

GCLS TO MITIGATE NATURAL CONTAMINATION FROM EXCAVATED ROCKS

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ABSTRACT

The adverse effects of acid rock drainage (ARD) on the environment are due to its low pH and subsequent release of metal, and could be intensified by climate change. Using a lining system in rock containment facilities is considered a cost-effective measure to prevent this problem from spreading. Factors that impact hydraulic conductivity and metal transport due to ARD permeation are discussed in this paper based on the authors' previous data. Moreover, authors' previous data was compared with results obtained by other researchers. The parameters that affect the hydraulic performance of GCLs can be classified into: type of bentonite, pH, and presence of metal type and concentration. Two relationships that predict the hydraulic conductivity were presented, one for granular and another for powdered bentonite. The retention of metals through GCLs is governed by pH, metals present in solution, as well as buffering capacity of the bentonite. Secondary sorption on ferrihydrite or gypsum of metalloids such as As, which cannot be sorbed by bentonite directly, also play an important role in the immobilization of contaminants.

Keywords: Geosynthetic clay liners, bentonite, hydraulic conductivity, acid rock drainage, sorption

INTRODUCTION

Natural contamination of soil and groundwater by metals and metalloids derived from waste rock and mine tailings has been the cause of serious health and environmental problems in many countries. Acid drainage, with subsequent heavy metal leaching (acid rock drainage, or ARD), is usually observed in countries located in geologically active areas, such as Japan (Katsumi et al. 2010), or in countries where mining is crucial for economic development but waste management is limited due to economic reasons, such as Peru.

ARD is produced when sulfide minerals, such as FeS₂ are oxidized in the presence of oxygen and percolating water. Although this phenomenon occurs naturally, mining and excavation for infrastructure construction accelerate the generation of ARD by increasing the quantity of sulfides exposed. Exposing these rocks to the atmosphere will destabilize them and, therefore, oxidation will occur through a variety of mechanisms. Sulfide oxidation

and host rock dissolution do not end until the mineral is fully weathered, which can take hundreds of thousands of years (Nordstrom 2009).

Climate change patterns have great influence on the water-chemistry of mine drainage. Prolonged dry periods and droughts will cause increases in the concentrations of heavy metals and sulfates, as well as acidity because the proportion of the surface runoff and shallow carbonate-buffered groundwater may decrease. Moreover, during wet season, intense rainstorms events will dissolve most of the soluble salts more rapidly leading to sudden increases in the concentration of acid and metals. Due to this, the toxic effect on the environment would be more severe without proper remediation or prevention systems (Nordstrom 2009). Therefore, remediation or prevention efforts that consider more extreme conditions than those found in the historical record become urgent in order to assure adequate supplies of water worldwide.

Conventional effluent treatment usually involves raising the pH and producing metal-rich precipitates

which are then settled and filtered out. Other remediation technologies have dealt with physical covers to reduce the production of acids by limiting the infiltration of water and oxygen (Barbour 1990, Simms et al. 2001). However, recent research has suggested that potentially toxic elements, such as As, are mobile under reducing conditions (Smedley and Kinniburgh 2002). Moreover, elements like molybdenum, manganese, zinc, cadmium, and arsenic can remain soluble at a pH near to and greater than 7. As a result, the mining industry is moving towards the separate disposal of hazardous materials in a lined containment facility (Lange et al. 2007). For sub-aqueous containment, Geosynthetic Clay Liners (GCLs) potentially represent an attractive means of controlling contaminants.

GCLs are thin (5 to 10 mm thick) factory-manufactured hydraulic barriers consisting of a layer of bentonite (granular or powdered), or another low-permeability material, sandwiched between two geotextiles or attached to a single polymer membrane and mechanically held together by needle punching, stitching, and/or gluing with an adhesive. GCLs maintain a low hydraulic conductivity over a range of conditions, possess high attenuation capacity toward contaminants (Lange et al. 2010a) and are simple to install: the panels (4-5 m in width and 30-60 m in length) are unrolled, overlapped and then covered with a geomembrane and/or soil (Ruhl and Daniel 1997). All these characteristics make GCLs cost-effective barriers for environmental protection in a wide range of applications, including recent applications in mining industry (Lange et al. 2010a, Shackelford et al. 2010, Hornsey et al. 2010). However, like all engineering materials, they need to be carefully and correctly placed, and protected from damage in order to maintain their performance for long time.

The GCLs' extremely low levels of hydraulic conductivity are attributed to the swelling of the bentonites contained in them. Since swelling is sensitive to chemicals, chemical compatibility becomes a critical subject when GCLs are applied to waste rock containment bottom liners. Many researchers have reported that permeation with chemical solutions will result in an increase in hydraulic conductivity. These effects can be explained by the changes in soil fabric and are categorized into (1) the dissolution of the clay particles and the chemical compounds resulting from strong acid and base solutions, (2) the restriction of the development of a diffuse double layer, and (3) the restriction of osmotic swelling for smectite clay (Katsumi 2010).

Besides mechanical properties of the GCLs, chemical changes and interactions that occur within the GCLs when permeated with solutions with low pH and high metal concentrations should be also taken into consideration. The large cation exchange

capacity (CEC = 80 – 100 meq/100 g) and surface area (800 m²/g) of sodium montmorillonites cause GCLs to have an affinity towards ions present in solutions. Many issues related to metal interactions with GCLs are often explained using data exclusively from sorption experiments on bentonite, performed under single or equimolar multi-metal permeants. However, some previous studies have shown that the chemical composition of solutions greatly affects the order in which metals are retained in GCLs (Lange et al. 2005, 2007). Thus, it can be inferred that the behavior of a single metal batch test cannot be simply extended or applied to ARD cases, because metal behaviors may differ when they are combined.

So, in order to understand to what extent hydraulic conductivity and metal transport are affected by ARD permeation and how the metals are retarded or retained into bentonite, this paper presents a thorough discussion using the author's previous data from long-term hydraulic conductivity experiments, as well as comparison with results of other previous research. Table 1 shows the parameters that are discussed in this paper.

Table 1 Effect of different parameters in the hydraulic conductivity and metal retention performance

Parameters	Hydraulic conductivity	Heavy metal retention
Type of bentonite	X	---
pH	X	X
Metal concentration and metal ion type	X	X
Short and long term performance evaluation	X	---
Bentonite buffering capacity	---	X
Metal precipitation	X	X

FACTORS AFFECTING HYDRAULIC CONDUCTIVITY

Numerous studies have been done on the impact of municipal solid waste (MSW) leachate on GCLs' performance using different kind of inorganic salt solutions such as NaCl, LiCl, CaCl₂, MgCl₂, as well as alkali solutions, acid solutions, MSW leachate, and sea water solutions (Katsumi et al. 2008, Petrov and Rowe 1997, Jo et al. 2005, Touze-Foltz et al. 2006). However, limited research has been conducted on the impact of ARD in GCLs' performance (Lange et al. 2010a, Shackelford et al. 2010, Hornsey et al. 2010).

Using GCLs in waste rock containment facilities for materials with ARD generation potential may not be a simple matter of transferring common technology used in landfills due to the extreme ranges in leachate characteristics observed in ARDs,

in terms of acidity and heavy metal concentration, compared to MSW leachates. Gates et al. (2009) have reported that leachates of excessive ion strength (> 0.3 M), usually found in ARD cases, elevated temperatures (> 60 °C) and strong acid ($\text{pH} < 3$) or alkaline solutions ($\text{pH} > 12$) may have detrimental effects on the hydraulic conductivity of GCLs, lowering its barrier performance. Hornsey et al. (2010) stated that bentonite inside GCLs undergoes dissolution at extreme pH, pore structure and loss of gel at elevated salinity, and shrinkage at elevated temperatures.

Therefore, evaluation of the performance and chemical compatibility of GCLs with ARDs becomes necessary before their field application in order to ensure long-term performance and prevent groundwater pollution. The potential use of GCLs in waste rock containment with ARD generation potential can be judged in terms of hydraulic conductivity and metal immobilization. According to previous studies there are many factors that affect these parameters, such as low pH and high heavy metal concentrations; ARD composition and type of ions present (cations and anions); type of bentonite (Ca-bentonite, Na-bentonite, granular or powdered bentonite, and smectite content) used in the GCLs; hydraulic conductivity change over time due to clogging; metal competition; and ion uptake mechanisms (ion exchange and precipitation). These parameters will be discussed in this paper in order to study to what extent ARD solutions impact GCLs performance and to evaluate if some relationships between parameters found for MSW leachate apply or fit also to GCL-ARD cases.

Effect of Type of Bentonite

Bentonites are classified into sodium bentonites (Na-bentonites) and calcium bentonites (Ca-bentonites), depending on the dominant exchangeable cation that is present. Ca-bentonites are much more available worldwide than Na-bentonites. However, the latter is known to have the lowest permeability of any naturally occurring geologic material (Koerner and Koerner 2010). Therefore Ca-bentonite is usually activated with soda (sodium carbonate or sodium hydroxide) so that the primary calcium ions are exchanged with sodium ions (so-called active bentonite), decreasing the permeability to that of the naturally occurring Na-bentonite (Egloffstein 2001).

The swell index of Na-bentonite is associated with the presence of montmorillonite (smectite) and depends on the valence of the cations and the ionic concentration between the crystalline layers. If monovalent cations, such as Na^+ , are present in the interlayer region, numerous layers of water molecules are retained electrostatically. Thus, less mobile water is available for flow, the swell volume

is large, and the hydraulic conductivity is low. If polyvalent cations, such as Ca^{2+} , Mg^{2+} , and heavy metal ions, replace the Na^+ cations due to their higher charge, bentonite shrinks. This occurs because the volume of bound water decreases until the interlayer spacing reaches four layers of water molecules. Accordingly, a smaller fraction of the water will be bound, a larger fraction will be mobile, and the hydraulic conductivity would increase (Shackelford et al. 2010, Jo et al. 2001).

Previous research conducted by the authors (Naka et al. 2011) has reported a decrease in swell index of a powdered bentonite (Bentofix® NSP 4900) from 32 mL/2 g bentonite (deionized water) to 8.5 mL/2 g after ARD permeation ($\text{pH}=3$, $\text{EC}=1192$ mS/m). This decrease in swelling volume correlated with an increase in hydraulic conductivity of one order of magnitude (5.0×10^{-10} m/s) compared to the water permeation case (1.4×10^{-10} m/s) as shown in Fig. 1.

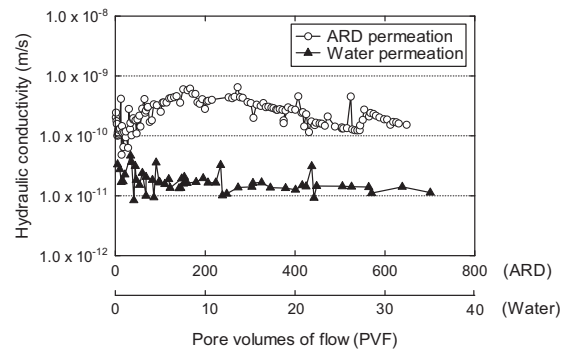


Fig. 1 Hydraulic conductivity of GCL a) permeated with distilled water and b) prehydrated and permeated with ARD. Data from Naka et al. (2011)

A relationship between hydraulic conductivity and free swell index for a powdered bentonite was found by Katsumi et al. (2007) for inorganic salts (Figure 2). This relationship was explored using 40 types of inorganic permeant solutions. According to the study, the permeability of a bentonite can be approximately given as a simple function of the free swell:

$$\log\left(\frac{y}{c}\right) = \exp(a(x-b)) \quad (1)$$

where x is the free swell index of the bentonite (mL/2 g solid), y is the hydraulic conductivity of the bentonite in m/s, a is -0.31, b is 8.69 mL/2 g solid, and c is 3.09×10^{-11} m/s, which is the hydraulic conductivity at x to infinity. These parameters are dependent on the effective stress confining the bentonite, which was fixed to 29.4 kPa. Applying this equation to the bentonite and artificial ARD system that was described above, for a swell index of 8.5 mL/2 g bentonite, the corresponding value of hydraulic conductivity of GCL is expected to be

3.6×10^{-10} m/s. This value is close to the experimental value (5.0×10^{-10} m/s) with 72% accuracy, which makes this relationship suitable even for ARD cases. Therefore, it constitutes a useful tool to easily estimate the barrier performance of GCLs, as free swell index can be evaluated much more rapidly than hydraulic conductivity.

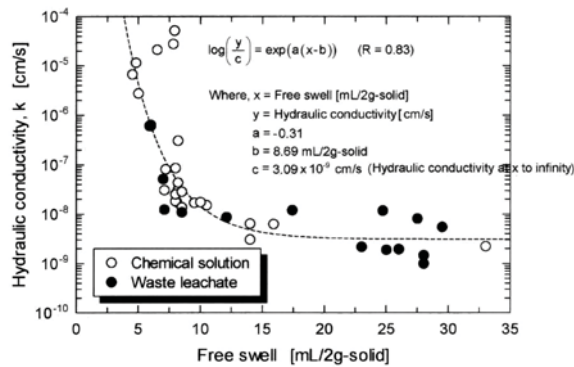


Fig. 2 Relation between the hydraulic conductivity and the free swell for GCLs confined at 29.4 kPa (Katsumi et al. 2007)

Another GCL classification can be made by the state of the bentonite used to produce GCLs: granular (aggregated) or powdered. Powder bentonites have a higher degree of processing than granular bentonites in terms of pulverizing, sieving, and size fractioning the mineral.

Previous research have shown that both GCLs are affected by chemical solutions, but that the powdered bentonite are more compatible than the granular bentonite, particularly with strong chemical solutions (Katsumi 2010). Vangpaisal and Bouazza (2004) observed that powdered bentonites generally hydrate uniformly from the outer surfaces of the GCL toward the center, resulting in rapid development of an effective seal against further water movement. In addition, pores of powdered bentonite are small (high specific surface area) even when the swelling is limited by acid or high metal concentration solutions and therefore lower hydraulic conductivity is observed (Katsumi 2010). On the other hand, in granulated bentonites, the outer surfaces of each individual granule wets first and therefore particles within aggregates wet slowly (Vangpaisal and Bouazza 2004). Besides, pores of the granules are not blocked due to the low swelling caused by aggressive chemicals and therefore higher hydraulic conductivity values are expected (Katsumi 2010).

Experiments conducted by Shackelford et al. (2010) on granular bentonite GCLs show that the hydraulic conductivity increases by three orders of magnitude after ARD permeation, compared to the water permeation case. Previous research done by the authors of this paper (Naka et al. 2011) using powdered bentonite have observed an increase of

one order of magnitude in hydraulic conductivity after permeation with an ARD with higher ionic strength, but slightly higher pH than reported by Shackelford et al. (2010). Information about the ARD composition, pH, ion strength, type of bentonite used and hydraulic conductivity results in both study cases are detailed in Table 2. From these results it can be said that the hydraulic conductivity of both granular and powdered bentonite are similar in the water permeation case. However, hydraulic conductivity values greatly differ after ARD permeation.

Table 2 Hydraulic conductivity comparison between prehydrated and non-prehydrated granular and powdered bentonite after ARD permeation. Data from Shackelford et al. (2010) and Naka et al. (2011)

	Shackelford et al. (2010)	Naka et al. (2011)
ARD composition	Al (31 mg/L) As (0.6 mg/L) Cd (4.3 mg/L) Ca (270 mg/L) Co (1.3 mg/L) Cu (51 mg/L) Fe (410 mg/L) Mg (1400 mg/L) Mn (180 mg/L) Ni (1.5 mg/L) SO ₄ (6900 mg/L) Zn (1800 mg/L)	Al (259.2 mg/L) Fe (4330.2 mg/L) Cu (86.9 mg/L) Zn (493.1 mg/L) As (49.1 mg/L) Pb (2.9 mg/L) K (31.8 mg/L) Na (413.9 mg/L) Ca (397.0 mg/L) Mg (214.0 mg/L)
pH	2.5	3.0
Ionic strength	350 mM	522 mM
Type of Na-bentonite	Granular	Powdered
<i>k</i> for water permeation	1.7×10^{-11} m/s	1.4×10^{-11} m/s
<i>k</i> for ARD permeation with prehydration	7.9×10^{-9}	1.1×10^{-10} m/s
<i>k</i> for ARD permeation without prehydration	3.9×10^{-8}	5.0×10^{-10} m/s

Similar to the relationship based on swell index to predict hydraulic conductivity, Kolstad et al. (2004) proposed an estimation of the hydraulic conductivity for non-prehydrated granular bentonite based on the ionic strength and the ratio of the monovalent and divalent cations:

$$\frac{\log K_c}{\log K_{DI}} = 1.085 - 1.097I + 0.03981I^2 RMD \quad (2)$$

where K_c is the hydraulic conductivity to the inorganic chemical solution, K_{DI} , the hydraulic conductivity to deionized water, I , the ionic strength (between 0.05 and 5 M), and RMD is the ratio of the concentrations of monovalent and divalent cations in

the permeant solution (for $RMD < 2.0 \text{ mM}^{1/2}$). The I and the RMD are calculated with the following equations:

$$I = \frac{1}{2} \sum_{i=1}^n c_i z_i^2 \quad (3)$$

$$RMD = \frac{M_M}{\sqrt{M_D}} \quad (4)$$

where c_i and z_i are the concentration of and the valence of the i th ion, respectively. M_M is the total molarity of monovalent ions and M_D is the total molarity of divalent cations in the solution. According to Shackelford et al. (2010) this correlation among k , I , and RMD proposed by Kolstad et al. (2004) provided reasonable estimates of k in most granular bentonite cases. Another important consideration of GCLs is the mineralogical composition of the bentonite, which in the end will determine the hydraulic performance. Guyonnet et al. (2009) have demonstrated that low smectite content results in a higher hydraulic conductivity. For example, they observed a two-order of magnitude higher hydraulic conductivity when the smectite content was less than 30% in weight. Smectite content higher than 70% in weight may provide good barrier performance in terms of hydraulic conductivity.

Effect of pH

It can be assumed that in general, $\text{pH} < 3$ will have detrimental effects on GCLs performance mainly due to dissolution of smectite (Gates et al. 2009). Alumina in the octahedral layers of the montmorillonite can be dissolved by hydrolysis, resulting in exchange of Al^{3+} for Na^+ in the exchange complex and a decrease in the volume of bound water (Norrish and Quirk 1954).

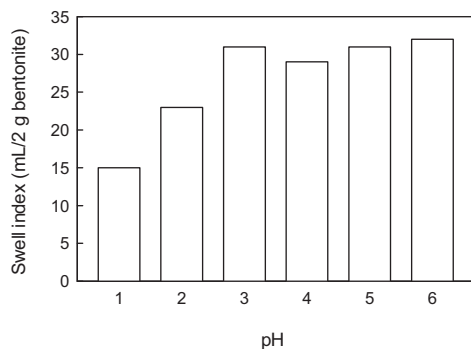


Fig. 3 Swell index at different pH (water acidified using $\text{H}_2\text{SO}_{4(\text{cc})}$). Data from Naka et al. (2011)

The volume of bound water, discussed in the previous section, may also decrease due to destruction of the structure of montmorillonite. Naka et al. (2010) have reported that swell index was smallest (15 mL/2 g bentonite) in strong acid ($\text{pH} =$

1) solutions, but increased rapidly with increasing pH up to $\text{pH}=3$. Swell index was then approximately constant (30 mL/ 2 g bentonite) until the pH reached 6 (Figure 3). Similar results were obtained by Jo et al. (2001). Ruhl and Daniel (1997) have reported a two-order of magnitude increase in GCLs hydraulic conductivity values after $\text{pH} = 1$ solution permeation.

Effect of Metal Concentration and ARD Composition

When the concentration of cations in the bulk solution increases, water moves out of the interlayer region due to the gradient in free energy induced by the elevated concentration in the bulk pore water (Jo et al. 2001). Moreover, an ion exchange of monovalent sodium ions against high amount of bivalent ions present in ARDs may reduce the spaces between the silicate layers (Katsumi 2010), changing the surfaces of the clay minerals into a central bivalent cation layer.

As a consequence of the presence of aggressive drainages with high amounts of divalent or higher valence cations, a rapid increase in hydraulic conductivity will occur. Some studies suggest that this effect can be minimized if the first liquid to permeate the GCL is water (Shackelford et al. 2010, Katsumi 2010, Shan and Lai 2002). For example, Naka et al. (2011) have observed a five-fold reduction in the hydraulic conductivity value when the GCL was prehydrated with water before ARD permeation. Shackelford et al. (2010) have found a one-order of magnitude difference in water prehydrated and ARD permeated case compared to non-prehydrated and ARD permeated cases.

Effect of Short and Long Term Performance Evaluation

Short term hydraulic conductivity evaluations provides accurate hydraulic conductivity values until the equilibrium (usually based on the electrical conductivity ratio of the influent and effluent between 0.9-1.1) has been reached. However, the hydraulic conductivity of GCLs may change over time especially due to metal precipitation, as shown in Figure 1. According to this test which was run for 9 months, the hydraulic conductivity of the ARD permeated case increased over time, until around 150 PVF. After this point, it stabilized, reaching an average permeability value of $5.0 \times 10^{-10} \text{ m/s}$. Around 300 PVF it started decreasing again due to the effect of physical clogging, mainly attributed to iron precipitation (ARD with high Fe concentration).

A reduction in hydraulic conductivity values was also reported by Katsumi et al. (2008) for long-term evaluation (1 to 7 years) of hydraulic conductivity of GCLs permeated with high ionic strength (I) solutions (especially for $I > 0.5$).

Although limited studies have been done on long-term performance of GCLs permeated with ARD solutions, changes in hydraulic conductivity over time becomes an important issue, considering that GCLs show promise for long-term containments. Long-term performance analysis will allow prediction and understanding the phenomenon that will occur after some time of ARD permeation and its influence on the GCLs performance as lining systems in waste rock containment facilities.

FACTORS AFFECTING HEAVY METAL RETENTION

All ARD around the world are different in acidity and metal concentration. They usually represent a threat to groundwater and surface water at mining sites because of their extremely low pH and high metal content. The most common elements found in ARD from metallic mine wastes are sulfur, iron, copper, zinc, silver, gold, cadmium, arsenic, and uranium (Ripley et al. 1996).

Using GCLs, metals can be immobilized through many adsorption mechanisms which include cation exchange, surface complexation, surface-induced precipitation, surface co-precipitation, surface colloid formation, and diffusion into particle micropores (Xu et al. 2008). The main parameters affecting adsorption are pH, ionic strength, nature and concentration of competing cations, all of which are discussed in this paper. Although, based on the cation exchange capacity (CEC), bentonite has a limited metal buffering capacity, its low k value make bentonite a suitable material for waste rock containment facilities with potential of ARD generation.

Effect of Buffering Capacity

Bentonite shows permanent negative surface charge due to the isomorphous substitution of cations of charge +4 and +3 with cations of charge +3 and +2, respectively. Either type of substitution creates a -1 charge that is usually compensated by interlayer cations. Cations balancing the layer negative charges are exchangeable with different ones present in solutions through an ion exchange mechanism. However, bentonite also presents exposed layer edges (OH⁻) with variable surface charge depending on the pH. At pH above the point of zero charge, the layer edges will have a negative charge, contributing to cation adsorption (Petrangeli and Majone 2002).

Ion exchange processes in bentonite are equilibrium processes. The occupation of a cation exchanger depends on the kind and concentration of the cations available for the exchange. Furthermore, the size and the charge of the cations are important.

It is known that bivalent cations are more easily exchanged against monovalent cations than vice versa (Egloffstein 2001). This illustrates that for ARD solutions there is considerable potential to retain metals, although this potential is limited by the buffering capacity of the bentonite.

Effect of pH

The influence of pH on the adsorption of bivalent and trivalent metal ions (Cd, Cr, Cu, Mn, Ni and Pb) on Na-montmorillonite was studied by Abollino et al. (2003). They demonstrated that the adsorption of metals decreases with decreasing pH because at low pH (between 2.5 and 3.5), the hydrogen ion competes with the heavy metals towards the superficial sites. Besides, the silanol (Si-O⁻) and aluminol (Al-O⁻) groups are less deprotonated and hence they are less available to retain metals. Sorption of metals increases at intermediate pH over a relatively small range called the pH-adsorption edge. At high pH values, the metal ions showed high retention on bentonite (Bradl 2004).

Effect of Metal Ions

Abollino et al. (2003) have reported that at pH < 3.5 metals are adsorbed on Na-montmorillonite in the following order: $\text{Cu}^{2+} < \text{Pb}^{2+} < \text{Cd}^{2+} < \text{Zn}^{2+} <$

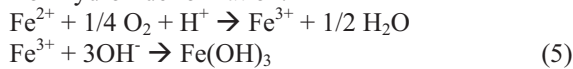
$\text{Mn}^{2+} = \text{Cr}^{3+} = \text{Ni}^{2+}$. However, a rule of metal

selectivity cannot always be predicted, especially in complex metal systems, because it depends on a number of factors, such as: the chemical nature of the surface at certain pH, the solid-liquid ratio, the pH at which adsorption is measured and the ionic strength of the solution. These factors all determine the intensity of competition by other cations for the bonding sites. All these variables may change the metal adsorption isotherms and it is necessary to consider all these factors to study a real bentonite/ARD system and effectively predict the fate of heavy metals in the environment. Preference or affinity is measured by a selectivity or distribution coefficient, K_d , extensively studied by Lange et al. (2007) through diffusion tests. They found significant attenuation of metals in GCLs from the measured diffusion profiles, where concentrations in the receptor reservoir remained very low for the duration of the tests. It helps to confirm that GCLs have potential use as a barrier material for the containment metal-bearing wastes.

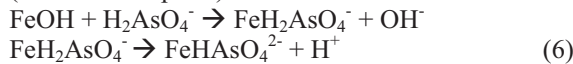
Effect of Gypsum and Ferrihydrite Precipitation

GCLs (bentonite) have high affinity toward cations, but relatively weak affinity for anions. Arsenic, which is an oxyanion, is one of the most toxic components present in ARDs, which suggest that special attention should be given to mobile metals that cannot be sorbed by GCLs. Previous studies done by the authors of this paper have shown that great amount of As was retained into GCLs mainly due to the high concentration of Fe present in ARD (Naka et al. 2011, Naka et al. 2010). Moreover, Lange et al. (2007) proposed an hypothesis of As retention due to the gypsum precipitation observed in XRD analysis after ARD permeation through GCLs. In case of As retention onto iron oxides, the following series of equations can be considered as the immobilization mechanism.

Iron hydroxide formation:



Anion adsorption onto iron hydroxide at pH < IEP (isoelectronic point):



Analysis using μXRD and μXRF techniques made by Lange et al. (2010b) on bentonite permeated with ARD showed that Fe-oxides also played a significant role in sequestering a range of metals such as Ni, Mn, and Zn. This increases the overall sorption capability of the GCL and confirms that solution composition is important in metal uptake behavior.

CONCLUSIONS

ARD composition around the world tends to be different in terms of acidity and metal concentration and, therefore, they constitute complex systems that negatively impact the performance of GCLs in waste rock containment facilities.

ARDs affect the hydraulic performance of GCLs because of their characteristic low pH (lower than pH 3) and presence of different metals and concentrations (especially the presence of bi-metals). The type of bentonite (Na-powdered bentonite with smectite content higher than 70% in weight show good performance) used to produce the GCL has an important role on their barrier performance.

The retention of metals present in ARD through GCLs are governed by the pH (higher retention at pH higher than 3.5), the metals that are present in the ARD (there are competition among metals which can be determined by the K_d), as well as the buffering capacity of the bentonite (determined by the CEC of bentonite). Secondary sorption on ferrihydrite or gypsum (formed through precipitation) of metalloids such as As which cannot be sorbed by bentonite directly also occur.

Determine the long term performance of GCLs permeated with different ARDs, as well as predicting the hydraulic conductivity values and the metal diffusion on GCLs by only having the composition of ARDs constitutes a challenge for future research.

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