Moisture-Suction Relationships for Geosynthetic Clay Liners

Courbes de rétention des membranes géotextiles chargées en argile

Hanson J.L., Risken J.L.
California Polytechnic State University, San Luis Obispo, U.S.A.
Yeşiller N.
Global Waste Research Institute, San Luis Obispo, U.S.A

ABSTRACT: A laboratory investigation was conducted to determine the moisture-suction relationships for Geosynthetic Clay Liners (GCLs) under as-received conditions (moisture contents in the range of 14-27%) and subsequent to wet-dry cycles (20 cycles at 50% moisture content). The moisture-suction relationships were developed using combined pressure plate, filter paper, and relative humidity methods over a wide range of suction. Tests were conducted on three types of common GCLs (two conventional and one multi-component) that contained granular bentonite and bonded with needlepunching. The responses of conventional and multi-component GCLs and as-received and wet-dry cycled GCLs were different. For the multi-component GCL, the air entry suction was lower for drying and higher for wetting than for the conventional GCLs. Residual suction for the multi-component GCL was higher than that for the other GCLs. The extent of hysteresis decreased and the differences between drying and wetting curves reduced for the wet-dry cycled specimens. Macro- and microstructural variations determined in grain size distribution and SEM analyses indicated increasing void sizes and nonuniformity in fabric due to wet-dry cycling supporting the observations of moisture-suction variations.

RÉSUMÉ : Une étude en laboratoire a été menée pour déterminer les courbes de rétention des membranes géotextiles chargées en argile dans les conditions de teneur en eau du commerce (de l'ordre de 14-27%) et suite à des cycles de mouillage-séchage (20 cycles à 50% d'humidité). Les courbes de rétention ont été mesurées en utilisant une plaque de pression et du papier filtre, et des méthodes de contrôle en humidité relative sur une large gamme de succion. Les tests ont été effectués sur trois types de membranes (deux conventionnelles et une multi-composants) qui contenaient de la bentonite granulaire et assemblés par aiguilletage. Les réponses des géomembranes conventionnelles et multi-composants étaient différentes selon les conditions d'essai. Pour la membrane multi-composants, la succion d'entrée d'air était inférieure après séchage et supérieure après mouillage à celle des membranes conventionnelles. La succion résiduelle pour la membrane multi-composants était également supérieure à celle des membranes conventionnelles. L'amplitude de l'hystérésis a diminué, de même que les différences entre les courbes de mouillage et séchage se sont réduites pour les échantillons ayant subi des cycles de mouillage-séchage. Les variations de la macro- et microstructure, en termes de distribution de la taille des grains et des analyses au MEB, ont montré une augmentation de la taille des vides et une non-uniformité de la structure induites par les cycles de mouillage-séchage. Ces résultats confirment les observations des courbes de rétention.

KEYWORDS: Geosynthetic Clay Liner, GCL, suction, moisture-suction curve, fabric, shrinkage, unsaturated.

1 INTRODUCTION

Geosynthetic clay liners (GCLs) are increasingly used to replace compacted clay liners in containment systems due to various perceived advantages of the GCLs including low thickness, low hydraulic conductivity, ease of installation, self-healing capability, and resistance to environmental conditions (e.g., cyclic freeze-thaw or wetting-drying). Even though GCL use has become commonplace in containment systems, concerns remain regarding the long-term field performance (NRC 2007).

Significant variations in the field moisture content of GCLs (e.g., Meer and Benson 2007, Scalia and Benson 2011) have been reported. Moisture transfer between GCLs and soils also has been reported (e.g., Olsen 2011). In general, GCLs remain unsaturated in service based on reported moisture contents. Limited information is available on moisture-suction relationships and water retention characteristics of GCLs, which control mechanical, hydraulic, and thermal properties of the GCLs as well as directly influence moisture transfer between GCLs and soils. Data for conventional GCLs indicated that the structure of GCLs affected moisture retention characteristics (Beddoe et al. 2011). Data are not available for multi-component GCLs or GCLs that have undergone wet-dry cycling.

This investigation was conducted to determine the influence of GCL type and wet-dry cycling on moisture-suction relationships. The investigation was supplemented by microscopy analysis of the bentonite component of the GCLs.

2 EXPERIMENTAL TEST PROGRAM

The test program included investigation of three types of GCLs (Table 1) representative of typical materials used in practice in the U.S. All of the GCLs were bonded by needlepunching and contained granular bentonite:

- WN2: conventional medium weight GCL with a lightweight slit-film woven geotextile and heavyweight nonwoven geotextile
- NN1: conventional heavyweight GCL with two heavyweight nonwoven geotextiles
- WNT: multi-component medium weight GCL with a lightweight slit-film woven geotextile and heavyweight nonwoven geotextile/textured geofilm (0.5 mm HDPE)

The GCL specimens were tested at as-received conditions and subsequent to 20 wet-dry cycles. The cycles consisted of wetting the specimens to 50% moisture content for 8 hours and then oven drying the specimens at 60°C for 12 hours for a total cycle duration of 24 hours. A common moisture content range of 45-62% was reported for GCLs exhumed from composite barriers in landfill covers (Scalia and Benson 2011). The 50% moisture content was selected as this moisture content is common in the field and also represents the threshold hydration water content to maintain low hydraulic conductivity (Scalia and Benson 2011).

Table 1. Properties of the GCLs used in the test program

Property	WN2	NN1	WNT
Cover geotextile	Nonwoven	Nonwoven	Woven
Cover mass (g/m^2)	200	200	105
Carrier geotextile	Woven	Nonwoven	Nonwoven/ Geofilm
Carrier mass (g/m^2)	105	200	200/605
Avg. bent. mass (g/m^2)	4000	3900	4000
As-received water content (%)	15-19	19-27	14-15

The moisture-suction characteristics of the GCLs were determined using combined pressure plate, filter paper, and relative humidity methods for the low (30-300 kPa), medium (10-100000 kPa), and high (5000-400000 kPa) suction ranges, respectively. Use of the three methods was required to investigate the wide range of moisture contents and associated suctions for the GCLs. The pressure plate tests were conducted in accordance with ASTM D6836 (Method C), the contact filter paper tests were conducted in accordance with ASTM D5298, and the relative humidity tests were conducted using procedures similar to the tests presented in Beddoe et al. (2011). Specimen diameters were 50, 100, and 100 mm for pressure plate, filter paper, and relative humidity methods, respectively. For drying branches, specimens were submerged to reach saturation whereas for wetting branches, specimens were hydrated with an atomizing sprayer to target moisture contents. Tests were conducted using deionized (DI) water to investigate solely the moisture-suction response of the GCLs without potential effects of chemical interactions from ionic species present in tap water. Microstructure of the specimens was investigated using scanning electron microscopy (SEM). Relatively undisturbed specimens were obtained by sampling clay from the GCL and then fracturing and pulling (instead of cutting and shearing) a subspecimen for image analysis.

3 RESULTS AND DISCUSSION

The results of the moisture-suction tests for the GCLs are presented in Figures 1-3 and Figure 4 for as-received and wet-dry cycled specimens, respectively. Gravimetric moisture contents were used due to the complexities and uncertainties associated with using volumetric moisture content for GCLs. The experimental data were modeled using the Fredlund and Xing (1994) and Pham and Fredlund (2008) methods. The Fredlund and Xing (1994) model commonly has been used for soils and also applied to GCLs (e.g., Beddoe et al. 2011). The Pham and Fredlund (2008) model had been developed to provide gravimetric moisture-suction relationships over the entire range of soil suction for soils that undergo volume change with suction and was adopted for this test program. The results of the Fredlund and Xing (1994) model are presented in Figures 1-4 and the model parameters for the two methods are provided in Tables 2 and 3. Data for air entry and residual suctions also are provided in the tables.

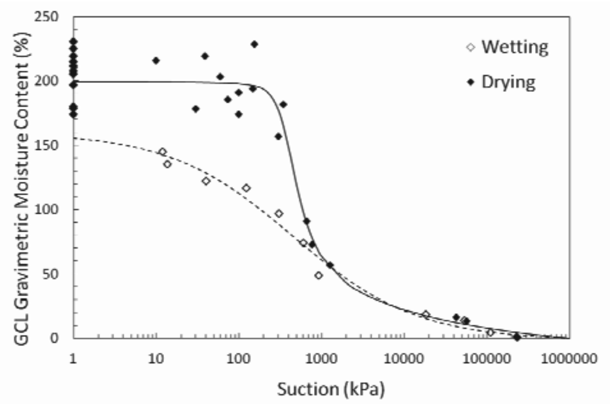


Figure 1. Moisture-suction relationships for WN2.

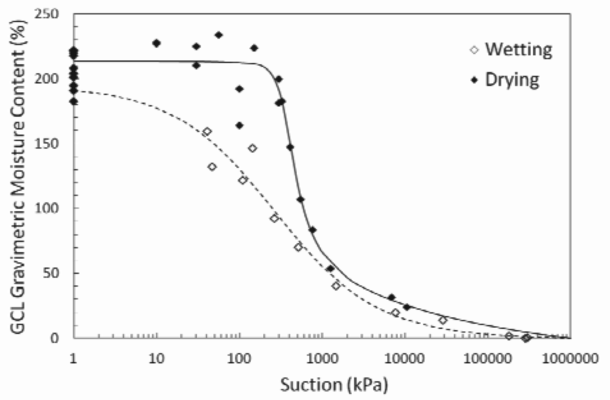


Figure 2. Moisture-suction relationships for NN1.

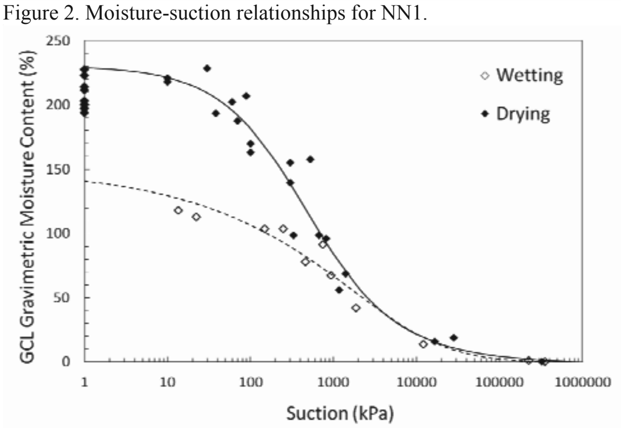


Figure 3. Moisture-suction relationships for WNT.

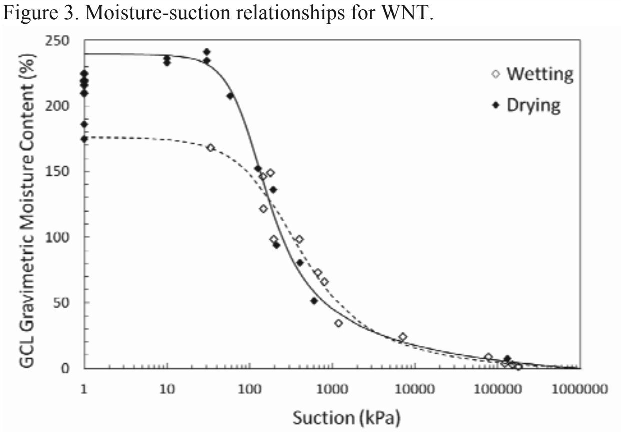


Figure 4. Moisture-suction relationships for NN1 at 20 cycles.

Table 2. Model parameters for drying branches

Parameter	WN2	NN1	NN1-20	WNT
a_f[1]	358	339	91.3	355
m_f[1]	0.678	0.626	0.93	2.01
n_f[1]	4.72	5.78	2.23	0.819
S_1[2]	15.5	0.974	6.86	15.4
S_2[2]	134	114	152	88.1
S_3[2]	11.5	13.5	8.74	8.76
ψ_{ae}[3] (kPa)	176	137	46.5	63
ψ_r[3] (kPa)	1620	1600	650	5220

[1]Fredlund and Xing (1994)
[2]Pham and Fredlund (2008)
[3]Based on Fredlund and Xing (1994)

Table 3. Model parameters for wetting branches

Parameter	WN2	NN1	NN1-20	WNT
a_f[1]	218	210	203	100000
m_f[1]	1.03	2.19	1.28	11.9
n_f[1]	1.28	0.695	1.29	0.368
S_1[2]	25.1	21.7	29.6	43.2
S_2[2]	74.8	72.2	101	115
S_3[2]	8.72	8.12	10.3	6.47
ψ_{ae}[3] (kPa)	78	30.3	66.9	125
ψ_r[3] (kPa)	8960	4250	2260	25000

[1]Fredlund and Xing (1994)
[2]Pham and Fredlund (2008)
[3]Based on Fredlund and Xing (1994)

The general shape and trends for the GCL moisture-suction relationships for the tested GCLs were similar to soils with discernable air entry and residual moisture characteristics and hysteresis observed between drying and wetting curves. The moisture-suction characteristics of as-received WN2 and NN1 were relatively similar, whereas the air entry suction value for the WNT specimens were lower than WN2 and NN1 for drying (Table 2) and higher for wetting (Table 3). Residual suction values for WNT were higher than those for WN2 and NN1 (Tables 2 and 3).

The extent of hysteresis observed for WNT was higher than that for WN2 and NN1. The similar moisture-suction relationships of WN2 and NN1 were attributed to the relatively similar structures of the GCLs. The presence of the geofilm impacted the response of WNT in line with the observations of Beddoe et al. (2011) indicating effects of GCL structure on material behavior.

Hysteresis observed in the tests was quantified for selected moisture levels for GCLs representing as-received/as-placed, common field exhumed, and limiting air entry and residual conditions for NN1 using as-received and wet-dry cycled conditions (Table 4). Wetting and drying cycles affected moisture-suction behavior of NN1 (Figures 2 and 4 and Tables 2-4). For drying, air entry and residual suctions decreased with cycling and for wetting, the opposite trend was observed (increasing air entry and residual suctions with cycling). The extent of hysteresis decreased (i.e., less difference between drying and wetting curves) in response to cycling (Table 4). The limited level of hysteresis observed for cycled specimens was consistent with findings reported by Fredlund et al. (2012) indicating that laboratory water retention tests provide extreme trends (i.e., bounds of limiting envelope) for wetting and drying branches of soil water characteristic curves (SWCCs), whereas in-situ soils are expected to demonstrate less extreme trends bound within the envelope. The GCL data were observed to be similar, in that data for the cycled GCLs representing in-service conditions were generally inside the limiting envelope.

Table 4. Extent of hysteresis between wetting and drying branches

Conditioning	Suction	Wetting Curve ψ (kPa)	Drying Curve ψ (kPa)	Hysteresis (kPa)
No cycles	ψ_r	4245	1602	266
	$\psi_{w=50\%}$	1215	1711	496
	$\psi_{w=75\%}$	521	829	308
	$\psi_{w=100\%}$	249	591	342
	$\psi_{w=125\%}$	118	480	362
	ψ_{ae}	30.3	137	107
20 cycles	ψ_r	2260	650	769
	$\psi_{w=50\%}$	1170	815	356
	$\psi_{w=75\%}$	577	386	191
	$\psi_{w=100\%}$	330	247	83
	$\psi_{w=125\%}$	190	178	12
	ψ_{ae}	66.9	46.5	55

Both macroscopic and microscopic changes occurred in the bentonite due to wet-dry cycling. On a macroscale, the agglomerated particles (i.e., granules) became larger in response to cycling. Grain size distributions of the granules were determined for as-received and cycled conditions. The percent retained on a No. 10 (2.0 mm) sieve for the cycled specimens was 10% greater than the percent retained for the as-received specimens. A photograph of the exposed bentonite component for as-received and cycled conditions is presented in Figure 5.

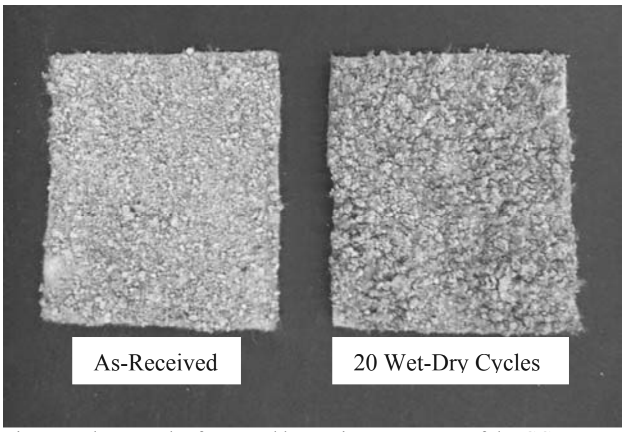
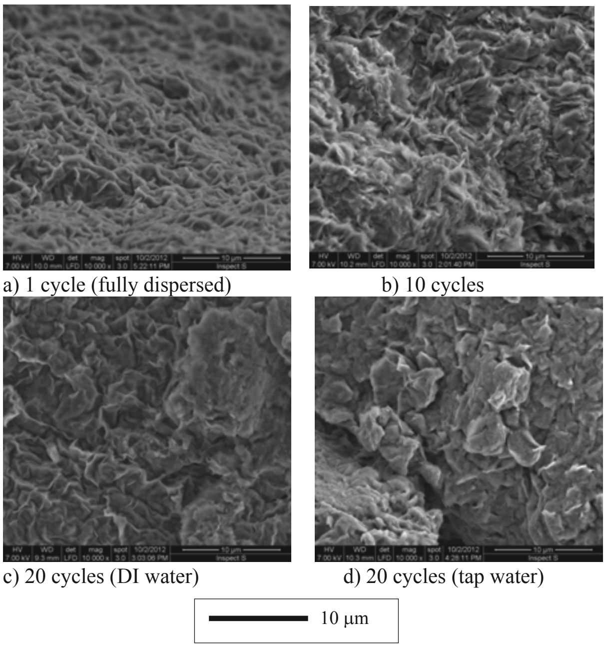


Figure 5 Photograph of exposed bentonite component of the GCLs.

Selected SEM images of bentonite from GCLs at varying stages of wet-dry cycles are presented in Figure 6. All images are presented using the same scale. Variation in the microstructure of the bentonite was observed in the images. The baseline (i.e., dispersed fabric) image for bentonite saturated with DI water (Figure 6a) is consistent with microscopic analysis of pulverized montmorillonite presented by Egloffstein (2001). The bentonite became progressively less oriented and more random with increasing wet-dry cycles. Spaces between particle agglomerations became visible, in particular for the specimens that underwent cycles with tap water. Ultimate shrinkage of the GCLs had occurred by the end of the 20 wet-dry cycles as presented in Olsen et al. (2012).



a) 1 cycle (fully dispersed) b) 10 cycles

c) 20 cycles (DI water) d) 20 cycles (tap water)

Figure 6. SEM images of bentonite from GCL specimens

Both macroscale and microscale effects observed due to wetting and drying may have promoted presence of larger voids and therefore lower values of suction for a given moisture content. The lower suction may have forced the drying curve closer to the wetting curve reducing the extent of hysteresis as observed in the test program for the cycled specimens.

4 CONCLUSION

A laboratory investigation was conducted to determine the moisture-suction relationships for GCLs under as-received conditions (moisture contents in the range of 14-27%) and subsequent to wet-dry cycles (20 cycles at 50% moisture content). The moisture-suction relationships were developed using combined pressure plate, filter paper, and relative humidity methods over a wide range of suction. Tests were conducted on three types of common GCLs (two conventional GCLs and one multi-component GCL) that contained granular bentonite and were bonded with needlepunching. Differences were observed between the conventional and multi-component GCLs and between the as-received and wet-dry cycled GCLs. The air entry suction value for the multi-component GCL was lower than that for the conventional GCLs for the drying branches of the moisture suction curves and higher for the wetting branches of the curves. The residual suction value for the multi-component GCL was higher than the residual suction values for the other two GCLs. The extent of hysteresis decreased and the differences between drying and wetting curves reduced for the wet-dry cycled specimens compared to the as-received specimens. Macro- and microstructural variations determined through grain size distribution and SEM analyses indicated increasing void sizes and nonuniformity in fabric due to wet-dry cycling, supporting the observations for variations in moisture-suction response. The moisture-suction data and model parameters obtained in the test program can be adapted for use for similar GCLs.

5 ACKNOWLEDGEMENTS

This study was partially supported by the Global Waste Research Institute and the South Central Solid Waste Authority. CETCO provided testing materials. Mr. Chris Athanassopoulos provided technical information.

REFERENCES

Beddoe R.A., Take W.A., and Rowe, R.K. 2011. Water retention behavior of geosynthetic clay liners, Journal of Geotechnical and Geoenvironmental Engineering, 137(11), 1028-1038.

Egloffstein T.A. 2001. Natural bentonites—influence of the ion exchange and partial desiccation on permeability and self-healing capacity of bentonites used in GCLs. Geotextiles and Geomembranes, 19, 427-444.

Fredlund D.G. and Xing A. 1994. Equations for the soil-water characteristic curve. Canadian Geotechnical Journal, 31(4), 533-546.

Fredlund D.G., Rahardjo H., and Fredlund M.D. 2012. Unsaturated soil mechanics in engineering practice. Wiley, Hoboken, New Jersey.

Meer S.R. and Benson C.H. 2007. Hydraulic conductivity of geosynthetic clay liners exhumed from landfill final covers. Journal of Geotechnical and Geoenvironmental Engineering, 133(5), 550-563.

National Research Council – NRC. 2007. Assessment of the performance of engineered waste containment barriers. The National Academies Press, Washington DC.

Olsen G.R. 2011. Dimensional stability of geosynthetic clay liners in landfill applications, M.S. Thesis, Cal Poly, San Luis Obispo, California, http://digitalcommons.calpoly.edu/theses/651/.

Olsen G.R., Yesiller, N., and Hanson, J.L. 2012. Dimensional stability of geosynthetic clay liners under varying hydration conditions. Proceedings, GeoAmericas 2012, 2nd Pan-American Congress on Geosynthetics, Lima, Peru, May 1-4, 2012.

Pham H.Q. and Fredlund D.G. 2008. Equations for the entire soil-water characteristic curve of a volume change soil. Canadian Geotechnical Journal, 45(4), 443-453.

Scalia J. and Benson C.H. 2011. Hydraulic conductivity of geosynthetic clay liners exhumed from landfill final covers with composite barriers. Journal of Geotechnical and Geoenvironmental Engineering 137(1), 1-13.