Avrupa Bilim ve Teknoloji Dergisi
Özel Sayı 28, S. 1269-1273, Kasım 2021
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Araştırma Makalesi

www.ejosat.com ISSN:2148-2683

European Journal of Science and Technology
Special Issue 28, pp. 1269-1273, November 2021
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Research Article

Influence of Mass Per Unit Area on the Hydraulic Conductivity of Geosynthetic Clay Liners (GCLs)

Fatih Polat[1*], Tuğçe Özdamar Kul[2], Ali Hakan Ören[3]

[1*] Dokuz Eylül University, Graduate Scholl of Natural and Applied Sciences, Izmir, Turkey, (ORCID: 0000-0001-5652-0433), polat.fatiih@gmail.com
[2] Dokuz Eylül University, Faculty of Engineering, Departmant of Civil Engineering, Izmir, Turkey, (ORCID: 0000-0003-3016-6477), tugce.ozdamar@deu.edu.tr
[3] Dokuz Eylül University, Faculty of Engineering, Departmant of Civil Engineering, Izmir, Turkey, (ORCID: 0000-0002-3024-3084), ali.oren@deu.edu.tr

(1st International Conference on Applied Engineering and Natural Sciences ICAENS 2021, November 1-3, 2021)

(**DOI:** 10.31590/ejosat.1013103)

ATIF/REFERENCE: Polat, F., Özdamar Kul, T., Ören, A.H. (2021). Influence of Mass Per Unit Area on the Hydraulic Conductivity of Geosynthetic Clay Liners. *European Journal of Science and Technology*, (28), 1269-1273.

Abstract

In the content of this study, barrier performance of geosynthetic clay liners (GCLs) in terms of mass per unit area of bentonite (MPUA) was investigated. For this purpose, a Na-GCL with MPUAs of 3.0 and 5.0 kg/m^2 were tested. Hydraulic conductivity tests were conducted with deionized water (DIW) and calcium chloride solutions prepared with various concentrations (i.e., 15 mM and 30 mM $CaCl_2$). The free swell characteristic of bentonite in GCL was also determined. The swell index results showed that increase in the $CaCl_2$ concentration results to a decrease in the swell index values. That is, swell indices were 23, 13, and 10 mL/2g with DIW, 15 mM, and 30 mM $CaCl_2$, respectively. The influence of MPUA on the hydraulic performance of Na-GCL was not observed with DIW. The hydraulic conductivity of GCL with MPUA of 3.0 and 5.0 kg/m^2 was 4.6×10^{-11} and 2.1×10^{-11} m/s, respectively. However, MPUA had a significant effect on the hydraulic conductivity when $CaCl_2$ solutions were used as the permeant. Increase in MPUA caused to a decrease in the hydraulic conductivity with $CaCl_2$ solutions. It was found with 30 mM $CaCl_2$ solution that the hydraulic conductivity of GCL with MPUA of 5.0 kg/m^2 was almost 16 times lower than that of GCL with MPUA of 3.0 kg/m^2 (8.3×10^{-9} vs 1.3×10^{-7} m/s).

Keywords: Hydraulic conductivity, geosynthetic clay liners, mass per unit area, swell index, calcium chloride.

Birim Alan Başına Bentonit Kütlesinin Geosentetik Kil Örtülerin (GKÖ'ler) Hidrolik İletkenliği Üzerine Etkisi

Öz

Bu çalışma kapsamında, geosentetik kil örtülerin (GKÖ'ler) bariyer performansı birim alan başına bentonite kütlesi (BABBK) açısından araştırılmıştır. Bu amaç doğrultusunda BABBK'si 3.0 ve 5.0 kg/m^2 olan Na-GKÖ'ler test edilmiştir. Hidrolik iletkenlik testlerinde deiyonize su (DS) ve farklı konsantrasyonlarda kalsiyum klörür (15 mM ve 30 mM $CaCl_2$) çözeltileri kullanılmıştır. Ayrıca GKÖ içerisindeki bentonitin serbest şişme karakteristiktikleri de belirlenmiştir. Şişme indeks deney sonuçları, $CaCl_2$ konsantrasyonundaki artışın şişme indeks değerlerinde azalmaya sebep olduğunu göstermiştir. Yani şişme indeksleri DS, 15 mM ve 30 mM $CaCl_2$ ile sırasıyla 23, 13 ve 10 mL/2g olarak elde edilmiştir. BABBK'nin Na-GKÖ'nün hidrolik performansı üzerindeki etkisi DS ile gözlenememiştir. GKÖ'nün 3.0 ve 5.0 kg/m^2 BABBK olan GKÖ'lerin DS ile hidrolik iletkenlikleri sırasıyla 4.6×10^{-11} ve 2.1×10^{-11} m/s olarak elde edilmiştir. Ancak süzdürme sıvısı olarak $CaCl_2$ çözeltileri kullanılması hidrolik iletkenlik üzerinde önemli bir etki yaratmıştır. $CaCl_2$ çözeltileri ile yapılan deneylerde BABBK'deki artış hidrolik iletkenlikte azalmalara neden olmuştur. 30 mM $CaCl_2$ çözeltisinde 5.0 kg/m^2 BABBK'ye sahip GKÖ'nün hidrolik iletkenliği 3.0 kg/m^2 BABBK'ye sahip GKÖ'nün hidrolik iletkenliğinden 16 kat daha düşük olduğu bulunmuştur (8.3×10^{-9} vs 1.3×10^{-7} m/s).

Anahtar Kelimeler: Hidrolik iletkenlik, geosentetik kil örtüler, birim alan başına bentonite kütlesi, şişme indisi, kalsiyum klorür.

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[*] Corresponding Author: polat.fatiih@gmail.com

1. Introduction

Geosynthetic clay liners (GCLs) are composite materials manufactured with geotextile and bentonite by needle punching, stitch or adhesive bonding (Koerner, 2005). Due to their low hydraulic conductivity and high swelling potential, sodium bentonite (Na-Bentonite) is used in GCLs when compared to other clays (Shackelford et al., 2000).

The barrier performance of GCLs are mostly evaluated with the laboratory hydraulic conductivity tests. Different testing conditions such as prehydration, permeant type and concentration, effective stress etc. can be simulated in the laboratory (Katsumi et al., 2008; Kolstad et al., 2004; Petrov et al., 1997; Shackelford et al., 2000).

Lee et al., 2005 investigated the index properties of two sodium bentonites which were taken from the GCLs. Then, they correlated index properties with the hydraulic conductivity of GCLs. DIW and $CaCl_2$ solutions were used as the permeant in the hydraulic conductivity tests in their study. According to the experimental results, the authors concluded that increase in the $CaCl_2$ concentration resulted to an increase in the hydraulic conductivity of GCLs. The reason of this increase during permeation was attributed to the cation exchange that took place between Na+ present in bentonite and Ca2+ present in permeant. That is, Na+ ions were exposed to chemical attacks of Ca2+ during the tests which result in cation replacement in the exchangeable cation sites of bentonite.

Lee and Shackelford., 2005 also investigated the impact of bentonite quality on the hydraulic conductivity of GCLs. They conducted hydraulic conductivity tests on GCLs with DIW and $CaCl_2$ solutions with various concentrations. In this study, it is revealed that the hydraulic conductivity increases with an increase in the $CaCl_2$ concentration.

Rowe et al., 2017 carried out hydraulic conductivity tests on exhumed GCLs after 5 and 7 years in a cover. The authors investigated the effect of mass per unit area (MPUA) on the hydraulic conductivity of GCLs under different conditions. They performed hydraulic conductivity tests with DIW on exhumed GCLs with MPUA ranged between 4.3 and 6.0 kg/m^2. According to the results, the hydraulic conductivity of GCLs decreased as the MPUA increased.

It is seen from literature studies that testing conditions can affect the hydraulic performance of GCLs. The influence of material properties such as MPUA of bentonite on the barrier performance of GCLs has been scarcely investigated in detail so far. Therefore, in the content of this study the influence of MPUA of bentonite on the hydraulic conductivity of GCLs to $CaCl_2$ solutions were investigated and discussed.

2. Materials and Methods

2.1. Materials

In this study, one local GCL was used. This GCL consist of a layer of sodium bentonite (Na Bentonite) sandwiched between woven and nonwoven geotextiles. GCL roll has a bentonite MPUA ranged between 3.0 and 6.0 kg/m^2. The specific gravity of bentonite taken from the GCL was 2.70 whereas the liquid limit and plasticity index was 231 and 170, respectively. The permeants used in this study were deionized water (DIW) and calcium chloride solutions ($CaCl_2$) prepared at 15 and 30 mM 15 mM $CaCl_2$ can be accepted as neither weak nor strong concentration level (i.e. medium), whereas 30 mM was accepted as the strong chemical salt herein. $CaCl_2$ solutions were used as the permeant to show the influence of cation exchange between the permeant and the GCL in terms of barrier performance. $CaCl_2$ solutions were prepared by dissolving $CaCl_2$.2H2O in DIW.

2.2. Methods

2.2.1. Sample Preparation

Circular GCL samples were cut from the roll. For this purpose, 110 mm in diameter circles were drawn on the GCL roll. Afterwards these circles were cut using a mini fabric cutter. The diameter and mass of the samples were measured, and their MPUAs were calculated. Then the samples were classified according to their MPUA values. The sample with specified MPUA was selected from that group. Then, the diameter of this group of GCL samples were reduced to 100 mm. The MPUA value of the specimen was recalculated and recorded.

2.2.2. Free Swell Test

Free swell tests were performed on Na-Bentonite which was taken from the GCL by following the ASTM 5890 (ASTM D5890 − 19, 2010). DIW and $CaCl_2$ solutions with different concentrations were used as the reagent water. Before starting to the test, bentonite was grounded with mortar and pestle to sieve from No. 200. U.S. Standard Sieve (0.075 mm). Then, bentonite was dried in an oven at 105°C for 24 hours. To start the test, approximately 90 mL of reagent water was filled in a 100-mL graduated cylinder. Then, 2.0 g of oven-dried bentonite was poured in the cylinder by 0.1 g increments. Between each increments, at least 10 minutes should be waited. Lastly, the additional reagent water was used to rinse any particles adhering to the sides of the cylinder and to fill the cylinder to 100-mL level. Swell index of was measured and recorded after 24 h.

2.2.3.Hydraulic Conductivity Test

Hydraulic conductivity tests were carried out using flexible-wall permeameters (Fig. 1) by following the ASTM: D6766-12 (ASTM:D6766-12, 2012). The falling head constant tail water method was applied throughout the tests. Instead of porous stones, heavy type of non-woven geotextiles were used. GCL sample was sandwiched between two heavy non-woven geotextiles and placed on the base pedestal of the permeameter cell. Then, the perimeter of the GCL sample was sealed with Na-bentonite to prevent sidewall leakage. Latex membrane was placed over the GCL and three O-rings were attached on top and bottom pedestals. The permeameter was filled with tap water. The hydraulic conductivity tests were performed under 35 kPa effective stress and an average of hydraulic gradient of 35. To simulate the field conditions, the flow direction was kept from top to bottom.

Fig. 1 General appearance of flexible wall permeameter cells

3. Results and Discussion

3.1. Swell Index

Swell index tests were conducted with DIW, 15 mM and 30 mM $CaCl_2$ solutions. The results of these tests are shown Fig. 2.

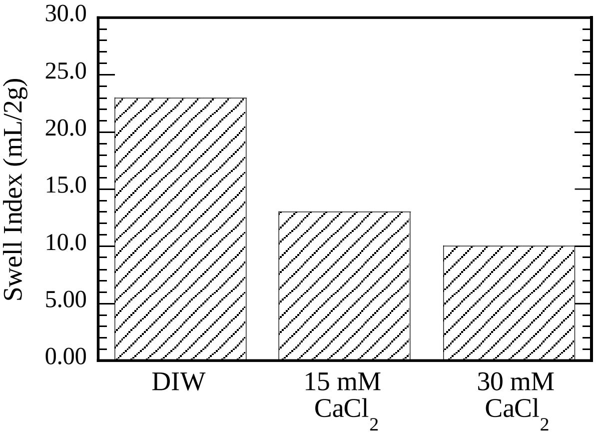

Fig. 2 Results of swell index tests performed on the Na-Bentonites with DIW and $CaCl_2$ solutions.

As seen in Figure 2, the swell index decreases while increasing the $CaCl_2$ concentration. Swell index was 23 mL/2g in DIW whereas it decreased to 13 mL/2g in 15 mM $CaCl_2$ and 10 mL/2g in 30 mM CaCl2 solution. The reason for this behaviour is the compression of the diffuse double layer surrounding the bentonite particles after cation replacement (Jo et al., 2001; Lee et al., 2005). Therefore, it can be stated that swelling of bentonite is restricted after bombarding the bentonite with Ca2+ ions. The swelling of bentonite was also affected from the CaCl2 concentrations. That is, increasing the concentration also increases the amount of divalent cations present in the permeant, resulting low swell index.

3.2. Hydraulic Conductivity

The results of hydraulic conductivity tests are shown in Figure 3 for GCLs with MPUA of 3.0 (shown with open symbols) and 5.0 kg/m^2 (shown with closed symbols).

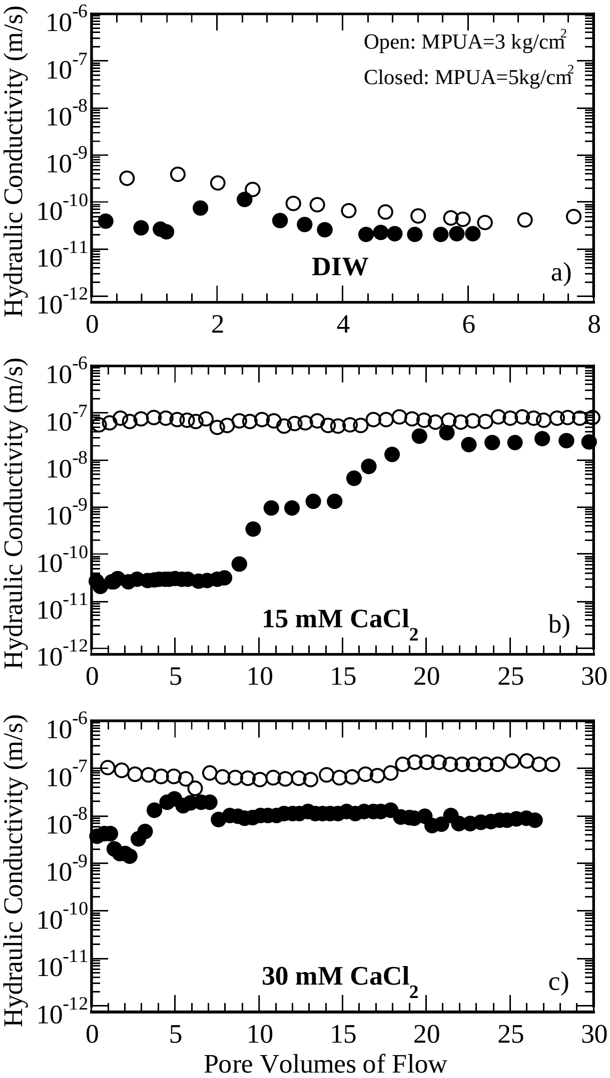

Fig. 3 Hydraulic conductivity of GCL to: a) DIW, b) 15 mM $CaCl_2$, c) 30 mM $CaCl_2$

Figure 3a shows the hydraulic conductivity behaviours of GCLs permeated with DIW. The hydraulic conductivity of GCL with MPUA of 3.0 kg/m^2 was approximately 3.1×10^{-10} m/s at the beginning of the test (up to ~2.6 PVF). Then, the hydraulic conductivity of this sample decreased to 4.6×10^{-11} m/s due to the swelling of bentonite during permeation. The hydraulic conductivity of GCL sample with higher MPUA (i.e. 5.0 kg/m^2) had lower hydraulic conductivity (i.e. ~3.0×10^{-11} m/s) even after the beginning of the test. When comparing final hydraulic conductivities between these two samples, the difference seems to be not significant, indicating MPUA has negligible influence on the hydraulic conductivity when DIW was used as the permeant. Since bentonites in GCLs have high swelling potential with DIW, particles swell incredibly and fill the inter aggregate pores (particles form aggregates in GCLs when air dried), regardless of the MPUA.

The hydraulic conductivities of GCLs with $CaCl_2$ solutions are shown in Figure 3b-c. As seen in Figure 3b, the hydraulic conductivity of GCL with MPUA of 3.0 kg/m^2 to 15 mM $CaCl_2$ was high (i.e. 1.3×10^{-7} m/s) throughout the test. As previously mentioned, 15 mM CaCl2 was medium level salt solution that may have an effect on the hydraulic conductivity. Indeed, the reason for high hydraulic conductivity was due to less amount of bentonite available in GCL. That is, less amount of bentonite could not swell sufficiently and fully fill the gaps between the aggregates to slow the flow across the GCL. In contrast, the hydraulic conductivity of GCL with MPUA of 5.0 kg/m^2 was initially low (1.0×10^{-11} m/s) and then increased about 4 orders of magnitude (~1.0×10^{-7} m/s). The greater amount of bentonite initially filled the inter aggregate gaps and formed an impermeable layer. Subsequently, however, Na+ in bentonite was exposed to cation exchange with Ca2+ in $CaCl_2$ solution during permeation. Therefore, the hydraulic conductivity of GCL increased with time (Figure 3b).

The hydraulic conductivity of GCL with MPUA of 3.0 kg/m^2 to 30 mM $CaCl_2$ was almost similar to that of 15 mM $CaCl_2$ (Figure 3c). The hydraulic conductivity of GCL with MPUA of 3.0 kg/m^2 was 1.3×10^{-7} m/s. The hydraulic conductivity of GCL with MPUA of 5.0 kg/m^2 was about 1.0×10^{-9} m/s at the beginning of the test and increased to 1.0×10^{-8} m/s after 3.8 pore volume of flow (PVF) passed across the sample. Although the amount of bentonite in GCL is relatively high, the cation exchange between the permeant solution and the GCL still took place, resulting high hydraulic conductivity. Higher $CaCl_2$ concentration accelerate the cation exchange mechanism and bentonite particles loss their swelling ability. The final hydraulic conductivity of GCL to 30 mM $CaCl_2$ with MPUA of 5.0 kg/m^2 was reached to 8.3×10^{-9} m/s when test was terminated (Figure 3c).

According to the obtained test results the final hydraulic conductivities were also calculated by taking the average of last four consecutive readings. The final hydraulic conductivities of GCLs are summarized in Table 1.

Table 1. Final hydraulic conductivities of GCLs

MPUA (kg/m^2)	**Permeant Solution**	**PVF**	**Hydraulic Conductivity (m/s)**
3.0	DIW	8.79	4.6×10^{-11}
3.0	15 mM $CaCl_2$	30.70	7.6×10^{-8}
3.0	30 mM $CaCl_2$	27.58	1.3×10^{-7}
5.0	DIW	6.10	2.1×10^{-11}
5.0	15 mM $CaCl_2$	36.83	1.5×10^{-8}
5.0	30 mM $CaCl_2$	26.55	8.3×10^{-9}

The effect of permeant type on the final hydraulic conductivity is shown in Figure 4. In this figure, the final hydraulic conductivities of GCLs which have the same MPUAs were compared. It is seen in Figure 4 that the final hydraulic conductivities of GCLs to $CaCl_2$ were significantly higher than those conducted with DIW. However, it is also seen that the final hydraulic conductivities of GCLs to 15 mM and 30 mM $CaCl_2$ solutions were close to each other.

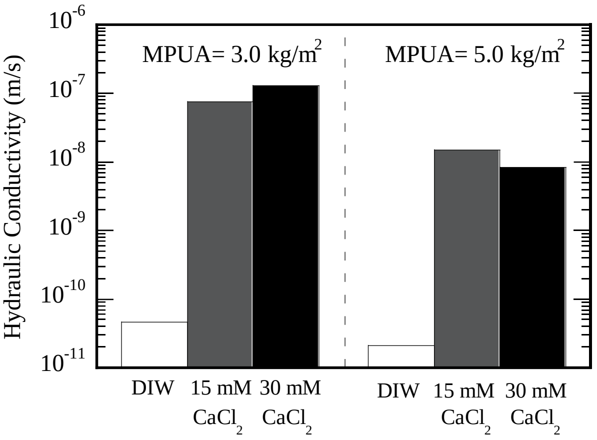

Fig. 4 Final Hydraulic Conductivities of GCL to $CaCl_2$ solutions

To show the influence of MPUA on the hydraulic conductivity of GCL, the hydraulic conductivity ratio (HCR) versus $CaCl_2$ concentration was presented in Figure 5. The HCR was calculated by dividing the final hydraulic conductivity of GCL with MPUA of 3.0 kg/m^2 to the final hydraulic conductivity of GCL with MPUA of 5.0 kg/m^2. As seen in Figure 5 hydraulic conductivity ratio increased with an increase in the $CaCl_2$ concentration. This shows that MPUA becomes a significant parameter when concentration of salt solution increased. Because HCR increased from factor of 2.2 to 16 when permeant was changed from DIW to 30 mM $CaCl_2$ solution.

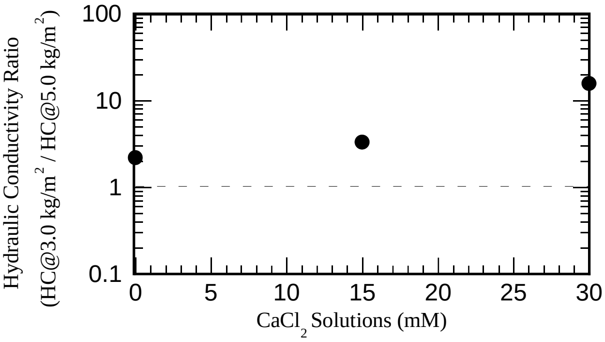

Fig. 5 Change in hydraulic conductivity ratio (HCR) as a function of $CaCl_2$ solutions

4. Conclusions

In this study, hydraulic conductivity and swell index tests were conducted to determine the influence of MPUA on GCLs. The obtained results are summarized below:

Swell index of bentonite was 23 mL/2g in DIW. However, it was 15 mL/2g in 15 mM and 10 mL/2g in 30 mL/2g $CaCl_2$ solution. The reduction in the swell index was expected because the thickness of diffuse double layer surrounding the bentonite particles suppressed with an increase in the concentration level and valence of the cation. The swell index obtained in 30 mM $CaCl_2$ solution (10 mL/2g) is a typical value for Ca-bentonite. Thus, the swell indices reported herein are in good agreement with the data reported in the literature.

The influence of MPUA on the hydraulic conductivity of GCLs was not observed apparently when DIW was the permeant. In contrast, the influence of MPUA was clearly seen when $CaCl_2$ solutions were used as the permeant. That is increasing MPUA caused a decrease in the hydraulic conductivity with $CaCl_2$ solutions.

The final hydraulic conductivity values of GCLs was affected from the permeant type and MPUA. However, the influence of MPUA on GCLs with $CaCl_2$ solutions may not always be visible in terms of final hydraulic conductivity. This effect could be apparently seen at the beginning of the hydraulic conductivity tests.

5. Acknowledge

This study has been financially supported by the Scientific and Technological Research Council of Turkey (TUBITAK) with a Grant No: 119R044. The writers are grateful to TUBITAK for this valuable support.

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