6.8 | 86.2 | 11.5 | 8.4 | 0.00 | 0.23 | 0.00 | 0.38 | 4.33 | 0.05 | 0.09 |
| | 30 March 2010 | 6.20 | 1.00 | 182 | 3.5 | 57.6 | 9.8 | 5.5 | 0.02 | 0.14 | 0.00 | 0.09 | 0.63 | 0.09 | 0.09 |
| | 27 May 2010 | 6.92 | 0.99 | 141 | 7.5 | 41.7 | 11.9 | 8.6 | 0.01 | 0.04 | 0.00 | 0.09 | 0.24 | 0.00 | 0.17 |
| | 28 June 2010 | 7.53 | 0.55 | 163 | 5.0 | 39.9 | 20.6 | 18.6 | 0.03 | 0.23 | 0.00 | 0.07 | 0.21 | 0.11 | 0.11 |
| | 15 September 2010 | 6.96 | 1.17 | 191 | 6.3 | 42.8 | 19.1 | 20.3 | 0.00 | 0.26 | 0.00 | 0.02 | 0.30 | 0.01 | 0.06 |
| | 3 November 2010 | 7.01 | 0.95 | 164 | 6.0 | 35.0 | 11.0 | 14.1 | 0.01 | 0.10 | 0.00 | 0.01 | 0.21 | 0.00 | 0.05 |
| Engineered cover | 16 December 2009 | 10.9 | 23.5 | 65.5 | 18.7 | 1.6 | 6,110 | 138 | 0.00 | 5.35 | 0.00 | 0.18 | 0.00 | 0.44 | 0.00 |
| | 30 March 2010 | 10.3 | 9.65 | 43.3 | 8.8 | 0.9 | 2,430 | 118 | 0.06 | 2.26 | 0.00 | 0.07 | 0.01 | 0.06 | 0.09 |
| | 27 May 2010 | 10.7 | 3.24 | 21.0 | 3.5 | 0.7 | 685 | 272 | 0.06 | 0.75 | 0.00 | 0.10 | 0.00 | 0.00 | 0.07 |
| | 28 June 2010 | 10.6 | 2.33 | 8.0 | 3.1 | 0.4 | 750 | 320 | 0.10 | 1.11 | 0.00 | 0.23 | 0.00 | 0.03 | 0.05 |
| | 15 September 2010 | 10.3 | 1.86 | 9.3 | 2.2 | 0.9 | 463 | 225 | 0.00 | 0.79 | 0.00 | 0.01 | 0.06 | 0.00 | 0.02 |
| | 3 November 2010 | 10.6 | 2.10 | 5.9 | 2.5 | 0.5 | 593 | 399 | 0.03 | 0.57 | 0.00 | 0.02 | 0.03 | 0.04 | 0.02 |

from upward leachate affected by the hardpan. This interpretation is confirmed by the fact that high levels of Na and Si were found from the dissolution of Na-salts, which are byproducts of the solidification process. Lower levels of Ca and Mg than in the simple soil cover system indicate the formation of calcium silicate matrix in the hardpan. Under the alkaline conditions of the engineered cover system, arsenic reached up to 5.35 mg/L, apparently due to its characteristic geochemical nature. However, at the later period, both EC and arsenic levels declined, and the levels of Fe, Mn, and Zn were similar or less than those with the simple soil cover. As the hardpan layer became gradually stabilized, the purpose of preventing metal leaching was achieved.

Rain water infiltrates simple soil covers, and this causes the primary dissolution of soluble components in tailings and leads to further oxidation of sulfide minerals. The generation of large amounts of leachate with high salt levels may be inevitable, and it is necessary to construct additional water prevention and treatment facilities. In contrast, with the engineered cover system, physical solidification and chemical stabilization of the hardpan was achieved about 6 months after installation. The goal of using hardpan to reduce water infiltration, acid generation and sulfide oxidation can be accomplished in tailings impoundments. A capillary break layer may be needed to prevent upward movement of high salt leachate in the early period. During the field application in this study, the hardpan layer was exposed to air for only several hours before being covered with soil, and if sufficient curing time was allowed, the objectives could be achieved in less than 6 months. If the tailings contain high levels of sulfide minerals and strong acidity, neutralizing effects of alkaline leachate in the hardpan layer can be anticipated.

5. Conclusions

In the design of mine tailings impoundments, especially for tailings with high acid generation potential and heavy metal content, an engineered hardpan layer can reduce acid drainage and stabilize the contaminants. First, a relatively simple solidification/stabilization method using hydrated lime and waterglass was developed, and it successfully attained a certain degree of physical strength and reduced heavy metal leaching. The addition of 10 wt.% of hydrated lime to tailings and waterglass at a L/S ratio of about 0.6 produced appropriately solidified material at ambient temperatures. Certain characteristics of the tailings, such as particle size distribution and weathered state, may affect its mechanical strength early, but a long curing period compensated for these effects. Heavy metals were stabilized as carbonate-bound phases and sulfide minerals were surrounded by calcium silicate matrix, preventing further reaction. A hardpan layer installed on top of tailings in the field with a thickness of 10 cm physically prevented water infiltration and reduced the chemical generation of leachate with high salt content after about 6 months. Notably, during the heavy rainfall season of the later monitoring stage, water infiltration was continuously prevented by the system. Although pore water samples from the soil layer showed alkaline pH and high levels of Na and Si, the hardpan seemed to become gradually stabilized. Considering the strong alkaline properties of binders and site-specific field conditions, it is reasonable to apply this system to high-risk tailings (i.e. strongly acidic and with high sulfide levels).

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