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Correlating the hydraulic conductivities of GCLs with some properties of bentonites

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Abstract. In this study, the relationships between hydraulic conductivity of GCLs and physico-chemical properties of bentonites were assessed. In addition to four factory manufactured GCLs, six artificially prepared GCLs (AP-GCLs) were tested. AP-GCLs were prepared in the laboratory without bonding or stitching. A total of 20 hydraulic conductivity tests were conducted using flexible wall permeameters ten of which were permeated with distilled deionized water (DIW) and the rest were permeated with tap water (TW). The hydraulic conductivity of GCLs and AP-GCLs were between 5.2×10^{-10} cm/s and 3.0×10^{-9} cm/s. The hydraulic conductivities of all GCLs to DIW were very similar to that of GCLs to TW. Then, simple regression analyses were conducted between hydraulic conductivity and physicochemical properties of bentonite. The best correlation coefficient was achieved when hydraulic conductivity was related with clay content (R=0.85). Liquid limit and plasticity index were other independent variables that have good correlation coefficients with hydraulic conductivity (R~0.80). The correlation coefficient with swell index is less than other parameters, but still fairly good (R~0.70). In contrast, hydraulic conductivity had poor correlation coefficients with specific surface area (SSA), smectite content and cation exchange capacity (CEC) (i.e., R < 0.5). Furthermore, some post-test properties of bentonite such as final height and final water content were correlated with the hydraulic conductivity as well. The hydraulic conductivity of GCLs had fairly good correlation coefficients with either final height or final water content. However, those of AP-GCLs had poor correlations with these variables on account of fiber free characteristics.

Keywords: bentonite, clay content, consistency limits, swell index, geosynthetic clay liners (GCLs), hydraulic conductivity, physicochemical properties

1. Introduction

Bentonite has high affinity for water. This leads bentonite to have high swell potential and hence, low hydraulic conductivity. Therefore bentonites are the primary constituents of geosynthetic clay liners (GCLs) which are factory-manufactured synthetic materials that consist of a thin layer of bentonite sandwiched between two geotextiles or glued to a membrane. Since they have low hydraulic conductivity, GCLs have been commonly used as base and cover liners in solid waste landfills to isolate the contaminants from the environment.

Hydraulic conductivity is the key parameter for the lining systems and for GCLs. However, determining the hydraulic conductivity in the laboratory is time consuming. The duration of the test may vary from one month to several years depending on the properties of permeant and the GCL (Bradshaw and Benson 2013, Scalia *et al.* 2013, Tian *et al.* 2016). Although performing hydraulic conductivity tests on GCLs are inevitably mandatory during the design of the solid waste landfill, it is more efficient to conduct these tests on the selected GCLs if there are many candidate GCLs for the application.

The index properties of bentonites, such as consistency limits, swell index etc., can be used for the preliminary selection of GCLs, because determining the index properties are easier and faster than performing a hydraulic conductivity test. To illustrate this, researchers have put some effort to establish relationships between the hydraulic conductivities of GCLs and index parameters of bentonites.

The hydraulic conductivity of GCLs has widely been interpretted with the swell index of bentonite (Ashmawy *et al.* 2002, Di Emidio *et al.* 2015, Hosney and Rowe 2013, Jo *et al.* 2001, Katsumi *et al.* 2008, Kolstad *et al.* 2004, Lee *et al.* 2005, Shackelford *et al.* 2000). In addition, some attempts have been made to evaluate the hydraulic conductivity with liquid limit (Lee *et al.* 2005, Liu *et al.* 2015, Mishra *et al.* 2011), sedimentation volume (Lee *et al.* 2005), cation exchange capacity (Guyonnet *et al.* 2009), exchangeable sodium percentage (Mishra *et al.* 2011) and smectite content (Ashmawy *et al.* 2002, Dananaj *et al.* 2005, Guyonnet *et al.* 2009, Shackelford *et al.* 2000) of the bentonite. Most of these studies basically investigate and

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report the influence of permeant type (i.e., inorganic salt solutions had been used in these studies) and the concentration of the permeant on the hydraulic conductivity of GCLs (Jo *et al.* 2001, Katsumi *et al.* 2008, Kolstad *et al.* 2004). However, only limited studies evaluate the hydraulic conductivity in terms of physico-chemical properties of bentonite (Lee *et al.* 2005, Mishra *et al.* 2011).

To understand the influencing factors on the hydraulic conductivity of GCLs to water, a laboratory program was carried out. For this purpose, 20 hydraulic conductivity tests were conducted on four brand new GCLs and six artificially prepared GCLs with distilled deionized water (DIW) and tap water (TW) as the permeants. The principal purpose of this study is to give a contribution to the better understanding of the relationships between hydraulic conductivities of GCLs and physico-chemical properties of bentonites.

2. Materials and methods

2.1 Materials

2.1.1 Geosynthetic clay liners (GCLs)

The hydraulic conductivity tests were conducted on four geosynthetic clay liners (GCLs). GCLs had been manufactured with sodium bentonite sandwiched between woven and non-woven geotextiles that are held together by needle-punching. In addition to sodium, bentonite in GCL-4 was treated with polymers. Nevertheless, the details about the polymerization are unknown. The initial water contents of GCLs were around 12%, whereas the thicknesses were within the range of ~0.4-0.6 cm. The mass per unit area of the GCLs were within the range of 4.0-5.0 kg/m^2.

2.1.2 Artificially prepared geosynthetic clay liners (AP-GCLs)

In addition to GCLs, six artificial GCLs were prepared in the laboratory. These AP-GCLs were neither needle punched nor stitch bonded (i.e., fiber free). The bentonites used in AP-GCLs were gathered from local companies in Turkey some of which were sodium (AP-GCL-1, 2, 3, 5) and AP-GCL-6 was polymer treated (Ören and Akar 2017). Except bentonite in AP-GCL-1, all bentonites were in powdered form. Bentonite in AP-GCL-1 was composed of granular particles (≤ 0.425mm). The initial water contents of bentonites were within the range of 9-12%.

AP-GCLs were prepared on the flexible wall permeameters. The base of the permeameter was dismantled and put on a table. Initially, a Drefon S-1000 type nonwoven geotextile was placed on the base that had 15cm diameter. The role of this geotextile was to use it as a porous stone. Then, a woven geotextile (i.e., carrier) of AP-GCL was placed on nonwoven geotextile. The target mass per unit area for the AP-GCLs were 5.0 kg/m^2. Thus, adequate amount of bentonite was weighted and poured on carrier geotextile. Additional care was taken not to pour outside of the geotextile. Then, nonwoven geotextile was placed on bentonite. To prevent the bentonite loss, the circumference of the AP-GCL was wetted using a squirt bottle. The base was then mounted on the permeameter and Drefon S-1000 type nonwoven geotextile was placed over AP-GCL as a top porous stone. Finally, the plexiglass top cap was placed on the nonwoven geotextile. The initial heights of AP-GCLs were more or less 0.6 cm. Other details about sample preparation can be found in Ören and Akar (2017).

Table 1 Physical properties of bentonites used in GCLs and AP-GCLs

GCLs	Fines Content (%)	Clay Content (%)	Liquid Limit (%)		Plastic Limit (%)
			Fall Cone	Casagrande	
GCL-1	83	57	99	108	60
GCL-2	93	67	232	310	26
GCL-3	95	72	236	320	30
GCL-4	87	25	800	1163	52
AP-GCL-1	98	67	189	283	48
AP-GCL-2	96	73	388	529	38
AP-GCL-3	99	78	450	552	41
AP-GCL-4	100	31	141	149	42
AP-GCL-5	100	78	305	397	34
AP-GCL-6	98	78	298	417	44

2.2 Methods

2.2.1 Index properties

The particle size distributions of the bentonites were determined by wet sieving method and hydrometer analysis (ASTM:D422-63 2007). The liquid limits of bentonites were determined with either Casagrande or fall-cone test apparatus by following ASTM:D4318-05 (2005) and BS 1377-2:90 (1990), respectively. The plastic limit tests were conducted in accordance with ASTM D4318.

Based on the sieve analysis, most of the bentonites had fines content greater than 93%. However, the fines content of GCL-1 was rather low (83%), indicating 17% sands were available in this GCL (Table 1). Similarly, the fines content of GCL-4 was 87%. During the sieve analysis for GCL-4, it was observed that many gel-like structures were retained on No.200 sieve (75 µm). This can be attributed to the polymer used in GCL-4. This resulted in the lowest clay content for GCL-4 among other GCLs (i.e., 25%). The second lowest clay content was obtained for AP-GCL-4. Although the fines content was 100%, the silt content and clay content of AP-GCL-4 was 69% and 31%, respectively.

Except GCL-4, the liquid limit of GCLs and AP-GCLs were within the range of 99-450% and 108-552% when determined with fall cone and Casagrande methods, respectively. Liquid limit of GCL-4 was significantly higher than those of others. Since GCL-4 was polymer treated, a sponge-like porous structure was formed when mixed with water. This structure was composed of interconnected pore network across the sample which could have been observed easily with naked eye. For this reason, liquid limit of GCL-4 was determined 800% from fall cone method and 1163% from Casagrande method.

Although Casagrande method was more eligible for high plasticity clays (Sridharan and Prakash 2000), fall cone

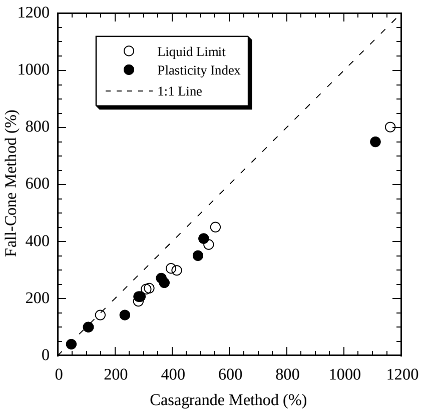

Fig. 1 Method dependency of liquid limit and plasticity index of bentonites

method was also used to determine liquid limit of bentonites. The results of these two methods are compared and illustrated in Fig. 1. Based on this figure, it is seen that the liquid limits obtained from Casagrande method was greater than the liquid limits obtained from fall cone method. This conclusion is consistent with the literature (Sridharan and Prakash 2000). The mechanisms that control the liquid limit behavior of bentonites are not the scope of this study, and hence, not discussed herein. However, the details can be found in Sivapullaiah and Sridharan (1985) and Sridharan and Prakash (2000).

2.2.2 Mineralogical analysis

The mineralogical compositions of the bentonites were determined by X-ray diffraction method (XRD). Powdered bentonites were used during the analyses which had been passed through No.200 (75 μm) sieve. GE Seifert XRD 3003-PTS diffractometer with Cu-Kα radiation was used to estimate the mineral phases in bentonites. The quantitative amounts of minerals were obtained using Rietveld method.

The mineralogical compositions of bentonites are presented in Table 2. The predominant minerals in all bentonites were smectite. The smectite content of bentonites varied from 61 to 77%. In addition to smectite, cristobalite, illite, quartz, calcite, and muscovite were the associate minerals existing in the bentonites (Table 2).

2.2.3 Specific surface area

Specific surface area (SSA) of the bentonites was determined with methylene blue spot test method (Yukselen-Aksoy and Kaya 2010). For this purpose, 1 g of methylene blue was mixed with 200 ml DIW to prepare a methylene blue solution. Then, 10 g oven dried bentonite was mixed with 30 ml deionized water (DIW). It has been suggested that methylene blue solution should be added on bentonite with 0.5 ml increments. However, this process is time consuming. Based on the previous experiences on measuring the SSA of bentonite, the test was started with 5 ml increments. After a while, the methylene blue increment was reduced from 5 ml to 0.5 ml. Hence, SSA was measured within couple hours. After each metyhlene blue addition, bentonite suspension was mixed with a magnetic stirrer for 1 minute. A drop was taken from the suspension with a glass stick and placed onto Fisher brand filter paper. This process was continued until occurring a light blue halo around the drop on the filter paper. This halo means that the entire surface of bentonite was coated with methylene blue and no more methylene blue was adsorbed on bentonite.

Table 2 Mineralogical compositions of bentonites used in GCLs and AP-GCLs

Minerals (%)	GCLs				AP-GCLs					
	1	2	3	4	1	2	3	4	5	6
Smectite	68	65	64	66	61	77	72	67	63	68
Cristobalite	9	2	4	3	5	10	14	15	2	3
İllite	4	3	6	6	2	3	5	2	4	8
Quartz	3	14	12	14	2	5	2	-	11	10
Calsite	4	3	-	-	15	-	-	-	6	6
Muskovite	3	1	4	2	-	-	-	3	4	-

Table 3 Specific surface area and cation exchange capacity of bentonites used in GCLs and AP-GCLs

GCLs	Specific Surface Area (SSA) (m^2/g)	Cation Exchange Capacity (CEC) (cmol/kg)
GCL-1	670	76
GCL-2	592	80
GCL-3	538	80
GCL-4	891	124
AP-GCL-1	832	85
AP-GCL-2	636	73
AP-GCL-3	607	105
AP-GCL-4	475	78
AP-GCL-5	587	61
AP-GCL-6	612	69

The SSA of GCLs and AP-GCLs are summarized in Table 3. The SSA varied between 475 m^2/g and 891 m^2/g. Polymer GCL (i.e., GCL-4) had the greatest SSA, whereas AP-GCL-4 had the lowest SSA. Note that the clay content for AP-GCL-4 was significantly less when compared to other GCLs (31%).

2.2.4 Cation exchange capacity

Cation exchange capacities (CEC) of bentonites were determined according to ASTM:D7503-10 (2010). The clay was initially sieved from No. 10 sieve (2.0mm). Air dried mass corresponding to 10g of solids was washed sequentially with 1M ammonium acetate, isopropanol and 1M potassium chloride solution. The suspension was filtered through 2.5 μm ashless filter paper which was placed on a Buckner funnel. Low suction (< 10 kPa) was applied during the filtration and the filtrate was collected in a volumetric flask. Then, 0.1 ml of potassium chloride extract was taken using a micro pipet and mixed with one dose of NH_4-1K reagent into the reaction cell.

Reaction cell was vigorously shaken with hand until the reagent dissolved. The sample was kept for 15 minutes and subsequently, the solution was analyzed for nitrogen concentration using Photolab S12 brand spectrophotometer.

Except polymer GCL (i.e., GCL-4), the CEC of GCLs was within a narrow range 76-80 cmol/kg. The CEC of GCL-4 had the highest CEC values among others (124 cmol/kg). In addition, the CEC of AP-GCLs was determined between 61 cmol/kg and 105 cmol/kg (Table 3).

2.2.5 Swell index test

Swell index tests were conducted by following the procedures described in ASTM:D5890-11 (2011) using DIW and TW. Tests were conducted with 2 g of oven-dried bentonite that passed through No 200 sieve. The 100 ml graduate cylinder was filled with water until 90 ml level. Then, 0.1 g of the bentonite was poured into the graduated cylinder within 30 seconds. Bentonite was allowed to settle and swell for 10 minutes. Then, another 0.1g was poured. This process was continued until all bentonite was fully poured. Then, the cylinder was filled with water to the 100 ml level. The top of the graduated cylinder was closed with a piece of parafilm and bentonite was left for swelling. After 24 hours of swelling, the free swell volume was recorded.

2.2.6 Hydraulic conductivity tests

Falling head hydraulic conductivity tests were conducted using flexible wall permeameters (ASTM:D6766-12 2014). The permeameters were eligible to measure the hydraulic conductivity of the GCLs with 10 cm in diameter. Once GCLs/AP-GCLs were placed in the permeameters, the circumference of the GCL and AP-GCL were sealed with bentonites extracted from each GCLs to prevent side-wall leakage. GCLs were covered with a latex membrane and three O-rings were attached at top and bottom pedestals. Subsequently, GCLs were prehydrated with DIW or TW for 48 h. During the prehydration process, the influent valve was open and the effluent valve was kept closed. At the end of prehydration, the effluent valve was open and the flow was begun through downwards. The outflow was collected in graduated cylinders.

Cell pressure of 100 kPa and an average hydraulic gradient of 200 were applied. The average effective stress throughout the test was 90 kPa. This effective stress is rather high. But it corresponds to 10 m of waste load over liner and thus, it is convenient to represent the performance of base liner in landfills. To simulate landfill liner conditions, no backpressure was applied during the hydraulic conductivity tests. The ratio of outflow to inflow was considered along the test duration (i.e., Q_{out}/Q_{in}). The termination criterion for the hydraulic conductivity test was $Q_{out}/Q_{in}=1.0\pm0.25$. Although this criterion was satisfied at the early stages, the hydraulic conductivity tests were lasted at least 6 months. Although 6 months test duration seems to be rather long, it was desired to see if there is any change in the hydraulic conductivities of GCLs within the applied test duration.

When hydraulic conductivity tests were terminated, the final thicknesses of the GCLs and AP-GCLs were measured using a Vernier caliper. Moreover, the final water contents were determined as well. To do this, the geotextile components of GCL were detached by cutting the needle punched fibers using a razor knife. Then, bentonite was removed with a spatula. This process was simpler for AP-GCLs than for GCLs because of fiber free characteristics of AP-GCLs.

3. Results and discussions

3.1 Hydraulic conductivity of GCLs and AP-GCLs

Total of 20 hydraulic conductivity tests were conducted on GCLs and AP-GCLs ten of which were permeated with DIW and the rest were TW. The final hydraulic conductivities for these GCLs are summarized in Table 4.

Table 4 Initial and final physical characteristics and hydraulic conductivity of GCLs

Test No	GCLs	Permeant Type	Initial GCL Height (cm)	Final GCL Height (cm)	Final Water Content (%)	Hydraulic Conductivity (cm/s)
1	GCL-1	DIW	0.58	0.82	92	1.2×10^{-9}
2	GCL-2	DIW	0.52	0.63	90	1.4×10^{-9}
3	GCL-3	DIW	0.50	0.69	109	1.4×10^{-9}
4	GCL-4	DIW	0.41	0.76	236	7.1×10^{-10}
5	AP-GCL-1	DIW	0.6	1.10	145	1.3×10^{-9}
6	AP-GCL-2	DIW	0.6	1.38	225	6.1×10^{-10}
7	AP-GCL-3	DIW	0.6	0.79	101	5.2×10^{-10}
8	AP-GCL-4	DIW	0.6	0.84	93	3.0×10^{-9}
9	AP-GCL-5	DIW	0.6	0.79	87	5.9×10^{-10}
10	AP-GCL-6	DIW	0.6	0.99	163	8.1×10^{-10}
11	GCL-1	TW	0.60	0.79	128	1.0×10^{-9}
12	GCL-2	TW	0.58	0.77	95	9.8×10^{-10}
13	GCL-3	TW	0.51	0.65	108	1.7×10^{-9}
14	GCL-4	TW	0.42	0.75	268	1.0×10^{-9}
15	AP-GCL-1	TW	0.6	1.10	139	1.5×10^{-9}
16	AP-GCL-2	TW	0.6	1.41	203	6.3×10^{-10}
17	AP-GCL-3	TW	0.6	0.79	108	8.5×10^{-10}
18	AP-GCL-4	TW	0.6	0.84	93	3.0×10^{-9}
19	AP-GCL-5	TW	0.6	0.79	87	6.2×10^{-10}
20	AP-GCL-6	TW	0.6	1.10	165	6.9×10^{-10}

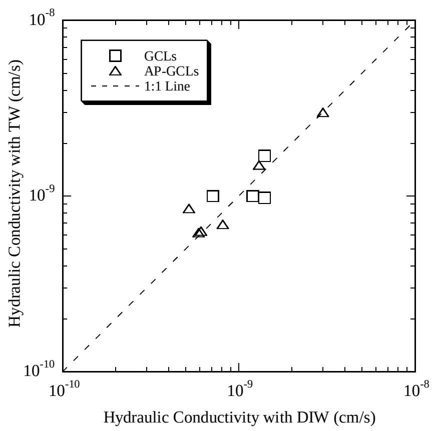

Fig. 2 Influence of permeant water on the hydraulic conductivity of GCLs and AP-GCLs

The values given in Table 4 are the average of last five readings. The final hydraulic conductivity of GCLs with DIW and TW are within the range of 7.1×10^{-10} – 1.7×10^{-9} cm/s and those of AP-GCLs are within the range of 5.2×10^{-10} – 3.0×10^{-9} cm/s (Table 4).

The impact of permeant water on the hydraulic conductivity of GCLs and AP-GCLs are evaluated in Fig. 2. The dashed line shows 1:1 line of perfect fit. The square symbols represent GCLs, whereas triangles denote AP-GCLs. Fig. 2 depicts that permeant water has negligible effect on the hydraulic conductivity of GCLs and AP-GCLs.

The aim of this study is to find out if there is any relationship between the basic characteristics of bentonite and hydraulic conductivity. Therefore, the hydraulic conductivity of GCLs and AP-GCLs are combined to increase the data set for better prediction. The hydraulic conductivity of bentonite is usually around 2.0×10^{-9} cm/s. However, this value is susceptible to atmospheric and environmental conditions and may dramatically change during time. For this reason, hydraulic conductivity is usually depicted on a logarithmic axis. The relationships given herein are interpreted on a semi-log axis: hydraulic conductivity is on the logarithmic axis and other variable is on the linear axis (x-axis). For simplicity, simple linear regression analyses were considered throughout this study. Thus, all proposed equations were given in terms of exponential functions. The coefficient of determinations (R-squared) and hence, correlation coefficients (multiple R or R) were calculated using least square method.

3.2 Relationship between index properties of bentonite and hydraulic conductivity of GCLs

Initially, some index properties of bentonite and hydraulic conductivities were evaluated. Since the index properties of bentonites were determined using DIW, the final hydraulic conductivities to DIW were taken into consideration while interpreting the relationships (Figs. 3(a) and 3(b)).

Although bentonites have wide range of liquid limits, hydraulic conductivities are in a narrower range (Fig. 3(a)). Increase in the liquid limit of bentonites reduced the hydraulic conductivity of GCLs. In fact, hydraulic conductivity linearly decreased up to liquid limit value of 600%, thereafter the hydraulic conductivity leveled off (Fig. 3(a)). In other words, liquid limit of GCL-4 is from 3 to 10 times greater than the others (Table 1). However, the hydraulic conductivity is only 3 times lower than those of other GCLs. Polymer treatment gives great advantage to GCL-4 in terms of water uptake. Hence, the water content at liquid limit is very high. However, such advantage was not seen on hydraulic conductivity. The relationship between liquid limit and hydraulic conductivity was evaluated by excluding the data for GCL-4 (Fig. 3(a)). Since liquid limits were determined using fall cone and Casagrande methods, two correlation equations are proposed for each method as in the following

$$k = 2.9\times10^{-9}\times e^{-0.003\,w_L}\ \text{(Cas. Met.)} \qquad (1)$$

$$k = 3.0\times10^{-9}\times e^{-0.004\,w_L}\ \text{(F.C. Met.)} \qquad (2)$$

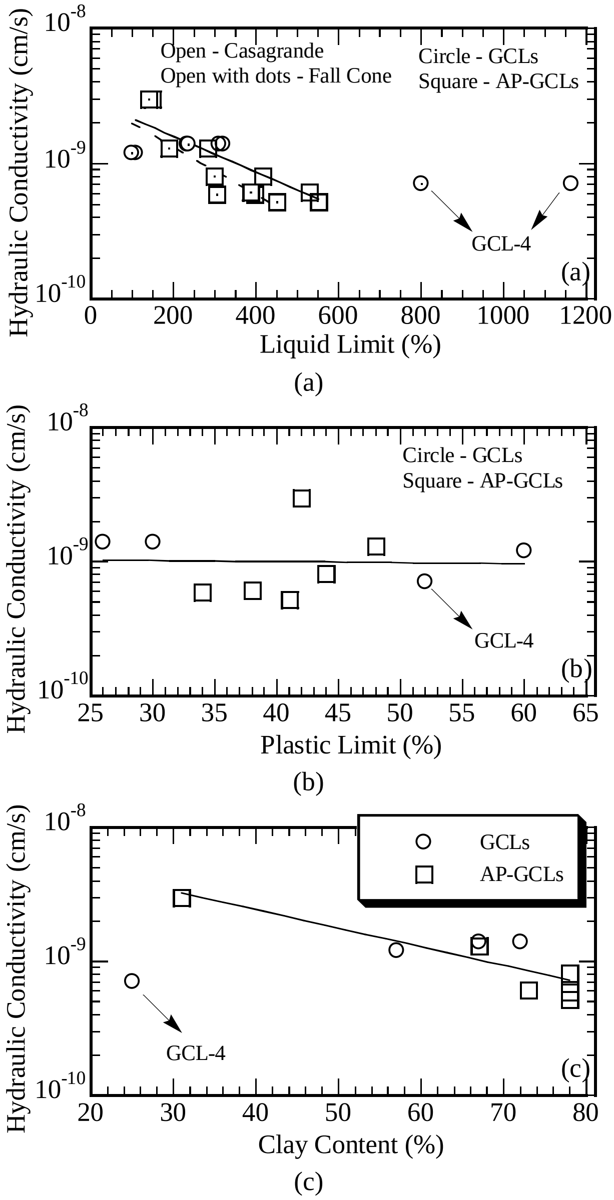

Fig. 3 Relationship between hydraulic conductivity of GCLs and (a) Liquid limits, (b) plastic limits and (c) clay contents

where, k is the hydraulic conductivity in cm/s and w_L is the liquid limit in percent. The correlation coefficients for both equations are good (R=0.82).

Another independent variable, plastic limit, was also evaluated with hydraulic conductivity to figure out whether there is any relationship or not. Although plastic limits of bentonites changed between 26% and 60%, the hydraulic conductivities did not change significantly within this plastic limit range. In other words, no relationship was found between plastic limit and hydraulic conductivity (Fig. 3(b)).

Some researchers stated that hydraulic conductivity of compacted clays can be estimated using plasticity index (Benson *et al.* 1994, Benson and Trast 1995). To evaluate the efficiency of this parameter on the hydraulic conductivity of GCLs, the plasticity indices of bentonites were taken into consideration as an independent variable.

Since two methods were used for the liquid limit, two correlation coefficients were obtained as well. Although it has good correlations with hydraulic conductivity, the correlation coefficients were not more than the coefficients obtained with liquid limit (i.e., 0.79 for the fall cone method and 0.80 for the Casagrande method).

A correlation also exists between clay content of bentonites and hydraulic conductivity of GCLs. Fig. 3(c) shows that the hydraulic conductivity decreased as the clay content increased. Despite linear trend, the data for GCL-4 is out of this relationship. This is because that the clay content for GCL-4 was very low with respect to others (i.e., 25%). Since bentonite for this GCL was polymer treated, the particles formed flocculated structure when faced with water and settled quickly during the hydrometer test. This can be attributed to inadequate amount of dispersing agent used during hydrometer test which was not able to disperse the particles. Thus, GCL-4 was not into consideration while evaluating the relationship. The linear regression equation between clay content and hydraulic conductivity is given in Eq. (3) and the correlation coefficient for this equation is greater than 0.85.

$$k = 8.7 \times 10^{-9} \times e^{-0.032\,CC} \tag{3}$$

where, k is the hydraulic conductivity in cm/s and CC is the clay content in percent.

3.3 Relationship between swell index of bentonite and hydraulic conductivity of GCLs

Swell index test is simple, cheap and rapid test method. Besides, the hydraulic conductivity of GCLs is basically governed by the swelling of bentonite particles and this test method shows this behavior in a practical way. In many studies conducted so far, the swell index of bentonites has been correlated with the hydraulic conductivity. In these studies, however, the swell volumes were generally determined in water, salt solutions and landfill leachates. Therefore, the dataset for the correlation was formed with these liquids. For example, it is well documented that the hydraulic conductivity of GCLs increased and swell index of bentonites decreased when aggressive concentrations were used in the solution (Ashmawy *et al.* 2002, Jo *et al.* 2001, Katsumi *et al.* 2008, Kolstad *et al.* 2004, Lee *et al.* 2005, Shan and Lai 2002).

The swell index test is so common that the free swell of bentonite in water is given as a characteristic property like index properties. However, if just water is the case, there is little information about the correlation between hydraulic conductivity and swell index (Mishra *et al.* 2011). Thus, the swell index of bentonite is correlated with the hydraulic conductivity of GCLs herein. Since swell index tests were conducted not only with DIW but also with TW, the correlation was evaluated with 20 data (Fig. 4).

Fig. 4 indicates that the hydraulic conductivity decreased when swell index of bentonite increased. The hydraulic conductivity is basically governed by the swollen bentonite particles. However, swelling amount is restricted by the fibers which connect the geotextiles of GCLs. GCL can swell up to a limit and thus, the void ratio of bentonite is not able to increase furthermore. The swollen particles block the flow paths and there is little pore space for mobile water. Thus, the hydraulic conductivity decreases. In other words, the greater the swelling of particles, the lower is the hydraulic conductivity of GCLs.

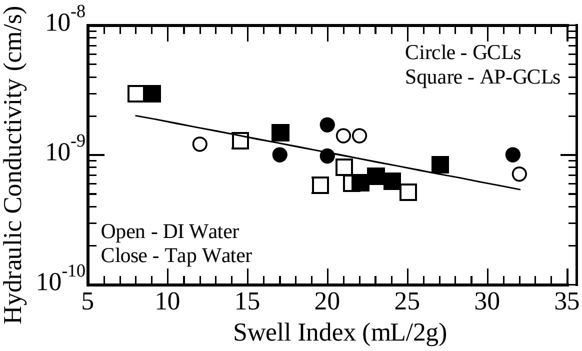

Fig. 4 Relationship between hydraulic conductivity of GCLs and swell index of bentonites

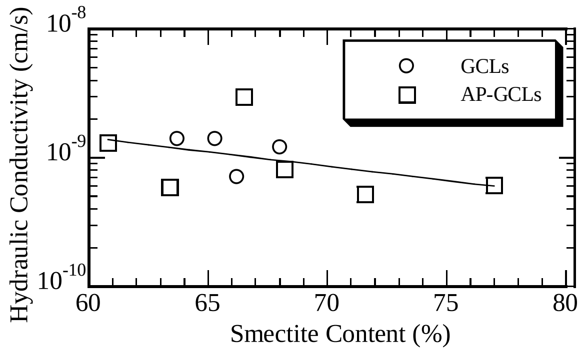

Fig. 5 Relationship between hydraulic conductivity of GCLs and smectite content of bentonites

Since there was negligible difference between the hydraulic conductivity of GCLs to DIW and those of GCLs to TW (Fig. 2), the relationship between swell index and hydraulic conductivity was assessed by combining the data from TW and DIW as one dataset. The correlation coefficient for this relationship is 0.68. The correlation equation is given as follows

$$k = 3.1 \times 10^{-9} \times e^{-0.055\,SI} \tag{4}$$

where, k is the hydraulic conductivity in cm/s and SI is the swell index in mL/2g.

3.4 Relationship between mineralogy of bentonite and hydraulic conductivity of GCLs

Smectite is a key factor for the hydraulic conductivity of GCLs. In general, barrier performance of GCLs increases with increase in smectite content. Ashmawy *et al.* (2002) indicated that the hydraulic conductivity of GCLs to water decreased from ~1.0×10^{-7} cm/s to $\geq 9.0\times10^{-9}$ cm/s when smectite content in the bentonite increased from 49 to 92%. Similarly, Lee and Shackelford (2005) reported the hydraulic conductivities of higher quality (HQ) and lower quality (LQ) GCLs with several permeants. The HQ GCL and LQ GCLs had 86% and 77% montmorillonite content, respectively. The hydraulic conductivity of HQ GCL to water was 7.0×10^{-10} cm/s, whereas that of LQ GCL was 2.4×10^{-9} cm/s.

Similar conclusion can be drawn in this study as well. The hydraulic conductivity of GCLs decreased from 2.0×10^{-9} cm/s to 5.0×10^{-10} cm/s as the smectite content increased from 60% to 77% (Fig. 5). The correlation coefficient for this relationship is rather poor (R=0.43), but it is in agreement with the general trends given in the literature (Ashmawy *et al.* 2002, Lee *et al.* 2005). The equation for the best fit line describing the relationship between smectite content and hydraulic conductivity is given below

$$k = 3.1 \times 10^{-8} \times e^{-0.051\,SC} \tag{5}$$

where, k is the hydraulic conductivity in cm/s and SC is the smectite content in percent.

3.5 Relationship between chemical properties of bentonite and hydraulic conductivity of GCLs

In addition to physical and mineralogical properties of bentonite, the relationship between hydraulic conductivity and chemical properties, such as specific surface area and cation exchange capacity, was also evaluated herein. Fig. 6(a) shows this relationship. Based on Fig. 6(a), there is an inverse relationship between hydraulic conductivity of GCLs and the specific surface area of bentonites. In other words, the hydraulic conductivity decreased with increase of specific surface area. The correlation coefficient for this relationship is 0.33. The correlation between specific surface area and hydraulic conductivity is given in Eq. (6)

$$k = 2.5 \times 10^{-9} \times e^{-0.001\,SSA} \tag{6}$$

where, k is the hydraulic conductivity in cm/s and SC is the specific surface area in m^2/g.

Although hydraulic conductivity slightly decreased as the cation exchange capacity of bentonite increased, this relationship is very poor (Fig. 6(b)). For this reason, neither equation nor correlation coefficient is given herein.

This study showed that there is poor correlation between hydraulic conductivity of GCLs and mineralogical and chemical properties of bentonite. However, Guyonnet *et al.* (2009) reported an increasing trend of CEC with smectite content. They proposed a range between these two variables, including the data from Kaufhold *et al.* (2002) as well. It should be noted that Koufhold *et al.* (2002) reported a range for smectite content in their study. Guyonnet *et al.* (2009) used mean values of this range with an uncertainty of ±5%. The findings of this study are plotted together with the data given in Kaufhold *et al.* (2002) and Guyonnet *et al.* (2009) as shown in Fig. 7. Most of the data gathered from this study falls within the proposed range. One data, which is for AP-GCL-1, is slightly outside of the proposed range. Other two data for GCL-4 and AP-GCL-3 are far from the proposed range due to having CEC values greater than 100 cmol/kg. These values seem to be slightly greater when compared to the values in Kaufhold *et al.* (2002) and Guyonnet *et al.* (2009). However, literature studies also report such greater values for bentonites (Hang and Brindley 1970, Kahr and Madsen 1995, Yukselen and Kaya 2008).

3.6 Relationship between post test properties of bentonite and hydraulic conductivity of GCLs

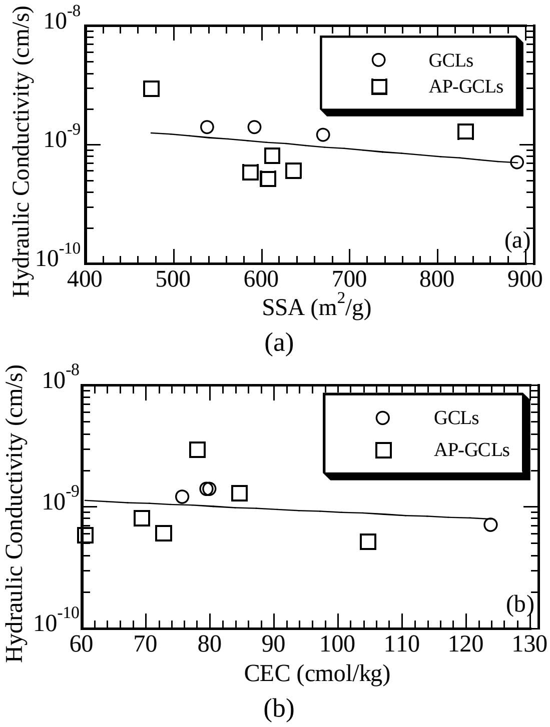

Fig. 6 Relationship between hydraulic conductivity of GCLs and (a) specific surface area (SSA) and (b) cation exchange capacity of bentonites

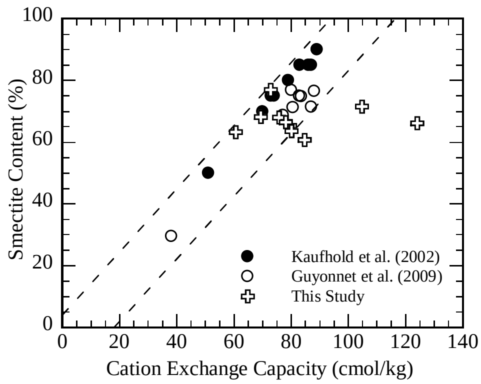

Fig. 7 Cation exchange capacity (CEC) versus smectite content of bentonites

As mentioned before, AP-GCLs were prepared in the laboratory without punching or bonding. That is, there was no fiber attaching the geotextile components. Thus, AP-GCLs were free to swelling during the hydraulic conductivity tests. Table 4 summarizes the final height and water content of GCLs and AP-GCLs. As expected, AP-GCLs had greater final heights than those of GCLs. Regardless of permeant water, the final GCL heights were between 0.63 cm and 0.86 cm. In contrast, the final GCL height for AP-GCLs was as much as 1.41 cm. In the case of GCL final water contents, except GCL-4, they were within the range of 90-128%. However, the final water content of GCL-4 was 236% which is almost twice of the other GCLs. This is possibly due to the polymerized bentonite used in GCL-4. The final water contents of AP-GCLs were ranged between 87% and 268%. In general, fiber free

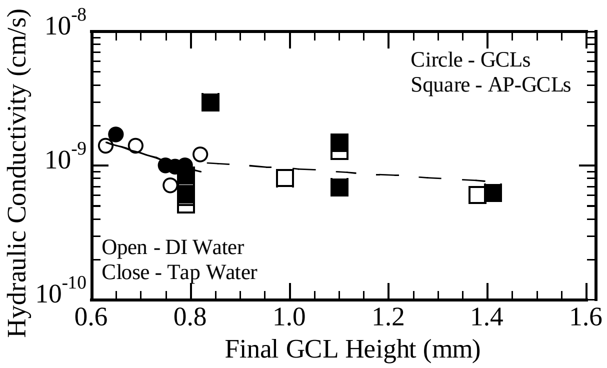

Fig. 8 Relationship between final height and hydraulic conductivity of GCLs and AP-GCLs

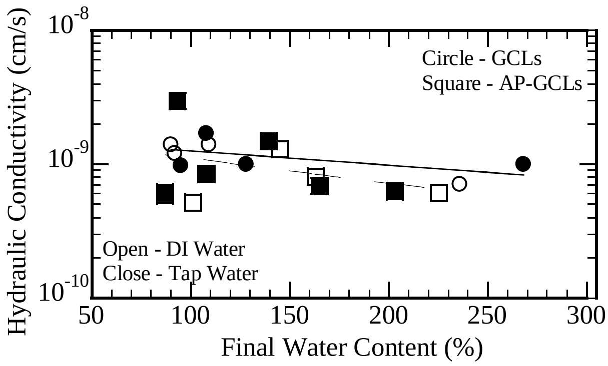

Fig. 9 Relationship between final water content and hydraulic conductivity of GCLs and AP-GCLs

characteristics allowed AP-GCLs to have greater water contents with respect to GCLs.

Initially, the hydraulic conductivity was correlated with final height of GCLs and AP-GCLs (Fig. 8). On account of fiber free characteristics for AP-GCLs, separate relationships were assigned for each of the synthetic material. The trends for both materials are the same and indicate that the hydraulic conductivity decreased when final GCL height increased. The data for AP-GCLs are rather scattered. Thus, the slope of best-fit line for AP-GCL is less than that for GCL. Even if the correlation coefficient is low for AP-GCL (R < 0.30), the correlation equation is given in Eq. (7). In contrast, the correlation coefficient for GCL is fairly good (i.e., R=0.66) which is also significantly greater than AP-GCL. The correlation equation of best-line for GCL is given as in the following

$$k = 1.7 \times 10^{-9} \times e^{-0.55\,FH} \text{ (AP-GCL)} \quad (7)$$

$$k = 8.0 \times 10^{-9} \times e^{-2.67\,FH} \text{ (GCL)} \quad (8)$$

where, k is the hydraulic conductivity in cm/s and FH is the final height of GCL and AP-GCL in cm. It is noteworthy that Eq. (8) should be used with care, because it is given for a limited range of GCL final heights. If final GCL height is greater than 0.8, it will be better using Eq. (7) instead of Eq. (8).

The final water content versus hydraulic conductivity is given in Fig. 9. Separate best-fit lines were assigned for GCLs and AP-GCLs. Fig. 9 shows that increase in the final water content decreases the hydraulic conductivity. The

Table 5 Summary of the multiple linear regression analyses

Dependent Variable	Independent Variables	R	F	F_{st}	S.L.
Hydraulic Conductivity	CC and w_L	0.90	12.1	5.14	0.008
	CC and I_p	0.89	11.1	5.14	0.010
	CC, w_L, I_p	0.94	13.2	5.41	0.008

F_{st}: $F_{statistics}$
S.L.: Significance Level

trends were similar for GCLs and AP-GCLs. However, the correlation coefficient for GCL is greater than that for AP-GCL (0.63 vs. 0.33). The correlation equations are given as follows

$$k = 1.7 \times 10^{-9} \times e^{-0.004\,FWC} \text{ (AP-GCL)} \quad (9)$$

$$k = 1.6 \times 10^{-9} \times e^{-0.002\,FWC} \text{ (GCL)} \quad (10)$$

where, k is the hydraulic conductivity in cm/s and FWC is the final water content of GCL and AP-GCL in percent.

3.7 Statistical evaluation of the results

In this study, the results were evaluated in terms of correlation coefficients. Based on the obtained results, it is found that physical parameters such as liquid limit, clay content, plasticity index had correlation coefficients greater than 0.8. It means 80% of the input data close to the fitted regression line or 80% of the total variation is described by the variation in independent variables.

In addition to this, ANOVA tests were applied throughout the study. This helps to analyze the variance analysis of the data in terms of calculated F and significance level, F (Benson *et al.* 2005; Ö ren and Kaya 2014). For this purpose, mean squares were determined by dividing sum of squares regression and residuals to their corresponding degrees of freedom. For simple regression analysis, the degree of freedom for the regression is one, whereas the degree of freedom for the residual is 7 or 8 depending on the total number of the data. In another words, the degree of freedom for the residual is 7 if total of 9 data was evaluated (sometimes GCL-4 was not considered) or 8 if total of 10 data was considered during the analysis. The degree of freedom for the residual is 18 when swell index was evaluated with hydraulic conductivity. F is the ratio of mean squares of regression to residual. The calculated F was compared with the F statistics ($F_{statistics}$) which can be found in many text books (Wilcox 2003). If there is no statistically significant variation between dependent and independent variables or F < $F_{statistics;}$ then the null hypothesis is accepted. In contrast, if F is greater than $F_{statistics}$, then the null hypothesis is rejected. That is, the relationship between hydraulic conductivity and independent variable is statistically significant. The significance level (α) was set at 0.05 for all analyses. This value means that the probability of regression is 5% by chance (Wilcox 2003).

Based on above explanation, the calculated F obtained from simple regression analyses were compared with the corresponding $F_{statistics}$. The null hypothesis was rejected for the physical properties of bentonite, when predicting the hydraulic conductivity. It is because of the fact that the calculated F for some physical parameters are remarkably greater than $F_{statistics}$=5.59 [for liquid limit F=14.1-14.8 and plasticity index F=11.8-12.9 (depending on the method); for clay content F=19]. The F for swell index is 15.6 which is greater than $F_{statistics}$=4.41 as well. The significance levels for liquid limit, plasticity index, clay content and swell index are 0.003, 0.08, 0.006 and 0.0009, respectively, all of which are close to zero. The smaller the significance of F, the greater the probability of the regression is not by chance. By assuming liquid limit, for example, this value means that only 0.3% of the output data is by chance.

In contrast, the calculated F for mineralogical and chemical parameters (SSA and CEC) are less than $F_{statistics}$=5.32 (for smectite content F=1.85, for SSA F=0.98 and for CEC F=0.29). The significance level for smectite content, SSA and CEC are 21%, 35% and 60%, respectively, which is much greater than the significant levels for the physical parameters. Therefore, the null hypothesis was accepted for the chemical properties of bentonite.

The multiple linear regression analyses were also conducted on the physical parameters. Since they had no statistically significant relationships with the hydraulic conductivity of GCLs, chemical parameters were not taken into account during the analyses. In addition to chemical parameters, the post-test parameters such as final GCL height and water content were not considered as an independent variable in multiple regressions because of their low correlation coefficients. Among physical parameters, the correlation coefficient with swell index is less than that with liquid limit, plasticity index and clay content. Besides, total number of the data for swell index is twice of the others. It is not convenient to apply multiple linear regressions on the independent variables that have different total number of data. Thus, swell index was not considered in the multiple linear regression analysis. During the analyses the combinations of liquid limit-clay content, plasticity index-clay content and liquid limit-plasticity index-clay content were considered as input parameters. The results of these analyses are summarized in Table 5. As presented, applying multiple linear regressions negligibly improved the coefficient of correlations and statistical significance when compared to simple linear regression model.

Based on these findings, it is seen that simple regression analysis can adequately be used to predict the hydraulic conductivity of GCLs rather than multiple regression analysis. The hydraulic conductivity can be estimated well with the physical parameters of bentonite rather than smectite content, SSA and CEC. The order of the physical parameters can be given as follows depending on their correlation coefficients: clay content > liquid limit > plasticity index > swell index.

4. Conclusions

This study discusses the hydraulic conductivity of GCLs and AP-GCLs to DIW and TW and its correlation with physicochemical properties of bentonites. The findings of this study are summarized below:

- The hydraulic conductivity of GCLs and AP-GCLs to DIW was close to the hydraulic conductivity to TW. Regardless of the permeant water, the hydraulic conductivities were within the range of 5.2×10^{-10} – 3.0×10^{-9} cm/s.
- The hydraulic conductivity of GCLs and AP-GCLs decreased as the liquid limit, plasticity index, clay content, swell index, smectite content, SSA and CEC decreased. In contrast, plastic limit had no influence on the hydraulic conductivity.
- Simple linear regression analyses were conducted for all relationships. Since these relationships were interpreted on a semi-log axis, the correlation equations were given in terms of exponential functions. Hydraulic conductivity versus clay content had the greatest correlation coefficient (i.e., R=0.85) among others. The correlation coefficients of hydraulic conductivity with liquid limit, plasticity index and swell index were good and 0.82, 0.80 and 0.68, respectively. In contrast, poor correlation coefficients were obtained when hydraulic conductivity was evaluated with smectite content, SSA and CEC (R < 0.5).
- In addition, some post-test properties of bentonite were also correlated with hydraulic conductivity. Final height and final water content were the independent variables in these correlations. Since AP-GCLs were fiber free, separate lines were fitted for GCLs and AP-GCLs. In case of final height, the correlation coefficient of GCL was 0.66, whereas that of AP-GCL was less than 0.3. Similarly, the correlation coefficients of GCLs and AP-GCLs with final water content were 0.63 and 0.33, respectively. Since they were free to swell, the data for AP-GCLs were rather scattered. Therefore, the correlation coefficients of AP-GCLs found less than those of GCLs.
- Multiple linear regression analyses were also applied to the data. Only physical parameters were taken into consideration as independent variables. Different combinations of liquid limit, plasticity index and clay content were used in the analyses. The results showed negligible increase in the correlation coefficients and calculated F. Thus, simple regression analysis has been suggested herein to determine hydraulic conductivity of GCLs because of its simplicity.

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