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Measuring the hydraulic performance through a Geosynthetic clay liner overlap in the horizontal flow direction

Mesurer les performances hydrauliques à travers un chevauchement de doublure d'argile géosynthétique dans la direction d'écoulement horizontal

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ABSTRACT: Geosynthetic clay liners (GCL) are a critical component of hydraulic barrier systems developed for numerous geotechnical and geoenvironmental applications. GCL panel overlaps play a significant role in maintaining the designed hydraulic performance of the liner system when deployed in the field. However, there is no specific standard laboratory test developed to measure the hydraulic performance of the GCL overlap. The necessity of recognising the liquid flow mechanism at the GCL overlap was therefore considered timely. The preferential flow path through the panel overlap was identified to have a horizontal component in liquid permeation in addition to the vertical component. This research study presents an element scale laboratory test method developed to measure the hydraulic conductivity through the GCL overlap in the horizontal flow direction. The permeameter cell test used in the ASTM D5887 standard is modified to measure the horizontal hydraulic conductivity in both the single GCL layer and overlap sections. The research results identified that the vertical hydraulic conductivity through a GCL single layer and overlap is 0.750 and 0.825 times the horizontal hydraulic conductivity for a GCL overlap of 300 mm overlap width and supplemental powder bentonite applied on the overlapping region. The research findings will allow practitioners to measure both horizontal and vertical components of the liquid flow through the GCL overlap, to evaluate the total liquid flow passing through the overlap.

KEYWORDS: Geosynthetic clay liner overlap, permeameter cell test, hydraulic conductivity, horizontal preferential flow

1 INTRODUCTION

Recent research confirms that geosynthetic clay liners play a major role in barrier applications with its significant ability to control leakage and transmissive flow in the field (Booker, et al., 2004; Koerner, 1990; Rowe, 2005; Weerasinghe, et al., 2019a; Weerasinghe, et al., 2021). The product is developed to perform as a hydraulic barrier, limiting liquid permeation through the material. They are used for long-term service life projects such as landfills, mines, and dams, where the barrier systems are designed to perform for many years.

However, in many reported cases, the industry has faced challenges in maintaining the design hydraulic performance at the GCL panel overlap due to manufacturing and installation faults as well as environmental conditions such as confinement and shrinkage (Brachman, et al., 2018; Cooley, et al., 1995; Gates, et al., 2019; Rowe, et al., 2016; Weerasinghe, et al., 2020; Yang, et al., 2015). Extensive research has been carried out in measuring and analysing the hydraulic performance of GCL overlaps with different design specifications under different environmental conditions; however, the mechanism of liquid flow through the overlap had not been studied adequately.

The focus of previous research was most commonly specified on the vertical flow of liquid through a GCL material, not specifically the liquid flow mechanism through the panel overlaps. Research emphasis was aimed at a mathematical correlation developed for a circular defect or transmissive vertical flow through the material (Athanassopoulos, 2013; Edil, et al., 2001; Mazzieri, et al., 2015; Mendes, et al., 2010).

In contrast, several researchers identified a preferential flow path along the GCL overlap based on their research observations (Kendall, et al., 2014; Mathieu, et al., 2004; Weerasinghe, et al., 2019b). However, a standard laboratory method to measure the identified horizontal preferential flow remained a research gap.

It was revealed through literature that using the permeameter cell test standardised by ASTM D5887 (ASTM, 2009) to measure hydraulic conductivity through GCLs is not applicable to overlap tests due to its small size and circular cross-section. Hence, the current practice is to use the model scale flow box test introduced by Daniel, et al. (1997) for GCL overlap testing.

In the current practice of sample preparation for a flow box test, the specimen prepared for a GCL overlap test comprised of a 300 mm overlap area and a 100 mm portion of a single GCL layer on both sides of the overlap when placed on the base plate of the flow box. Hence, the measured flow through the GCL overlap was the resultant volume of water collected from the two sections: the overlap area and the two single-layer sections on either side of the overlap. The specific horizontal preferential flow could not be captured separately. Weerasinghe, et al. (2019b), therefore highlighted the necessity of further research on this specific problem, to evaluate the hydraulic performance at the panel overlaps and thereby to improve the barrier designs to achieve a better service life.

This study presents an element scale laboratory test method developed to measure the horizontal hydraulic conductivity through a GCL/GCL overlap. The experiment was developed as a modification of the standard element-scale permeameter cell test.

2 MATERIALS AND METHOD

2.1 *Materials*

A commercially available needle-punched geosynthetic clay liner material was used throughout this study (Figure 1). The Geosynthetic clay liner samples contain powdered sodium bentonite sandwiched between a non-woven cover geotextile, and a woven scrim reinforced carrier geotextile, made from polypropylene, and were bonded by needle-punching.

Figure 1 GCL product used in this study

from 0.3μm to 1mm, with 75% finer than 75μm (0.075mm). The physical characteristics of the GCL specimen are provided in Table 1.

Table 1 Properties of GCL used in this study (Geofabrics Australia, 2015)

Properties	Units	Method	Values
Cover nonwoven geotextile MPUA	g/m^2	AS3706.1	240
Bentonite MPUA @ 0% Moisture Content	g/m^2	ASTM D5993	4000
Carrier woven geotextile MPUA	g/m^2	AS3706.1	110
GCL Total MPUA @ 0% Moisture Content	g/m^2	ASTM D5993	4350
Typical Panel dimensions	m^2		4.7*35
Typical Panel Mass	kg		1050
Thickness	mm	AS3706.1	~7
Bentonite free swell index	ml/2g	ASTM D5890	>25
Peel strength	N/m	ASTM D6496	830
CBR Puncture	N	AS 3706.4	2100
Strip Tensile MD	kN/m	ASTM D6768	>8
Moisture Content	%	ASTM D5993	~10
Hydraulic Conductivity	m/s	ASTM D5887	1.9E-11
Fluid Loss	ml	ASTM D5981	<15
Bonding Process	Needle punched and thermally treated W/NW		

*MPUA-Mass per unit area

* W= woven, NW=non-woven

The mineralogy of the bentonite material extracted from the GCL was analysed using X-ray diffraction (XRD) in QUT CARF laboratory facilities and identified as comprising of 72% montmorillonite, 14% quartz, 8% albite and 4% cristobalite (all estimated within 1% error).

2.2 *Testing Apparatus*

The flexible wall permeameter cell was used to measure the hydraulic conductivity of GCLs in the laboratory following the standard ASTM D5887. The GCL specimen laid in between two porous end pieces, enclosed by a flexible membrane sealed at the cap and base by two acrylic disks, are subjected to controlled fluid pressures in the permeameter cell. A schematic diagram of the permeameter cell used in this study is shown in Figure 2 (ASTM, 2009).

As shown in Figure 2, the cell pressure (sample confining pressure), influent pressure, and effluent pressure was controlled independently. Different influent and effluent pressures, which were lower than the cell pressure, were assigned to the GCL enclosed by a flexible membrane to initiate the flow through the specimen. Influent and effluent levels recorded referring to the measuring tubes, were used to calculate the flow rate and the hydraulic conductivity using the falling head method described in ASTM standard D5887.

This is the standard element-scale laboratory test method used to measure the hydraulic conductivity through a GCL material in the vertical direction.

Based on the findings in literature, a presumption was built that, and GCL/GCL overlaps are non-homogenous and the additional flow through the GCL overlap could possibly be a horizontal transmissive flow.

Figure 3 Permeameter cell setup proposed for measuring horizontal flow through the GCL specimen

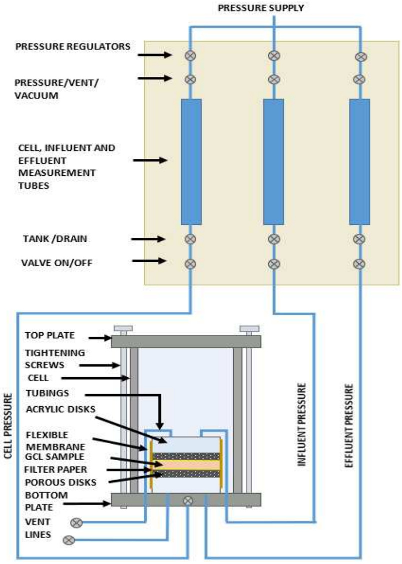


Figure 2 Permeameter cell test apparatus

2.3 *Standard permeameter cell testing*

A single GCL and GCL overlap were initially tested for hydraulic conductivity using the standard ASTM D5887 method in the permeameter cell test apparatus as baseline tests for analysis. The results of the vertical hydraulic conductivities of the two specimens were obtained, as presented in Table 2.

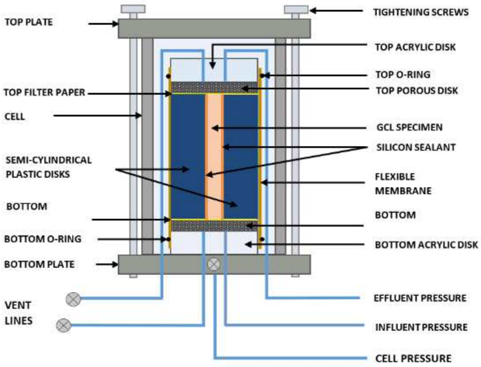
Table 2. Vertical Hydraulic conductivity of a single GCL and GCL overlap specimen

Test Specimen	Vertical Hydraulic conductivity Results
Single GCL	2.10×10^{-11} m/s
GCL overlap	1.65×10^{-11} m/s

3 MODIFICATIONS OF PERMEAMETER CELL TEST

The standard test method specified in ASTM D5887 (Figure 2) was modified to facilitate a GCL specimen placed along the vertical axis of the permeameter cell, to create a liquid flow through the horizontal cross-section of the GCL. Figure 3 presents a schematic diagram of how the permeameter cell test was assembled for the new experiment. The test method was developed to measure the GCL horizontal hydraulic conductivity.

The test apparatus was developed, incorporating a 100 mm diameter PVC cylinder cut in half along its central axis with a spacing of 10 mm to incorporate the GCL specimens. The initial experiment was conducted using PVC cylinders, which were 140 mm in height and consisted of a width of 100mm. The dimension of 140 mm was selected to replicate the nearest height to a minimum



overlap requirement of 150 mm, that a commercially available permeameter cell could hold. The 100 mm width was the standard sample size (standard specimen diameter) that could be incorporated in a permeameter cell. The PVC cylinders designed for the experiment are presented in Figure 4.

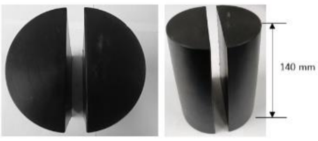


Figure 4. PVC half cylinders of 140 mm height (a) side view (b) top view (the mid spacing is to place the GCL specimen)

A rectangular GCL specimen was sampled and sandwiched between the two PVC half-cylinders to measure the transmissive flow through the material.

3.1. *Sample preparation and setting up the GCL specimen*

Rectangular single GCL specimens of dimensions 140 mm × 100 mm were sampled from a GCL panel and were prepared for testing as presented in Figure 5.

Figure 5 GCL specimens sampled for hydraulic conductivity tests conducted in the horizontal flow direction

The GCL specimen was ready for placement between the PVC half-cylinders. However, the surface texture of the PVC cylinder walls was smooth and did not thoroughly contact the geotextile surfaces of the GCL, hence causing a possibility of leakage along the PVC wall interface. Kendall, et al. (2014), in his attempt to develop a similar test method, achieved a very high GCL hydraulic conductivity value of 6.7 × 10^{-11} m/s along the horizontal direction. He then pasted the boundary walls contacting with the GCL with additional paste bentonite in order to hinder any liquid flow or leakages along the surfaces. This resulted in a horizontal hydraulic conductivity of 1.8 × 10^{-11} m/s which was even lower than the GCL vertical hydraulic conductivity of ~2.10 × 10^{-11} m/s. Given that the horizontal cross-section of a GCL has a geotextile interface which is not obstructed by bentonite, an uncertainty arose whether the horizontal cross-section with bentonite paste on the side walls replicate the field condition. The liquid flow along the GCL-boundary wall interface and the bentonite thickness used to calculate the hydraulic conductivity in his experiment were not justified. Thus, a decision was made to use silicon sealant to hinder the additional flow along the PVC cylinder walls. Figure 6 (a) presents an image of the two silicon-pasted half-cylinders used for the experiment.

The silicon sealant was observed to have the ability to restrict water flow or leakages along the PVC walls and only allow water passing through the GCL specimen in this newly developed permeameter cell test.

A pre-hydrated single GCL specimen was placed in between the PVC half-cylinders (Figure 6 (b) & (c)). The specimen was pre-hydrated to allow the specimen to achieve the steady-state condition in a short period of time. Silicon paste was further applied entirely along the longitudinal axis of the GCL and along its outer edges on the top and bottom cross-sections of the half-cylinders to seal all the boundaries from any leakages occurring. The specimen sandwiched between the two half cylinders was kept for a few minutes, for the sealant to dry and seal the material boundaries well.

The permeameter cell was assembled following the schematic diagram in Figure 3. A saturated porous disk was placed on top of the bottom acrylic disk attached to the base plate of the permeameter cell, and a saturated filter paper was placed on top of it. The assembly of the two half-cylinders, with the GCL specimen sandwiched in between, was placed on top of the filter paper. Another saturated filter paper was placed on top of the specimen assembly, along with another saturated porous disk placed last. The specimen assembly, filter papers, porous disks, and top and bottom acrylic disks were enclosed in a latex membrane, and the top and bottom caps were sealed with O-rings. The influent tubing was already connected to the bottom acrylic disk, and similarly, the effluent tubing was connected to the top acrylic disk. The permeameter cell was placed on the grooves of the base plate. The top plate grooves were then carefully connected to the permeameter cell. Then, the bottom plate, the top plate, and the permeameter cell, were tightened by the three tightening screws. The complete apparatus setup for experimentation is presented in Figure 6 (d).

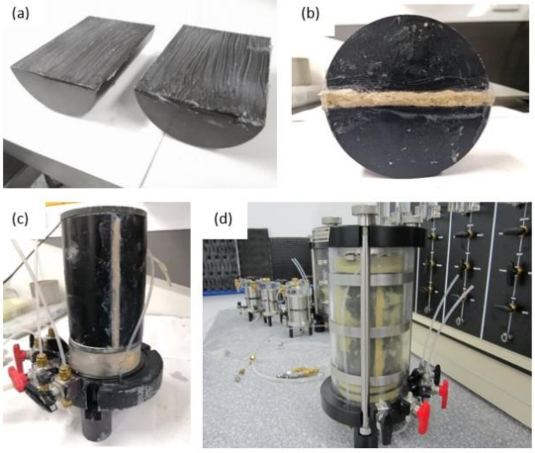


Figure 6 (a) Silicon pasted PVC half-cylinders (b) Top view of the specimen prepared and sandwiched between the two half-cylinders (c) Side view (d) Side view of the permeameter cell when the specimen is setup and ready for experimentation

This new setup allowed the measurement of transmissive flow along the length of the rectangular GCL specimen horizontally. A hydraulic head of 3.5 m and a total overburden confinement of 35 kPa was applied to the specimen following the standard ASTM D5887 method.

The specimen was saturated at an extremely slow rate, and after approximately 5 months, an initial flow was observed in the effluent measurement. However, the specimen still had not achieved a steady-state equilibrium condition in the flow rate. This observation agreed with the hypothesis by Kendall et al. (2014) that the flow could have been through the boundary walls along the outer surface of the GCL specimen but not through the GCL specimen. From this test, it speculated that the 140 mm of specimen height was too long to be adapted in a laboratory test to measure horizontal hydraulic conductivity of GCL/GCL overlap.

3.2 *Identifying the optimum specimen height*

The optimum height of the GCL specimen that is viable for this proposed laboratory test was discussed. A series of hydraulic conductivity tests were performed with four different sample heights, namely, 20 mm, 30 mm, 50 mm, and 70 mm, following the above proposed method to measure the horizontal hydraulic conductivity. Four sets of PVC half-cylinders were designed and manufactured, as shown in Figure 7, to hold the GCL specimens with different heights.

Following the sizes of the PVC half-cylinders, GCL specimens of 100 mm × 20 mm, 100 mm × 30 mm, 100 mm × 50 mm and 100 mm × 70 mm, in length and width (height of the half-cylinder), respectively, were prepared.

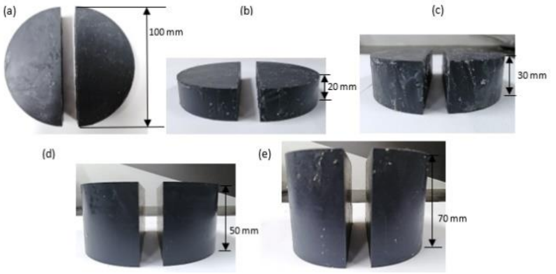


Figure 7. PVC half-cylinders used (a) Top view (b) Side view 20 mm height (c) 30 mm (d) 50 mm (e) 70 mm

Following the sample preparation and permeameter cell setup method discussed earlier, the GCL specimens were sandwiched between PVC half-cylinders and sealed with silicon paste, as shown in Figure 8. The specimens were set up in the permeameter cells and hydraulic conductivity tests were conducted.

Figure 8. Top view and side views of the GCL specimens sandwiched between two PVC half cylinders and sealed with silicon paste (The images are from 30 mm height experiment)

The head losses across the specimen at consecutive time intervals were measured and recorded. The hydraulic conductivity of the specimen was then calculated using the Darcy's Law equation following the ASTM standard D5887.

Special consideration was given, in measuring the "t" and "A" parameters of the Darcy's law equation in this calculation.

- 'T' corresponding to the thickness of the clay component of the GCL specimen refers to the thickness of the material through which the liquid flows. In this new test method, this implies the 'height of the rectangular GCL specimen placed upright' which is also the height of the PVC half-cylinders. For example, if the 100 mm × 30 mm GCL specimen was used, the thickness was determined as 30 mm ≈ 0.03 m.
- 'A' corresponds to the cross-sectional area of the specimen in m^2, which refers to the surface area of the cross-section of the material through which the liquid flows (Figure 6(b)). Again, in this case, the cross-section of the surface area subjected to the liquid flow direction is measured for this parameter.

A = thickness of the clay component of the GCL specimen (m) × width of the rectangular GCL specimen (diameter of the PVC half-cylinders) (m).

If the same example of the 100 mm × 30 mm GCL specimen was considered and the saturated thickness of the specimen is 8 mm,

$A \approx 8 \text{ mm} \times 100 \text{ mm} \approx 0.008 \text{ m} \times 0.1 \text{ m} = 0.0008\text{m}$.

The hydraulic conductivity was hence calculated. The weighted average of the last three hydraulic conductivities were continuously determined. A plot of the weighted average hydraulic conductivity of GCL specimen was plotted against the time. Figure 9 presents an example graph plotted for the '100 mm × 30 mm single GCL specimen' tested.

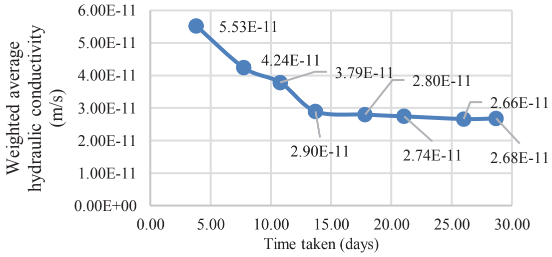


Figure 9. Weighted average horizontal hydraulic conductivity of the single GCL experimented in the newly developed permeameter cell apparatus

The plot was monitored until the results established a consistent flow and achieved a steady-state condition. The last weighted average hydraulic conductivity (m/s) was recorded as the horizontal hydraulic conductivity of the GCL specimen for the specific experiment. The test was terminated. The minimum time period taken to complete each experiment varied drastically with the height of the specimens. The thickness of the GCL specimens was approximately 8 mm and was similar to the saturated GCL thickness of the specimen used to measure the vertical hydraulic conductivity. The results obtained from the laboratory tests are presented in Table 3.

Table 3. Hydraulic conductivity results obtained from the first established set of permeameter cell tests conducted to measure the horizontal flow through a GCL

Specimen height	Horizontal Hydraulic conductivity	Time taken to achieve a steady-state liquid flow condition
20 mm	2.7×10^{-11} m/s	≈1-2 months
30 mm	2.8×10^{-11} m/s	≈1-2 months
50 mm	Did not achieve a steady-state equilibrium flow (at 5 months)	
70 mm	Did not achieve a steady-state equilibrium flow (at 5 months)	

The specimens having the 20 mm and 30 mm heights gave equivalent results within a comparatively shorter period of time. Both 50 mm and 70 mm height specimens did not seem to achieve the steady-state equilibrium

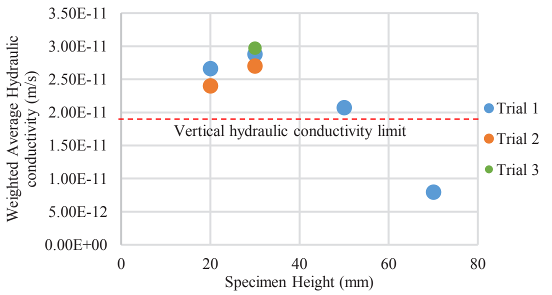


Figure 10. Hydraulic conductivity values for permeameter cell tests conducted in four sample height configurations

condition. Therefore, the experiments with 20 mm and 30 mm were repeated to observe the accuracy of the hydraulic conductivity values obtained. Another reason for repetition was to make sure that the immediate flow within a short period of time was not because of the very short length, which might lead to flow paths created along the sidewalls of the cylinders or through the membrane due to shortcomings encountered in setting up the experiment. The results obtained were compared, as presented in Figure 10.

The repeated 20 mm and 30 mm height GCL specimens gave similar results in all trials. The 50 mm and 70 mm height specimens did not achieve a steady-state flow condition even after 5 months. However, hydraulic conductivity values measured were compared. The knowledge obtained from Weerasinghe, et al. (2019b) indicated that the horizontal hydraulic conductivity across the GCL specimen should have a similar or higher value than the vertical hydraulic conductivity of the material. The fibre-bentonite interface of the GCL cross-section is expected to allow higher flow than through the bentonite layer encountered in the vertical direction of flow.

The lower values observed through the 50 mm and 70 mm height GCL specimens and the fact that the steady-state flow condition was not achieved in these experiments, implied that the optimum liquid flow through the GCL specimen had not passed through the specimen yet. This is attributed to the higher length of flow encountered in the horizontal flow path in both 50 mm and 70 mm specimens.

The 30 mm height was selected as a more appropriate specimen height to continue experimentation with. The 20 mm height was not selected as it might account for human errors or shortcomings in setting up the permeameter cell test, due to its limited height. On the other hand, the 30 mm height specimen was not too lengthy and would not consume an unreasonably long time period to achieve its steady-state hydraulic conductivity value.

Subsequently, the average horizontal hydraulic conductivity value obtained from the permeameter cell test at 30 mm sample height was chosen as the horizontal hydraulic conductivity (K_{HS}) through a geosynthetic clay liner material.

3.3 *Measuring the horizontal hydraulic conductivity through the GCL overlap*

The verified sample height (30 mm) and testing procedure were employed to measure the horizontal hydraulic conductivity through the panel overlap. The modified permeameter cell test was used, and the schematic diagram of the setup developed is presented in Figure 11.

A new set of PVC half-cylinders (30 mm height) were moulded with a mid-spacing of approximately 15 mm to hold two saturated GCL layers. Learning from the observations of the single GCL tests, it was ascertained that a thin layer of silicon boundary is sufficient to seal the boundaries, hence 15 mm was identified as adequate to incorporate the saturated specimens.

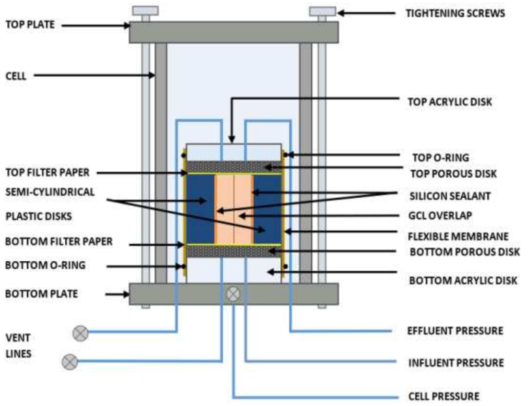


Figure 11. Permeameter cell setup proposed for measuring the horizontal flow through the GCL overlap

The following steps were followed to measure the horizontal hydraulic conductivity of the GCL overlap with supplemental bentonite:

- Two rectangular (100 mm x 30 mm) GCL specimens were sampled from the overlapping section of a GCL panel (with supplemental bentonite applied on to it)
- These two specimens were overlapped and placed in between two half-cylinders; silicon sealant was applied onto the surfaces of the PVC half-cylinders that were in touch with GCL specimens. Further, silicon was applied on the sides of the specimens where they are in contact with the membrane to restrict any liquid flowing through interfaces.

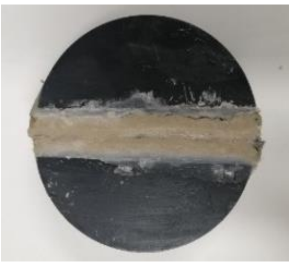


Figure 12. Top view of the two GCL layers sampled from the GCL overlap sealed in between two PVC half-cylinders (of 30 mm of height)

- The specimen set up was in the permeameter cell.
- The experimental conditions for this GCL overlap were assigned following the same experimental conditions described for the single GCL permeameter cell test. A hydraulic head of 3.5 m and a total overburden confining stress of 35 kPa was applied to the specimens following the standard test method ASTM D5887.

The experiment was conducted following the same method previously described to measure the horizontal hydraulic conductivity of a single GCL specimen. The horizontal hydraulic conductivity of the GCL overlap with supplemental bentonite (K_{HO}) was determined as 2.00×10^{-11} m/s by the experiment.

3.4 *Evaluating the GCL overlap hydraulic performance*

Hydraulic conductivity values, in both vertical and horizontal flow directions of the single GCL and the GCL overlap zone, (K_{HS}, K_{VS}, K_{HO} and K_{VO}) were measured using the permeameter cell tests and were compared as presented in Table 3.

Table 3. Permeameter cell setup proposed for measuring horizontal flow through the GCL overlap

Hydraulic conductivity	Experimental results obtained
K_{HS} – Hydraulic conductivity through a single GCL layer in the horizontal flow direction	2.80×10^{-11} m/s
K_{VS} – Hydraulic conductivity through a single GCL layer in the vertical flow direction	2.10×10^{-11} m/s
K_{HO} – Hydraulic conductivity in the horizontal flow direction through two GCL layers sampled from the overlapping area of the GCL panel	2.00×10^{-11} m/s
K_{VO} – Hydraulic conductivity in the vertical flow direction through two GCL layers sampled from the overlapping area of the GCL panel	1.65×10^{-11} m/s

Both the horizontal hydraulic conductivities in the single GCL and the overlap were higher than the vertical hydraulic conductivity values, as expected. This proved the validity of the hypothesis that the fibre-bentonite interface of the GCL specimens allowed higher flow horizontally than through the vertical flow direction. Comparing the single and GCL specimens, the flow through the overlap region is much lesser than the single GCL in both horizontal and vertical directions. This could be attributed to the lower bulk void ratio due to the higher amount of bentonite particles in the GCL overlap being saturated and acting as a well-seamed continuous barrier.

4 CONCLUSIONS

This paper presents an experimental analysis conducted to develop a laboratory element-scale setup to measure the GCL overlap horizontal hydraulic conductivity.

The hydraulic conductivities obtained as a ratio of vertical to the horizontal direction for both single GCL and panel overlap conditions were as follows.

- K_{VS}/K_{HS} was defined as 0.750 for the single-layer material section where K_{HS} is input as 2.8×10^{-11} m/s
- K_{VO}/K_{HO} was defined as 0.825 for the overlap material section where K_{HO} is input as 2.0×10^{-11} m/s.

The element-scale laboratory test method could be standardised to further study the liquid flow mechanism at the GCL overlap at different overlap specifications in specific field conditions. Designers could use this test method to improve the panel overlap performance and lengthen the service life of barrier systems.

5 ACKNOWLEDGMENTS

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