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TECHNICAL ARTICLE

Hydraulic Conductivity of Geosynthetic Clay Liners Permeated with Acid Mine Drainage

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Abstract

We investigated the potential use of two geosynthetic clay liners (GCLs) as basal liners for acid mine drainage (AMD) from a coal gangue impoundment. One contained natural sodium bentonite (GCL-N), while the other contained sodium-activated bentonite (GCL-S). Chemical compatibility and the effects of effective stress and type of bentonite were evaluated. The test results showed that permeation with a synthesized AMD caused the hydraulic conductivity of the GCL-N and GCL-S to increase by 33 and 104 times, respectively, at an effective stress of 10 kPa. Under an effective stress of 50 kPa, the hydraulic conductivity of the GCL-N and GCL-S permeated with AMD was 1.1 and 6.6 times higher, respectively, than the values based on permeation with distilled water. However, when the effective stress was increased to 200 kPa, the AMD had no negative effect on hydraulic performance. The difference in hydraulic conductivity because of the type of bentonite was only observed at effective stresses of 10 and 50 kPa, with the GCL-N consistently having less hydraulic conductivity than the GCL-S. Thus, the detrimental effects of AMD permeation and low quality bentonite can be countered by applying high effective stress to the GCLs. Both GCLs types may be suitable as effective basal liners for coal gangue impoundments where relatively high stress can be applied.

Keywords Coal gangue · Bentonite · Effective stress · Swell

Introduction

Coal mining is a major industry in China, in terms of both economic importance and employment. However, coal mining activities also produce large amounts of solid waste, which in China is generally referred to as coal gangue (Wu et al. 2017). It was estimated in 2013 that the amount of coal gangue accumulated in China had reached ≈ 4.5–5.0 Gt and was still increasing at the rate of 0.37–0.55 Gt per year (China National Coal Association 2014). Historically in China, almost all coal gangues have been deposited behind a dam, directly onto the natural ground. In general, coal gangues contain various pyritic minerals (e.g. pyrite and marcasite), which can be oxidized when exposed to oxygen and water and then generate acid mine drainage (AMD). This AMD is characterized by low pH (<3.0) and high concentrations of contaminants, including metals, dissolved sulfate ions, and others (Qureshi et al. 2016; Sracek et al. 2010). AMD can migrate from the coal gangue into the surface water or groundwater around the waste piles. The uncontrolled release of AMD adversely affects the quality of the water systems and results in the loss of drinking water resources (Price and Wright 2016).

Disposal of coal gangue in engineered facilities (impoundment) with a basal liner that can minimize AMD migration into the groundwater is a viable choice. The basal liner is generally constructed with clay soils. However, suitable and economical clay soil resources cannot always be obtained in mining districts. Therefore, several mining companies are constructing basal liners for coal gangue impoundment with geosynthetic clay liners (GCLs).

GCLs are manufactured hydraulic liners that consist primarily of a thin layer of bentonite sandwiched between two geotextiles or glued to a geomembrane (Benson et al.

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2010; Bouazza 2002; Bradshaw et al. 2016; Egloffstein 2001; Petrov and Rowe 1997; Sarabian and Rayhani 2013; Scalia et al. 2014; Shackelford et al. 2000; Shan and Lai 2002). GCLs have several advantages over traditional compacted clay liners, including relatively low cost, ease of installation, occupying significantly less space and low hydraulic conductivity to water (Jo et al. 2001; Kolstad et al. 2004; Shackelford et al. 2010).

If GCLs are used in this way, an important issue that must be addressed is the long-term hydraulic performance of the GCLs in contact with the AMD. The hydraulic conductivity of GCLs that do not contain a geomembrane mainly comes from the sodium (Na) bentonite encased by the geotextiles. The hydraulic conductivity of Na bentonite permeated with water or relatively low ionic-strength liquids at low effective stress (10–20 kPa) is on the order of 1.0×10^{-11} m/s, which is significantly less than the maximum hydraulic conductivity typically allowed for waste containment liners (1.0×10^{-9} m/s). However, the hydraulic conductivity of Na bentonite can be changed by waste leachate, because waste leachate generally contains various multivalent cations (e.g. Ca^{2+} and Mg^{2+}), which can exchange with the native monovalent cations (Na^{+}) present in the Na bentonite, because of their higher charge. These exchange processes tend to contract the diffuse double layer and *c*-axis of bentonite, increasing the hydraulic conductivity of the GCLs.

Although numerous studies have been conducted to determine the effect of waste leachate on the hydraulic performance of GCLs, most of these studies have used leachate from municipal solid waste landfills as the permeant liquids (Bradshaw et al. 2016; Bradshaw and Benson 2014; Rauen and Benson 2008; Rosin-Paumier and Touze-Foltz 2012; Rubl and Daniel 1997; Shan and Lai 2002; Thiel and Criley 2005). To the author's knowledge, there is no published data on the impact of AMD from coal gangue impoundment on the hydraulic performance of GCLs.

AMD from coal gangue impoundment is a complex chemical solution; its characteristics are different from the leachate generated in municipal solid waste landfill. First, AMD generally has a lower pH relative to municipal solid waste leachate. AMD also has higher concentrations of soluble multivalent cations (e.g. Ca^{2+} and Mg^{2+}). A variety of field investigations have shown that the concentrations of Ca^{2+} and Mg^{2+} present in AMD can be as high as 1000 mg/L. Moreover, AMD generally does not contain suspended solids (including biologically active material) that can plug the flow paths within the bentonite and reduce the hydraulic conductivity of the GCLs. All these characteristics make AMD more aggressive than municipal solid waste leachate. So, the adoption of hydraulic conductivity test results from municipal solid waste leachate for application to AMD may not be appropriate. Accordingly, the aim of the present study was to assess the impact of AMD from coal gangue on the hydraulic performance of GCLs.

Materials and Methods

Geosynthetic Clay Liners

The two GCLs used in this study are commercially available from a GCL manufacturer in China. Except for the bentonite type, all of the other properties of the two GCLs are essentially identical. One GCL contains natural Na bentonite (GCL-N), while the other one was manufactured using Na-activated bentonite (GCL-S). Because of its lower price, Na-activated bentonite is widely used to manufacture GCLs in China. Both bentonites are granular and sandwiched between two polypropylene geotextiles, one woven and the other nonwoven, that are bonded by needle-punched fibers. The initial unconfined height of the two GCLs ranges from 5 to 6 mm, and the initial bentonite moisture content is about 9–12%. The bentonite content is about 4.5 kg/m^2 for the two GCLs. Results of X-ray diffraction reported by Dong et al. (2018) showed that the montmorillonite contents for the natural Na bentonite and Na-activated bentonite are 23% and 62%, respectively.

Permeant Liquids

Distilled water and a synthesized AMD were used as permeant liquids. The synthetic AMD was prepared in the laboratory based on AMD sampled from a creek in Guiyang city, Guizhou province, China, which receives drainage from several coal mine waste piles and is fairly representative of the AMD of southwestern China. The synthetic AMD was prepared by dissolving analytical grade metal sulfate or chloride salts in deionized (DI) water and adjusting the pH with sulfuric acid (H_2SO_4). The characteristics of the freshly prepared AMD are shown in Table 1.

Hydraulic Conductivity Tests

The hydraulic conductivity tests were conducted using flexible-wall permeameters with falling-headwater and constant tailwater elevation, and were generally consistent with ASTM D 6766 (ASTM 2012), D 5084 (ASTM 2010), and Scalia et al. (2014). The GCLs were trimmed to a nominal diameter of 101 mm, as described in ASTM D 6766 (ASTM 2012). A small amount of distilled water was applied along the perimeter of the GCL specimen using a squirt bottle to avoid bentonite loss. Following cutting, the initial thickness and weight of each GCL specimen were measured using a laboratory scale (± 0.1 g) and a caliper (± 0.01 mm). The initial thickness was measured at four different locations

Table 1 Chemical composition of synthetic acid mine drainage (AMD) used as permeant liquid

Parameter		Source compound	Value	
			Actual AMD[a]	Synthetic AMD
pH	–	H_2SO_4	2.49	2.5
Na^+	mg/L	NaCl	–	550
K^+	mg/L	KCl	–	35
Mg^{2+}	mg/L	$MgCl_2$	301.10	300
Ca^{2+}	mg/L	$CaCl_2$	52.00	50
Al^{3+}	mg/L	$Al_2(SO_4)_3{\cdot}18H_2O$	–	15
Fe	mg/L	$FeSO_4{\cdot}7H_2O$	256.00	250
Mn^{2+}	mg/L	$MnSO_4{\cdot}H_2O$	9.25	10
Cu^{2+}	mg/L	$CuSO_4{\cdot}5H_2O$	0.31	1.0
Zn^{2+}	mg/L	$ZnSO_4{\cdot}7H_2O$	2.28	2.5
Cl^-	mg/L	–	–	148
SO_4^{2-}	mg/L	–	–	2842
EC	mS/cm	–	3.25	5.0

[a]The actual AMD was sampled from a creek affected by the drainage from coal waste piles

along the GCL specimen, and the average value of the four measurements was used in the test. The total mass of the GCL specimen was measured using a balance (determined as the measured mass minus half of the mass of the distilled water used).

These specimens were then placed between filter papers and porous stones, and finally set on the base pedestal of the flexible-wall permeameters, after which the flexible-wall permeameters were assembled. The cell pressure lines were connected to a pressure control panel (pressure was provided by an air compressor) and the influent lines were connected to a gravimetric burette. An effective stress of 10 kPa pressure was then applied, and distilled water was introduced to the gravimetric burette and the influent lines to remove any air bubbles. The inflow valve on the flexible wall permeameter was left open, and the effluent valve was closed to allow the GCL specimens to hydrate. The GCL specimens were prehydrated with distilled water with no hydraulic gradient for approximately a week, as suggested by Rubl and Daniel (1997) and Jo et al. (2001). The prehydration process was intended to mimic soaking of the GCLs with potable water after deployment (Benson et al. 2008, 2010).

The hydraulic conductivity tests were run under effective stresses of 10, 50, and 200 kPa to simulate field scenarios where the GCLs will be subjected to a variety of stresses, ranging from low stress before disposal of coal gangue to very high stress after the impoundment has been filled with coal gangue. The tests were conducted in two stages. First, the GCL samples were permeated with distilled water to obtain a baseline hydraulic conductivity. Once the baseline hydraulic conductivity was obtained, the second stage was started by switching the permeant liquid to synthetic AMD. Permeation was initiated by opening the effluent valve and connecting the effluent lines directly to Teflon-coated sample bags. No backpressure was used so that the effluent could be conveniently collected for measurement of volume and electrical conductivity (EC) (Kolstad et al. 2004; Lee and Shackelford 2005). The hydraulic conductivity gradients used in the present study were ≈ 300, substantially higher than the 30 specified in ASTM D 5084 (ASTM 2010). However, hydraulic gradients ranging from 50 to 600 are typically used in measuring the hydraulic conductivity of GCLs, and the use of such high gradients generally does not significantly affect the testing results (Shackelford et al. 2000).

For the tests involving distilled water as the permeant liquid, the tests were terminated when the termination criteria specified in ASTM D 5084 (ASTM 2010) were met. According to ASTM D 5084 (ASTM 2010), the hydraulic conductivity test should be continued until equilibrium is established; i.e. the ratio of the inflow rate to the maintained outflow rate ranged from 0.75 to 1.25, and the variation of computed hydraulic conductivity was within ± 25% of the average value for at least four consecutive hydraulic conductivity measurements. For the tests involving AMD as permeant liquid, the tests were performed until the general termination criteria stipulated in ASTM D 6766 (ASTM 2012) were attained: the permeation was continued until at least two pore volumes of the permeant solution had passed through the GCL specimens and chemical equilibrium was established. Chemical equilibrium was considered to have been established when the ratio of the effluent to influent EC was 1.0 ± 0.1.

During the test period, the effluents of the GCLs were collected and measured periodically for volume and EC. After the permeation tests, the GCL specimens were removed from the flexible-wall permeameters, and their final thickness and weight were measured immediately using the same procedure as for testing the unused GCL specimens.

Free Swell Tests

To verify that the changes in hydraulic conductivity were caused primarily by the changes in swell behavior of the bentonite within the GCLs, free swell tests were conducted according to ASTM D 5890 (ASTM 2006), using both distilled water and AMD. Air-dried bentonite from a GCL was crushed with a mortar and pestle until 100% passed the 100 mesh U.S. Standard sieve and 65% passed the 200 mesh U.S. Standard sieve. Then, the bentonite was oven dried at 105 °C for 24 h. Approximately 90 mL of distilled water or AMD solution was added to a 100 mL graduated cylinder. Subsequently, 2.0 g of the oven-dried bentonite was dusted over the entire surface of the testing liquid in the graduated cylinder in 0.1 g increments over a period of ≈ 30 s. To allow the bentonite to wet, hydrate, and settle to the bottom of the graduated cylinder, the duration between increments was set at 10 min. Afterwards, additional testing liquid was added to the graduated cylinder to rinse the adhering particles from the sides of the cylinder into the liquid and to reach a final volume of 100 mL. The swell volume (mL/2 g) was recorded after 24 h, which was sufficient time to establish chemical equilibrium (Jo et al. 2001; Kolstad et al. 2004).

Results

Hydraulic Conductivity

The hydraulic conductivity of GCLs specimens permeated with distilled water (basal values) ranged from 7.2×10^{-12} to 8.1×10^{-11} m/s and decreased as the effective stress increased (Table 2). It is important to note that the hydraulic conductivities of the GCL specimens (5.1×10^{-11} m/s for GCL-N and 8.1×10^{-11} m/s for GCL-S) tested at effective stress of 10 kPa were higher than the values typically reported in previous literatures (Katsumi et al. 2008; Shackelford et al. 2010). The reason for these relatively high measured hydraulic conductivity values is, in part, the low quality of the bentonite within the GCLs. Compared with the bentonites reported in previous literatures, the bentonites within the GCLs used in this study had relatively low montmorillonite contents. For example, the montmorillonite content of the natural Na bentonite used in this study was only 23%, whereas the montmorillonite content for bentonite used in previous investigations were generally > 70%. Less montmorillonite results in less swelling capacity and more open structures associated with bentonite, and in return results in a higher hydraulic conductivity for GCL (Lee and Shackelford 2005).

When the permeant liquid was switched to AMD, the GCL specimens under different effective stresses experienced significantly different changes in hydraulic conductivity (Fig. 1a–c). For example, at an effective stress of 10 kPa,

Table 2 Hydraulic conductivities for GCLs permeated with distilled water and acid mine drainage (AMD) at various effective stresses

Test no.	Effective stress (kPa)	GCLs type	Measured hydraulic conductivity k_{water} (m/s)	k_{AMD} (m/s)	k_{AMD}/k_{water}
1	10	GCL-N	5.1×10^{-11}	1.7×10^{-9}	33
2		GCL-S	8.1×10^{-11}	8.5×10^{-9}	104
3	50	GCL-N	1.6×10^{-11}	1.8×10^{-11}	1.1
4		GCL-S	1.9×10^{-11}	1.2×10^{-10}	6.3
5	200	GCL-N	7.3×10^{-12}	4.5×10^{-12}	0.6
6		GCL-S	7.2×10^{-12}	4.8×10^{-12}	0.7

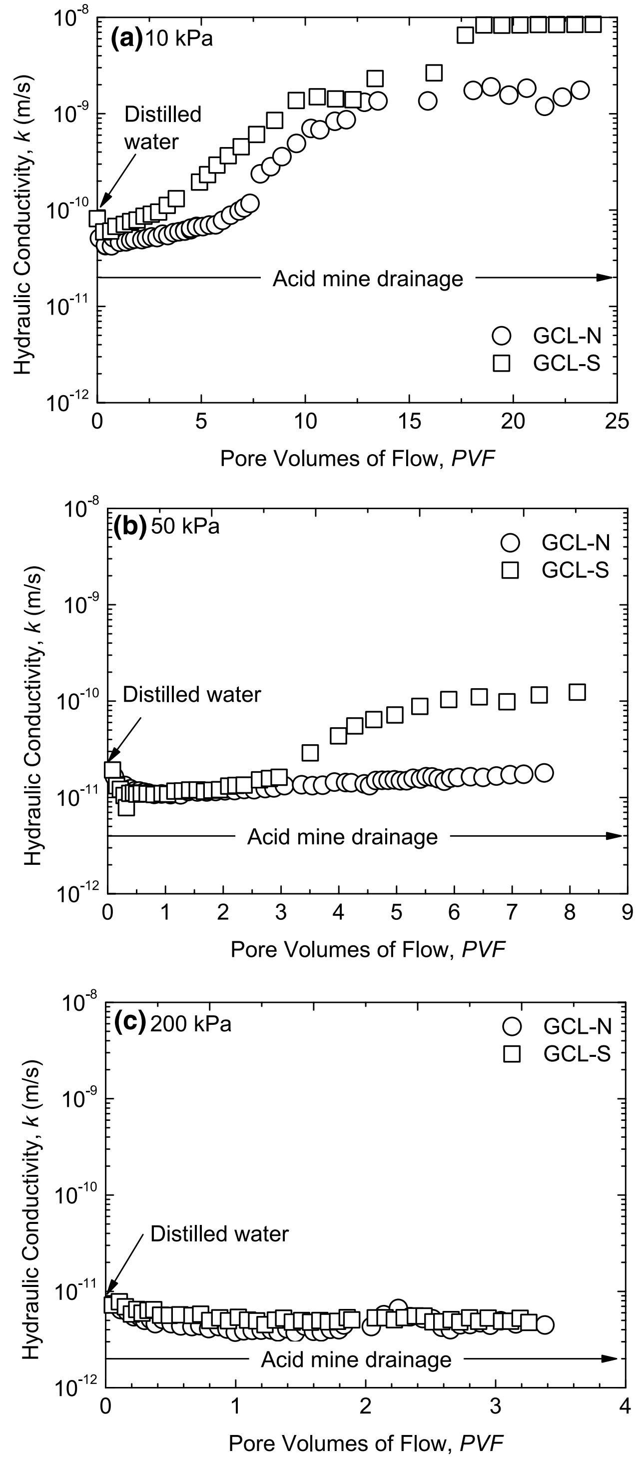

Fig. 1 Hydraulic conductivity versus pore volumes of flow for GCLs permeated with acid mine drainage at effective stress of 10 kPa (**a**), 50 kPa (**b**) and 200 kPa (**c**)

the hydraulic conductivity for the GCL-N and GCL-S specimens initially decreased to approximately 4.3×10^{-11} m/s and 5.8×10^{-11} m/s after 0.67 pore volumes of flow (PVF) and 0.3 PVF of permeation, respectively. Subsequently, the hydraulic conductivity gradually increased to 1.7×10^{-9} m/s and 8.5×10^{-9} m/s for the GCL-N and GCL-S specimens, which was ≈ 33 and 104 times greater than the hydraulic conductivity based on distilled water permeation, respectively (Table 2). At 50 kPa, both hydraulic conductivities decreased to approximately 1.0×10^{-11} m/s after about 1.0 PVF of the AMD had passed through. The hydraulic conductivity of GCL-N specimen then increased slightly to 1.8×10^{-11} m/s at the end of the test. In contrast, the hydraulic conductivity of the GCL-S specimen increased by almost an order of magnitude to 1.2×10^{-10} m/s at test termination. When the effective stress was increased to 200 kPa, the hydraulic conductivity values for the GCL-N and GCL-S specimens initially decreased to ≈ 4.5×10^{-12} m/s and 4.8×10^{-12} m/s, respectively, after about 0.5 PVF, after which there was no further change in hydraulic conductivity during the remainder of the test.

The ratios of the final steady state hydraulic conductivities based on permeation with AMD to those based on permeation with distilled water at a given effective stress are shown in Table 2. The final steady state hydraulic conductivity is defined as the average value of the last three consecutive hydraulic conductivities prior to the completion of tests. Clearly, the ratio decreased with increasing effective stress. This suggests that GCLs tend to be less susceptible to increases in hydraulic conductivity with AMD permeation if high effective stress is applied. It should be noted that the ratios for both types of GCL specimens at an effective stress of 200 kPa were less than unity (Table 2). These results show that permeation of AMD did not detrimentally affect the hydraulic performance for these GCL specimens at an effective stress of 200 kPa. This will be discussed further later.

Changes in Void Ratios

The values of void ratio, e_{GCL}, for the GCL specimens permeated with AMD measured at the end of the tests are given in Table 3. The void ratio of the GCLs, e_{GCL}, is defined as the ratio of the void volume to the volume of solids (including both bentonites and geotextiles) in the GCL specimens (Petrov and Rowe 1997). The value of the e_{GCL} decreased with increasing effective stress for both GCLs (Table 3).

Table 3 Void ratio (e_{GCL}) of GCL specimens at various effective stresses

GCL types	Void ratio		
	10 (kPa)	50 (kPa)	200 (kPa)
GCL-N	3.05	1.78	1.46
GCL-S	4.29	1.56	1.16

This can explain why the hydraulic conductivity of the GCLs decreased with increases in effective stress.

Termination Criteria

The ratios of volumetric flow of outflow (Q_{out}) to inflow (Q_{in}), Q_{out}/Q_{in} and the EC ratio of outflow (EC_{out}) to inflow (EC_{in}), EC_{out}/EC_{in} for the tests using AMD as permeant are presented in Figs. 2, 3 and 4. As indicated in Figs. 2 and 3, the values of Q_{out}/Q_{in} and EC_{out}/EC_{in} for the GCL specimens tested at effective stresses of 10 and 50 kPa were within 1.0 ± 0.25 and 1.0 ± 0.1 at the end of the tests, showing that the tests conducted on the GCL specimens had been stopped after the termination criteria specified by the ASTM D 6766 (ASTM 2012) had been met. However, for the GCL specimens tested at 200 kPa, the tests were not run until the termination criterion had been satisfied because the value of EC_{out}/EC_{in} was not within 1.0 ± 0.1

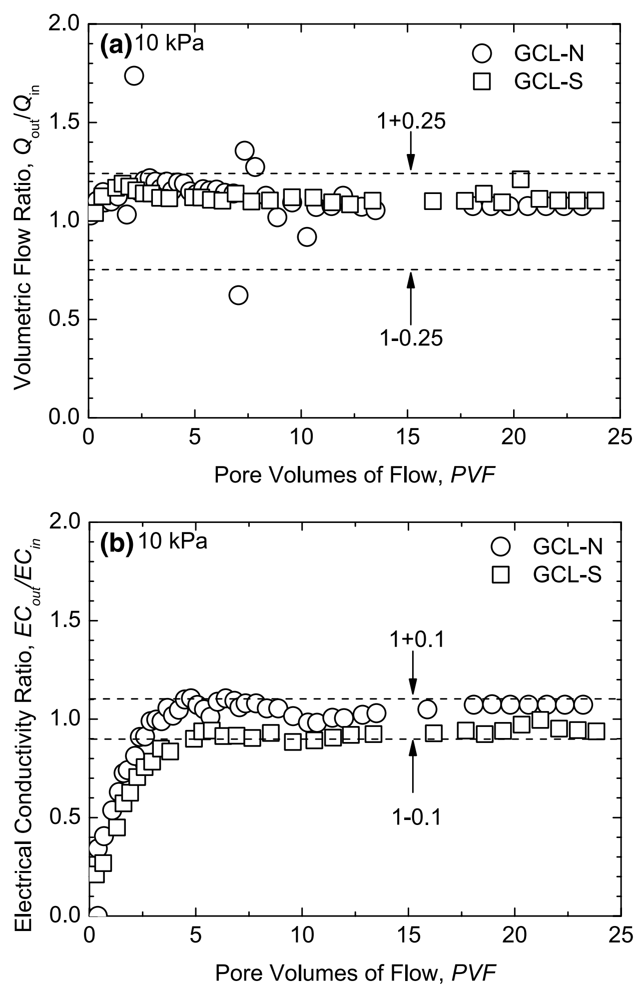

Fig. 2 Volume flow ratio Q_{out}/Q_{in} (**a**) and electrical conductivity ratio, EC_{out}/EC_{in} (**b**) and versus pore volumes of flow for GCLs permeated at effective stress of 10 kPa

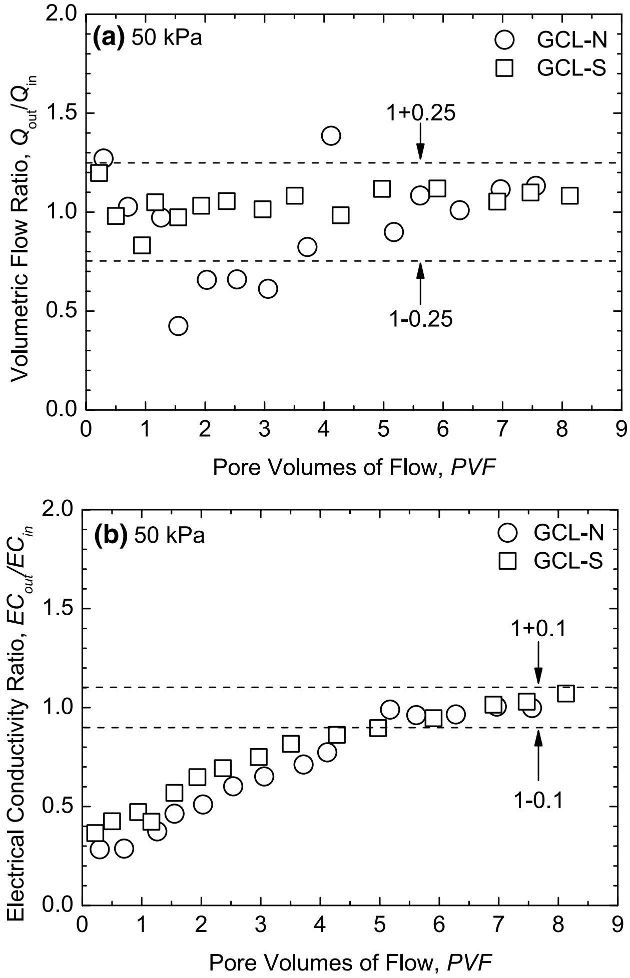

Fig. 3 Volume flow ratio Q_{out}/Q_{in} (**a**) and electrical conductivity ratio, EC_{out}/EC_{in} (**b**) and versus pore volumes of flow for GCLs permeated at effective stress of 50 kPa

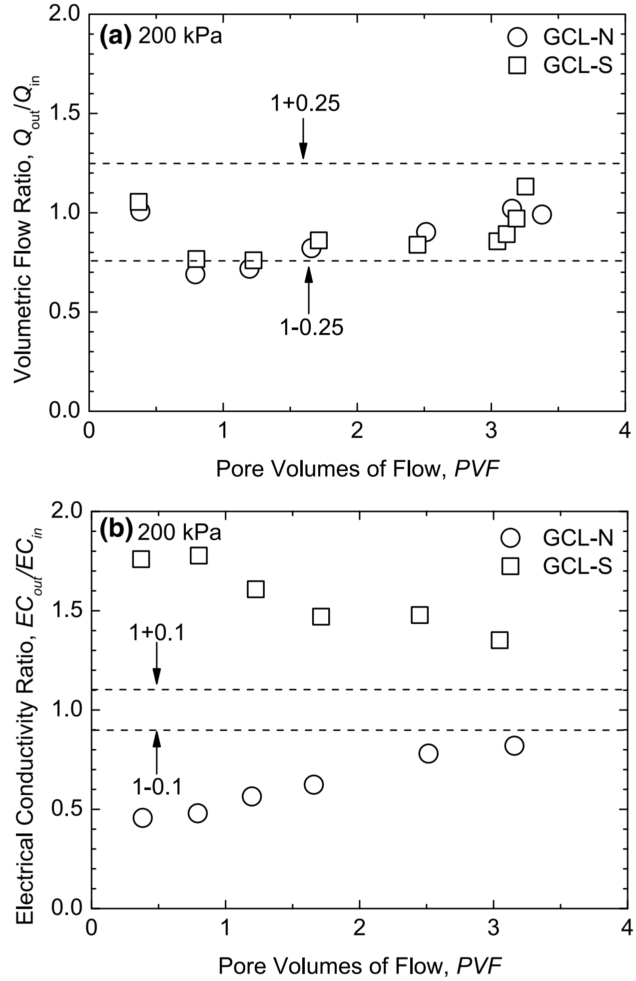

Fig. 4 Volume flow ratio Q_{out}/Q_{in} (**a**) and electrical conductivity ratio, EC_{out}/EC_{in} (**b**) and versus pore volumes of flow for GCLs permeated at effective stress of 200 kPa

(Fig. 4b). The hydraulic conductivities for the GCL specimens tested at an effective stress of 200 kPa were so low that it was not practical to wait for chemical equilibrium to occur. Due to the limited project schedule, the tests were discontinued.

Although the termination criterion in ASTM D 6766 (ASTM 2012) was not reached, it is logical to assume that no significant increase in hydraulic conductivity would occur in the subsequent permeation process. This is supported by the test results of Liu et al. (2013), who conducted hydraulic conductivity tests on GCL permeated with 0.015 M sulfuric acid solution under an effective stress of 200 kPa. When the chemical equilibrium had been established after 149 days and 21 PVFs permeation of sulfuric acid, the hydraulic conductivity was 2.0×10^{-12} m/s, which was just slightly higher than that (1×10^{-12} m/s) of the GCL tested under the same conditions, except when using DI water as the permeant liquid.

Free Swell

Results of the free swell index tests are shown in Fig. 5. The natural Na bentonite swelled to 20 mL/2 g in distilled water, which was less than the values reported in previous investigations (Lee et al. 2005; Lee and Shackelford 2005; Scalia et al. 2014). The relatively smaller swell index for natural Na bentonite should be attributed to its lower montmorillonite contents (23%). In contrast, the montmorillonite content for the bentonite used in previous studies was generally up to 70% or more. Due to relatively higher montmorillonite content (62%), the Na-activated bentonite swelled to 29.5/2 g, which is similar to the value (≈30 mL/2) given in previous literature (Lee et al. 2005; Lee and Shackelford 2005; Scalia et al. 2014). However, the higher swell index of Na-activated bentonite does not correspond to a lower hydraulic conductivity for the GCL-S; i.e. the hydraulic conductivity of GCL-S specimen was higher than that of GCL-N when

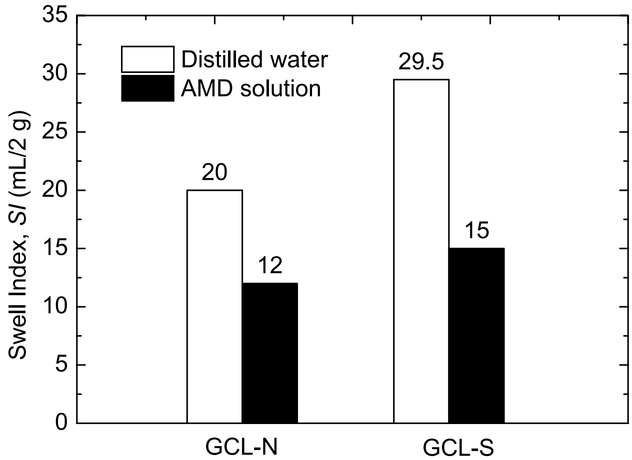

Fig. 5 Swell index of the bentonites taken from two GCLs using distilled water and acid mine drainage

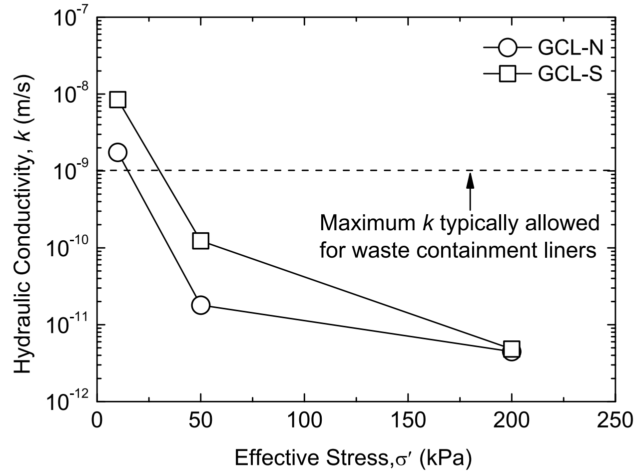

Fig. 6 Hydraulic conductivity versus effective stress for GCL specimen permeated with acid mine drainage

permeated with distilled water. This suggests that the high swell index of the Na-activated bentonite is a false indication of the hydraulic performance of the GCL-S specimen.

When the testing solution was changed from distilled water to AMD, the swell index for the natural Na bentonite decreased from 20.0 to 12.0 mL/2 g, and the swell index for the Na-activated bentonite decreased from 29.5 to 15 mL/2 g. As shown by the comparative bar chart in Fig. 5, the extent of decrease for the Na-activated bentonite was greater than that of natural Na bentonite. A possible explanation for this is that the Na ions within the Na-activated bentonite are more easily displaced from the exchange sites of montmorillonite than those within natural Na bentonite when permeated with a given chemical solution (AMD in the current study). Similar results were obtained from the hydraulic conductivity tests (Table 1; Fig. 1a, b), where GCL-S had a relatively higher hydraulic conductivity than the GCL-N at effective stresses of 10 and 50 kPa.

Discussion

The impact of AMD on the hydraulic conductivity of GCLs can be explained by the diffuse double-layer theory (Petrov and Rowe 1997). The multivalent cations (Ca^{2+}, Mg^{2+} and many metals) present in the AMD can exchange with the Na ions natively present. This exchange process will cause the double-layer and *c*-axis of the bentonite to contract gradually (i.e. domain formation, face-to face flocculation), resulting in larger pores, a greater effective pore space for AMD flow, and an increase in hydraulic conductivity (Petrov and Rowe 1997). The contraction of the double-layer and *c*-axis can be certified by the test results of the free swell. As shown in Fig. 5, the swell index decreased approximately 40% and 49% for natural Na bentonite and Na-activated bentonite, respectively, as the test liquid was switched from distilled water to AMD solution.

Dissolution of aluminosilicate minerals induced by AMD permeation may be another reason for the changes in hydraulic conductivity (Liu et al. 2015). The dissolved minerals would leach out from the GCL specimens, creating macropores in the GCL specimens. In another study (Kashir and Yanful (2001), in which the hydraulic conductivity of Na bentonite paste mixtures permeated with AMD was tested, the dissolution of aluminosilicate minerals was also considered to be one of the reasons for increased hydraulic conductivity in the test specimens.

Although AMD has the ability to degrade the hydraulic performance of GCLs, this does not mean that AMD permeation necessarily results in more permeable GCLs, because hydraulic conductivity is also affected by the effective stress (Liu et al. 2015; Thiel and Criley 2005). The conductivity values presented in Fig. 6 are the arithmetic mean values of the last three consecutive measurements prior to termination of the test. As shown, the hydraulic conductivity of the GCL specimens decreased as the effective stress increased. These trends are consistent with those reported by several previous investigators (Kang and Shackelford 2009; Petrov and Rowe 1997; Thiel and Criley 2005) who permeated GCL specimens with deionized water or chemical solutions at a range of confined stresses. Petrov and Rowe (1997) concluded from their experiment that GCLs appeared to be less susceptible to increases in hydraulic conductivity when permeated with chemical solutions if high confining stresses were applied. Consolidation theory has commonly been used to explain changes in hydraulic conductivity of GCLs under high effective stress. In general, greater effective stress decreases the void ratio (Table 3), which in turn leads to less hydraulic conductivity if all other test conditions are equal (Kang and Shackelford 2009; Liu et al. 2015; Petrov and Rowe 1997; Shackelford et al. 2000).

As previously mentioned, the decrease in hydraulic conductivity of GCLs is the result of a reduction in void ratio caused by consolidation. These results are encouraging and suggest that effective stress can mask or depress the damaging impacts caused by the AMD. As noted by Petrov and Rowe (1997), this has practical implications with respect to the possible use of GCLs as bottom liners in a waste disposal facility (e.g. the coal gangue impoundment in the current study).

An interesting observation is that the hydraulic conductivity values obtained at effective stresses of 50 kPa and 200 kPa were all less than 1.0×10^{-9} m/s, which is a common regulatory specification in various countries for waste disposal impoundment liners. When GCLs are used as bottom liners for coal gangue impoundments, they will be subjected to high stresses after the disposal impoundment has been filled with the coal gangue. For example, Fourie et al. (2010) indicated that the vertical pressure on the bottom liners produced by the overlying mining waste could range from 0.8 to 4.5 MP. Thus, it can be expected that the GCLs should be able to maintain a hydraulic conductivity of 1.0×10^{-9} m/s or less when used as a coal gangue impoundment bottom liner.

The impact of bentonite type on the hydraulic conductivity of GCLs permeated with AMD also can be seen in Fig. 6. All other things being equal, GCL specimens with natural Na bentonite should have a lower hydraulic conductivity than specimens with Na-activated bentonite when permeated with a chemical solution, because the Na ions within natural Na bentonite are generally more difficult to be displaced from the exchange sites of montmorillonite than those within Na-activated bentonite (Alther 1987; Guyonnet et al. 2009; Norotte et al. 2004). As shown in Fig. 6, the test results obtained at effective stresses of 10 and 50 kPa followed the expected trends. Similar results were reported by Benson et al. (2008), where GCL-N (with natural Na bentonite) specimens permeated with alumina residue leachate were approximately three orders of magnitude less permeable than GCL-S (with Na-activated bentonite) specimens at an effective stress of 50 kPa. However, the results obtained at an effective stress of 200 kPa were unexpected; i.e. the hydraulic conductivity of the GCL-N specimen (with natural Na bentonite) was comparable to that of the GCL-S specimen (with Na-activated bentonite). This unexpected result should be attributed to the high effective stress (200 kPa) applied in the test, which completely masked the difference resulting from bentonite type. Clearly, the impact of bentonite type on the hydraulic conductivity of GCL specimens depended on the magnitude of the effective stress used in the hydraulic conductivity test. The poor hydraulic performance of the GCL-S specimens (with Na-activated bentonite) may be offset by increasing effective stress.

Conclusions

The potential of two types of geosynthetic clay liners (GCLs) to serve as basal liners for coal gangue impoundments has been examined. One GCL had natural Na bentonite (GCL-N) while the other used Na-activated bentonite (GCL-S). Both GCLs were permeated with distilled water and acid mine drainage (AMD) using flexible-wall permeameters at various effective stresses (10, 50, and 200 kPa). The following conclusions are based on the results:

1. The hydraulic conductivities of both GCLs ranged from 5.1×10^{-11} to 8.1×10^{-11} m/s when tested at an effective stress of 10 kPa, using distilled water as permeant solution. These values were higher than the values typically reported.
2. The hydraulic conductivity of GCLs permeated with AMD depended on the magnitude of the effective stress applied in the tests. Increasing the effective stress can mute the detrimental effect of the AMD.
3. The type of bentonite in the GCLs affected the hydraulic performance of the GCLs at effective stresses of 10 and 50 kPa. At these low effective stresses, the GCL with natural Na bentonite had less hydraulic conductivity than the GCL with Na-activated bentonite. However, when the effective stress was increased to 200 kPa, there was no difference in the hydraulic conductivity between the two types of GCLs.
4. The two types of GCLs used in the present study may be suitable as effective basal liners for coal gangue impoundment when higher stress (50 kPa or higher) can be applied to them.

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