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Research article

Effect of overburden confining stress on hydraulic performance of geosynthetic clay liners (GCLs)

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ABSTRACT

Geosynthetic clay liners are a rapidly evolving geosynthetic product used in most hydraulic barrier applications in the geo-environmental industry. Continuous research has led to new insights to overcome the shortcomings faced in deploying GCLs in the field. These include shrinkage due to shear failure on side slopes, the effect of temperature variation, and inadequacy of minimum timely confinement to achieve optimum hydraulic performance. This paper presents previous experimental data and an additional dataset from this research gathered to observe the effect of overburden confining stress on GCL hydraulic conductivity and how the findings can be used to predict the performance of a geosynthetic clay liner for a given field application. An inverse power relationship is identified between these two parameters along with the reduction in the order of the degree of hydraulic conductivity depending on the permeant material passing through. A relationship is determined to estimate the GCL hydraulic conductivity as a function of the overburden confining stress, given that it is pre or post hydrated and the permeant liquid passing through the product. It is proposed that the relationship can be used to predict the GCL hydraulic performance in the field and provide guidance in improving the serviceability of hydraulic barrier designs.

1. Introduction

The application of geosynthetics in the geo-environmental industry is increasing rapidly due to its vast number of applications (Cheah et al., 2016, 2017; Gallage et al., 2019; Garcia et al., 2007; Jayalath et al., 2018; Weerasinghe et al., 2019a, 2020). Geosynthetic clay liners are one such composite geosynthetic product with a core of low-permeability sodium bentonite clay sandwiched between two geotextiles or adhesive bonded to a geomembrane. This product is used in a number of applications such as, in barriers to reduce the contamination from leachates to the surrounding environment in landfills and mining applications, resisting leakage of hydrocarbons in secondary containment applications, in vertical cut-off barriers such as irrigation canals, gas and vapour seals, used as a successful waterproofing material in construction and also in water containment facilities such as dams and ponds (Benson et al., 2005; Daniel, 2012; Part, 2001; Rowe, 1998). It has become a huge challenge for GCL manufacturers to design barrier products to suit the requirements of all these different applications.

The most significant challenge faced by the industry is the failure of the liner systems due to separation of panels on side slopes, separation of panels due to shrinkage, punctures and wrinkles, installation faults, liner design faults etc (Fox et al., 1998; Rowe, 2014; Rowe et al., 2017; Thiel et al., 2005). Hence, significant research is being carried out to investigate how the overall hydraulic performance of the GCL could be improved by maintaining its optimum capacity throughout the barrier application (Daniel et al., 1997; Egloffstein et al., 2012; Mazzieri et al., 2015; Rowe et al., 1997, 2016; Weerasinghe et al., 2020; Xiong et al., 2009). The main factors identified affecting the hydraulic conductivity of the GCL are the overburden confining stress, shrinkage effect occurring due to the temperature variation, chemical compatibility of the bentonite to restrict various permeants, wrinkle effect due to the overlying geomembrane, and side slope shear effects (Fox et al., 1998; Thiel et al., 2005; Weerasinghe et al., 2019a). Research helps to overcome these limitations using advances in material properties of the GCL product. As a result, over the past two decades, the hydraulic performance of GCLs has improved from approximately 1×10^{-7} m/s to 1×10^{-12} m/s (Kendall et al., 2014; Petrov et al., 1997b; Weerasinghe et al., 2020). A reduction in hydraulic conductivity is considered as an improvement of hydraulic performance as it reduces the ability of liquids to pass through the hydraulic barrier.

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Laboratory experiments are being conducted continuously to address the challenges observed in the field and to optimise the product for improved barrier performance. Different laboratory testing apparatus such as fixed ring permeameter cell, double ring permeameter cell and flexible wall permeameter cell have been used by various researchers and it has been identified that all these element scale tests give relatively similar results (Cooley et al., 1995; Daniel et al., 1992; Garcin et al., 1995; Heyer, 1995; Petrov et al., 1997a, 1997b; Salemi et al., 2016; Weerasinghe et al., 2019b). The ASTM standard D5887 has established the flexible wall permeameter as the standard apparatus for measuring GCL hydraulic conductivity (ASTM, 2009). The standard permeameter cell test is an element scale standard laboratory method which can incorporate 100mm diameter GCL specimens. The small sample size resulting in edge effects has less accuracy and applicability to the field conditions. A very high total confining stress is supplied to the specimen as the cell pressure to reduce this effect. Further, these tests are not able to replicate the overlapping condition of two GCLs which causes significant impact in barrier performance failures. The constraints of the laboratory testing apparatus hence limit the ability to research shortcomings of the GCL at the laboratory element scale.

The flow box test was developed by Daniel et al. (1997) as a solution to the drawbacks of the element scale testing method. These tests are much larger laboratory model tests which can accommodate the width of a GCL overlap. However, the model test method has its own limitations in replicating the actual field condition due to its complexity in handling due to the large size, limit in confinement that could be applied to the sample, and longer testing period which can be up to 2–3 months for one test. It has been a constant challenge to replicate the expected actual performance of a geosynthetic clay liner in the field using laboratory test methods. An effective method to predict the hydraulic performance of a GCL in the field using existing laboratory data would be considered timely.

This research study focuses on one of the many factors that has been identified to be controlling the advective flow through Geosynthetic clay liners; the overburden confining stress acting on the product. Geosynthetic clay liners which are most commonly used in the composite barrier design in liquid containment facilities are loaded with a liquid or solid material which is expected to degrade and liquefy over time. The material that is being gradually loaded provides a confinement on to the GCL bottom liner over time. The effect of variation of this confinement has been explored by many researchers (Petrov et al., 1997a; Rowe et al., 1997; Shackelford et al., 2000; Yang et al., 2015). A significant decrease in GCL hydraulic conductivity with the increase in confining stress has been identified by these studies, presumably as a result of lower bulk void ratios (Bouazza et al., 2002; Rowe et al., 1997). It is also affected by whether it is pre-hydration or post-hydration confinement (Rowe et al., 1997).

These researchers have analysed the impact of low, intermediate and high confining stresses affecting the hydraulic conductivity of a given GCL product. A range of results for lower confining stresses less than 30 kPa were collected using flow box test results along with permeameter cell test results in a varied stress region from low figures around 10–30 kPa to high pressure values up to more than 250 kPa (Bouazza et al., 2002). Bouazza's research compiling a considerable set of experimental data from various sources clearly shows the decrease in hydraulic conductivity by an order of magnitude of two with the increase in overburden confining stress.

This paper proposes a method to estimate the hydraulic conductivity of a geosynthetic clay liner in the field condition using existing research datasets. Additional data were gathered from experiments conducted in this research study to supplement existing datasets and address a gap in research data. Data on GCL hydraulic conductivity versus the overburden confining stress were gathered from the existing research and this research study and analysed to observe the trends at varied experimental conditions. The effect of GCL hydraulic conductivity were observed when subjected to pre and post hydration confinement with the two liquids, water, and leachate, at increasing overburden confinement stresses. It is proposed that the relationship developed is used to predict the GCL hydraulic performance at a given overburden confining pressure and hydration condition, to provide guidance in improving the serviceability of hydraulic barrier designs such as landfills, mines, ponds and dams.

2. Material used

A commercially available needle punched GCL was used for the laboratory experiments (Figure 1). The GCL consisted of a non-woven polypropylene geotextile cover layer with a woven scrim-reinforced carrier geotextile encapsulating a powder sodium bentonite core which was thermally treated.

The particle size of bentonite used in the GCL varies from 0.3μm to 1mm, with -75% finer than 75μm (0.075mm). The physical characteristics of the GCL specimen is provided in Table 1.

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

3. Testing apparatus

The GCL hydraulic conductivity tests are conducted using both the element-scale and model-scale tests to cover a range of confining stresses

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

Properties	Units	Values
Cover nonwoven geotextile Mass per unit area	g/m^2	240
Bentonite Mass per Unit Area @ 0% Moisture Content	g/m^2	4000
Carrier woven geotextile Mass per unit area	g/m^2	110
GCL Total Mass per Unit Area @ 0% Moisture Content	g/m^2	4350
Bentonite free swell index (ASTM Standard D5890)	ml/2g	25
Bonding Process	Needle punched and thermally treated W/NW	

Figure 1. Geosynthetic clay liner product used in this study.

that could be applied using the two laboratory-scale test methods. The flexible wall permeameter cell was used to measure hydraulic conductivity of GCLs at the element level following the standard method ASTM D5887 (ASTM, 2009). The permeameter cell is an apparatus which the GCL specimen and porous end pieces, enclosed by a flexible membrane sealed at the cap and base, are subjected to controlled fluid pressures. This method is used to test hydraulic conductivity in GCL samples subjected to an overburden confining stress of 35 kPa and higher. A schematic diagram of the permeameter cell used in this study is shown in Figure 2.

A "Flow box" apparatus, developed by Kendall et al. (2014) following Daniel et al. (1997), was used to conduct model scale tests for geosynthetic clay liners at confining stresses lower than 35 kPa. The flow box consisted of 1 m × 0.5 m × 0.3 m length, width and height, respectively. The GCL sample was subjected to an overburden gravel load of 5–10 mm thickness up to a height of 300 mm, 1600 kg/m^3 in density. A hydraulic head is provided using a header tank above the flow box and the height of the header tank could be varied from 1.3 m to 3.5 m. The flow that is released from the GCL layer is measured gravimetrically to a precision of 0.01g. A schematic diagram of the two apparatus is presented in Figure 3.

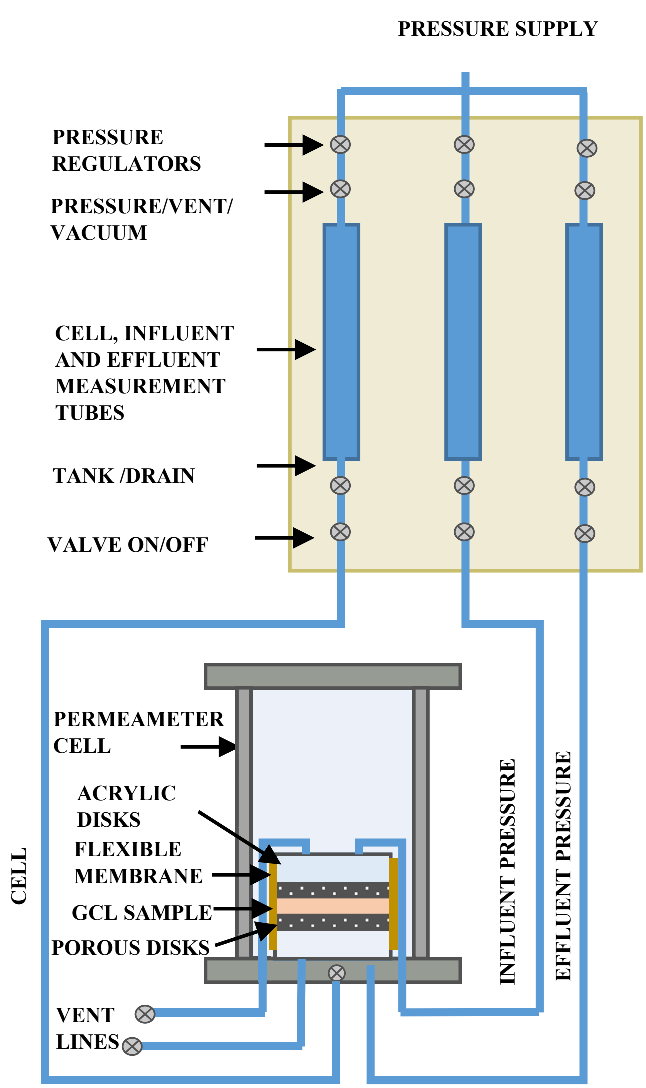

Figure 2. Permeameter cell set up (ASTM D5887).

4. Method

4.1. Data from published research

Hydraulic performance data for GCLs over a wide range of overburden confining stresses were gathered from previously published literature to investigate the effect of overburden confining stress on the hydraulic conductivity of the product. Only three comprehensive studies on hydraulic conductivity versus the overburden confining stress acting on the GCL were identified to have sufficient experimental results available for analysis (Bouazza, 2002; Petrov et al., 1997a; Rowe et al., 1997). Table 2 shows a summary of the studies identified and the conditions that these tests were carried out in.

All the research studies have used a GCL material with dry natural sodium bentonite of 3500–4000 kg/m^2 sandwiched and needle punched between the woven and non-woven geotextiles. All these published research studies observed a decreasing trend in the relationship between the hydraulic conductivity and the overburden confining stress. However, the effect of pre and post hydration confinement as well as the effect of the permeant liquid on the performance were not clearly observed. The focus of this research was hence to observe the trend in the relationship with respect to the condition of the confinement expected in different field applications.

As sufficient information of the confinement condition and the permeant were not available in Bouazza (2002), only the data from studies conducted by Rowe et al. (1997) and Petrov et al. (1997a) were considered for further analysis. The existing hydraulic conductivity data consisted of both pre and post hydration confinement data of GCLs where the permeant liquid passing through was leachate. However, only pre-hydration confinement data was available when water was considered as the permeant for the material. Hence, a laboratory hydraulic conductivity test series was developed for post-hydration confinement using water as the permeant in order to address the gap in research and provide sufficient data for the analysis. This laboratory test series was also used to evaluate and establish the trend observed in previous research studies.

The laboratory test series was carried out using both element scale and model scale test apparatuses due to the inability of each apparatus to cover a wide range of confining stresses. Hence, three flow box (model tests) tests and four permeameter cell tests (elements tests) were carried out at 7 different overburden confining stress values: 13 kPa, 25 kPa, 35 kPa, 50 kPa, 65 kPa and 80 kPa. Three flow box tests were conducted on three GCLs providing 13 kPa, 25 kPa and 35 kPa overburden confining stress on the material. The overburden stresses 35 kPa, 50 kPa, 65 kPa and 80 kPa for the permeameter cell tests were applied onto the material as a difference of the cell pressure and influent pressure as described in ASTM D5887. The results obtained from the laboratory tests were compiled together to develop relationships for the overburden confining stress applied on each GCL specimen versus the hydraulic conductivity obtained at each stress condition.

4.2. Laboratory element tests

Four element scale permeability tests were conducted using the permeameter cell setup shown in Figure 2 for the four different overburden confining stresses applied onto the GCL specimen. The GCL specimens were prehydrated and setup in the permeameter cells following ASTM standard D5887. The hydraulic conductivity of these GCLs were measured using the falling head method. The flexible wall permeameter cell was initially subjected to a total confinement stress of 550 kPa and a backpressure of 515 kPa. This confinement is expected to be maintained for more than 48 h to allow consolidation to occur at standard conditions. Once the specimen is saturated, the pressure on the influent channel towards the test specimen was raised to 530 kPa in order to introduce water flow through the GCL specimen. The permeated GCL specimen of 100 mm diameter was subjected to a 1.5 m hydraulic head and the total

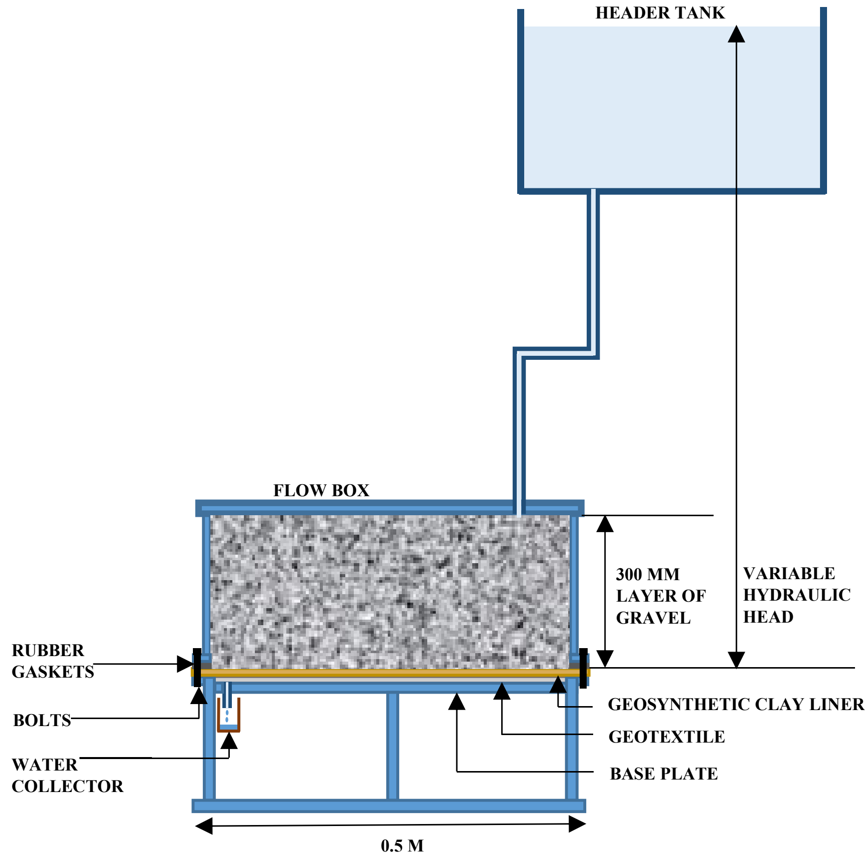

Figure 3. Flow box apparatus.

Table 2. Sources of studies on effect of confining load on hydraulic performance.

Specific research focus	Permeant Liquid	Source
Pre-hydration confinement	Water	(Rowe et al., 1997)
Pre-hydration confinement	Water	(Petrov et al., 1997a)
Pre-hydration confinement	Synthetic MSW Leachate	
Post-hydration confinement	Synthetic MSW Leachate	
Results compiled from various sources for GCL hydraulic performance under different confining stresses varying from 0-300kPa: confinement condition not defined	Not specified	(Bouazza, 2002)

confinement of 35 kPa within the cell. The total confining stress was increased from 35 kPa to 50 kPa, 65 kPa and 80 kPa for the same specimen by increasing the cell pressure from 550 kPa to 565 kPa, 580 kPa and 590 kPa, and the corresponding flow through the GCL specimen at a given time period was measured. The hydraulic conductivity of the specimen was calculated at each of the overburden confining stresses according to ASTM D5887 (ASTM, 2009).

The hydraulic conductivity of GCL specimen was plotted against the time (Figure 4).

The values were monitored until a consistent flow was established and a steady state condition was achieved. The last weighted average hydraulic conductivity (m/s) was recorded as the hydraulic conductivity of the GCL specimen for the specific experiment. A time period of 2–3 months was utilised to complete the experiment at standard conditions.

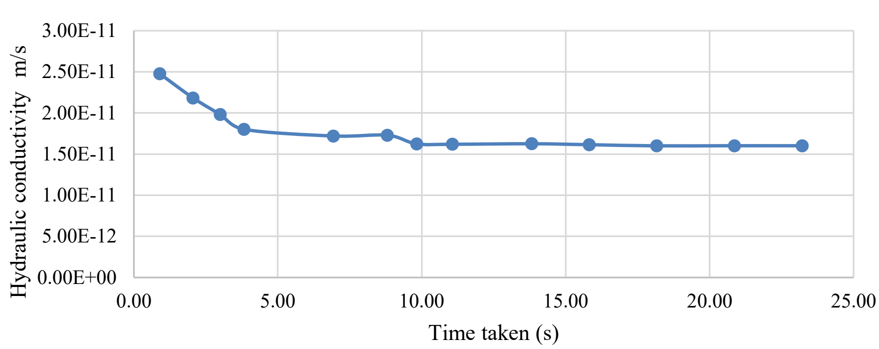

Figure 4. Hydraulic conductivity of a single GCL experimented in the permeameter cell test.

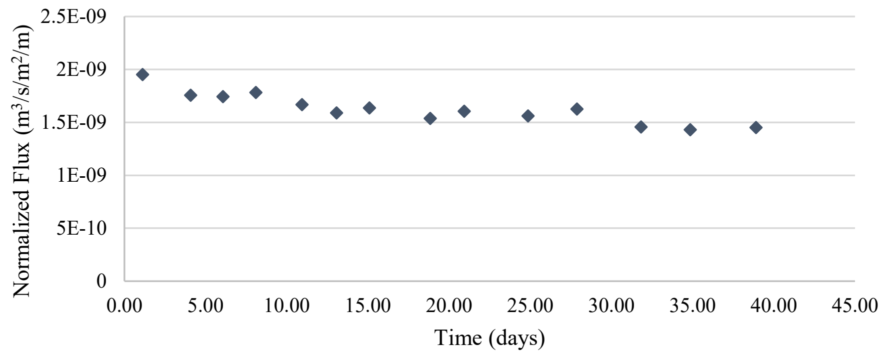

Figure 5. Normalised Flux recorded for the single GCL flow box test conducted at 3.5 m hydraulic head.

4.3. Laboratory model tests

The permeameter cell test only had the ability to measure the hydraulic performance of GCLs at total confining stresses higher than 35 kPa. Hence, to achieve the lower confining stresses, model tests were conducted using the flow box apparatus at the total overburden confining stresses of 13 kPa, 25 kPa and 35 kPa.

The GCL material was placed on the base plate of the flow box apparatus and the flow box frame was bolted onto the base. The GCL specimen was sized 50 mm larger than the perimeter of the flow box to account for the area that is bolted, to make sure no side wall leakages occur. The specimens were prehydrated, and a 0.3 m height of gravel was filled onto the GCL specimen in the flow box. Then the flow box was enclosed using the top lid which was connected to the header tank filled with water and provides the necessary hydraulic head.

Three model tests were conducted at 1.3 m, 2.5 m and 3.5 m hydraulic heads which attributed to approximately 13 kPa, 25 kPa and 35 kPa of total overburden confining stresses. The total pressure values were measured using a vibratory-wire type pressure sensor for each flow box condition.

It took approximately three weeks to commence flow across the GCL. The water passing through the GCL was collected through the outlet made in one corner of the base plate to a water container. Once the water began to flow, similar to the element tests, the flow passing through the GCL was collected at regular time intervals; typically, every three days, and the flow rate (m^3/s) was measured. The experiment was then kept running for 1–2 months to reach the steady-state flow condition. Figure 5 shows experimental data from a flow box test to demonstrate how the steady-state condition was achieved after the commencement of the flow.

The hydraulic conductivity was calculated using the constant head method provided in the ASTM D5887 (ASTM, 2009).

The test was then terminated, and specimens were removed from the flow box to measure the mass, thickness and moisture content. It took about two - three months to fully complete one flow box test. All three flow box tests discussed in this research study were conducted following a similar procedure.

4.4. Analysis

The results obtained from both element-scale and model-scale tests were combined to graphically represent the relationship between the hydraulic conductivity (m/s) of the GCL specimen versus the overburden confining stress (kPa) applied.

Previously published data (Petrov et al., 1997a; Rowe et al., 1997) and the experimental results were compiled to observe the effect of confining stress on the hydraulic conductivity of GCLs and the trend in relationship under different hydration conditions were considered. These observations were then used to develop a correlation between the two parameters, the hydraulic conductivity of a GCL product versus the overburden confining stress applied in given field conditions. A summary of how the developed relationship can be used to predict the hydraulic performance of any given GCL product at a given overburden confining stress can be determined.

5. Results and discussion

5.1. Data from published research

The data obtained from the previously published research studies were digitised and compiled into plots of overburden confining stresses (kPa) versus their hydraulic conductivities (m/s). The data collected from each of the selected research studies are graphically presented in

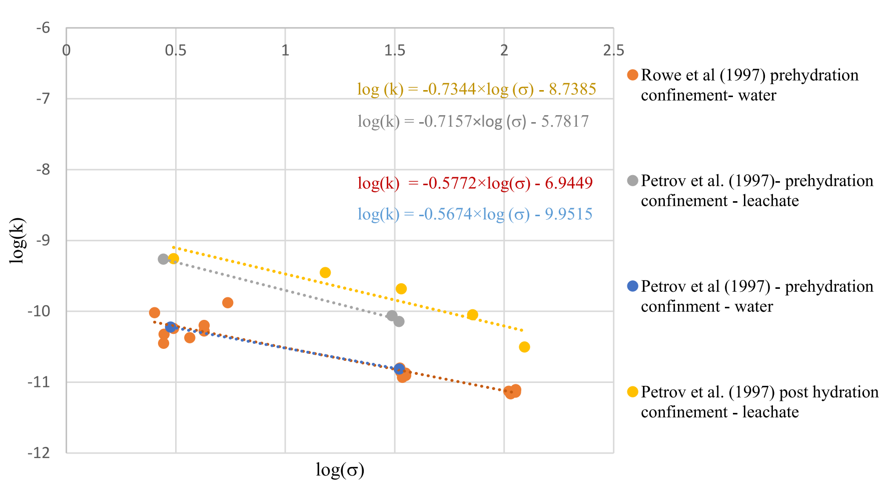

Figure 6. Data from previously published research studies – Hydraulic conductivity versus the total overburden confining stress acting on the GCL specimen.

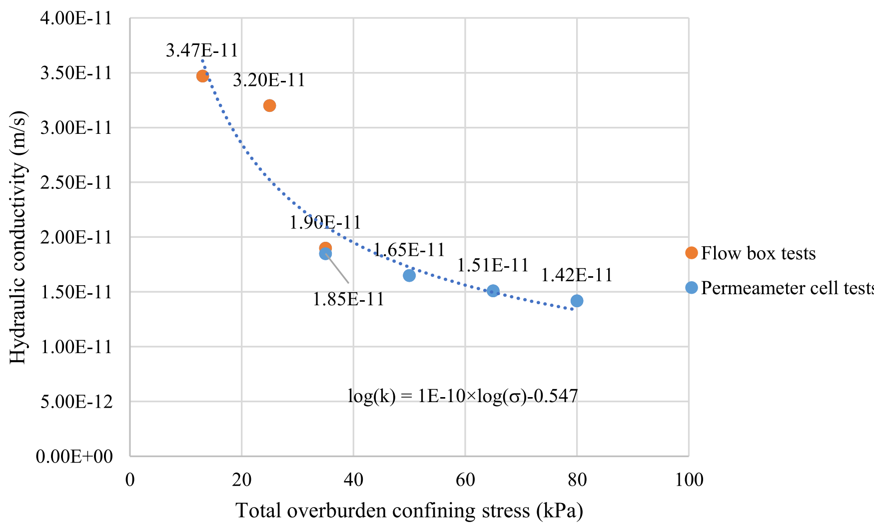

Figure 7. Hydraulic conductivity results of the experiment series.

Figure 6. A logarithmic scale was used to represent all research work in one plot clearly following previous research.

The logarithmic scale representation clearly shows that the hydraulic conductivity has decreased with a power function with increasing overburden confining stress. This infers a linear representation of hydraulic conductivity inversely proportional to the overburden confining stress in the logarithmic scale. Similar trends in the effect of confining stress on the hydraulic performance of the GCLs was observed for each data set. Each curve illustrated a similar pattern even though the order of degree of hydraulic conductivity seemed to vary from each study due to the effect of the different permeant liquids passing through the GCL material.

Petrov et al. (1997) collected experimental data on both pre-hydration confinement and post-hydration confinement of GCLs when permeated with leachate. The study observed that the hydraulic conductivity of the GCLs subjected to post hydration confinement was three times higher than the hydraulic conductivity of the GCLs subjected to pre-hydration confinement. The ability of the bentonite to swell freely when hydrated before applying a confinement to the material is hypothesised to increase the hydraulic conductivity through the material subjected to post hydration confinement. In contrast, when subjected to pre-hydration confinement, swelling of bentonite material is limited and therefore results in a lower hydraulic conductivity. However, the decrease in trend with the increase in overburden confining stress of the GCL specimens of each case was similar.

It is also important to identify the effect of the variation of pre and post hydration confinement of GCLs with water as the permeant, as GCLs are widely used in water containment facilities such as dams and ponds as well. Petrov et al. (1997) conducted hydraulic conductivity tests for GCLs with pre-hydration confinement using water as the permeant in addition to the experiments conducted on leachate. This possessed a similar decreasing trend to the other datasets but had a lower order of degree of hydraulic conductivity. The trend in decrease was consistent with the data (Rowe et al., 1997) presented in Rowe's research study (Rowe et al., 1997) validating the comparability of results obtained in both studies. The lower hydraulic conductivity observed when the permeant liquid is water compared to leachate is attributed to the phenomena of less cationic exchange in bentonite occurring in water compared to other permeant liquids such as leachate (Petrov et al., 1997a).

However, research on the effect of post-hydration confinement on GCLs permeated with water had not been studied before. To observe the effect of post-hydration confinement on GCLs permeated with water and its relationship to the existing data, a laboratory test series was conducted.

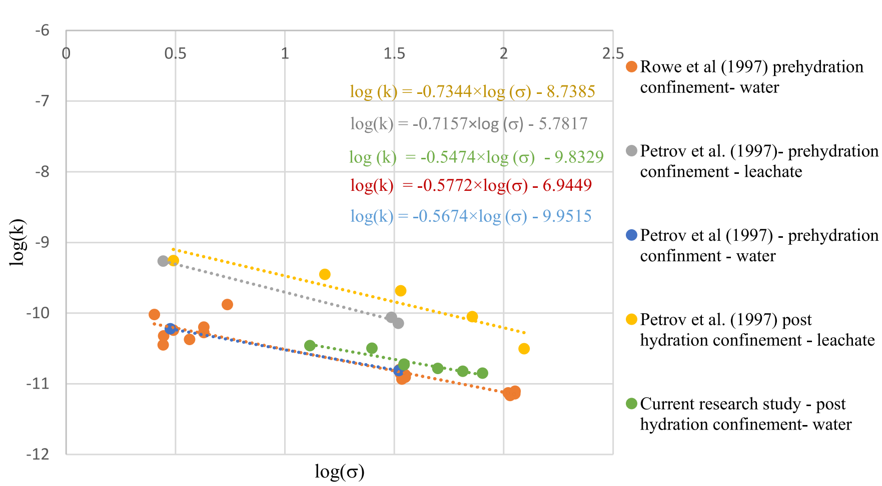

Figure 8. Comparison of results from previous studies versus the experimental results of this study – hydraulic conductivity versus total overburden confining stress in logarithmic scale.

5.2. Experimental results

Four permeameter cell tests (element scale tests) and three flow box (model scale tests) tests were carried out for 7 different overburden confining stress values: 13 kPa, 25 kPa, 35 kPa, 50 kPa, 65 kPa and 80 kPa. The results obtained from the laboratory tests were compiled to generate the relationship between the total overburden confining stress applied on each GCL specimen versus its hydraulic conductivity shown in Figure 7. The best fit curve was developed connecting both the element and model test results and was extrapolated in order to cover the complete range of overburden confining stresses.

An inverse power relationship was observed between the two parameters. The hydraulic conductivity has reduced drastically with the increase in total overburden confining stresses. This relationship was consistent with the general trend of the inverse power form observed in previous literature (Bouazza, 2002; Petrov et al., 1997a; Rowe et al., 1997).

5.3. Comparative analysis

The experimental data was compared with the trends observed from the previous studies for further analysis on the relationship to the existing data. Figure 8 presents a combined graphical representation of the previously published data and experimental results obtained from this research study.

As shown in Figure 8, the hydraulic conductivity results obtained from this research followed a trend similar to previous studies. Observing the overall trend within the dataset, this relationship possessed a similar variation in relationship between the pre-hydration and post-hydration confinement using leachate as the permeant material (Petrov et al., 1997a). The hydraulic conductivity values obtained were 1.5 times higher than the values observed from the data at pre-hydration confinement with water. This variation was half of the variation in values observed for hydraulic conductivities between pre and post hydration confinement when permeated with leachate (Petrov et al., 1997).

It is hypothesised that the observed relationship between the hydraulic performance and the overburden confining stress could be used in estimating the product performance for any given GCL application given the type of permeant liquid passing through. Industry design engineers could use this relationship to estimate the hydraulic conductivity of the GCL liner system in order to provide appropriate design life depending on the type of application, the product is used in.

This study recognises that the estimate of the hydraulic conductivity obtained might have discrepancies in accuracy to the actual hydraulic performance in each field application. This could be attributed to the effect of other factors such as type and concentrations of various permeants, temperature, hydraulic head, quality of different manufacturers' GCL products, affecting the performance.

6. Implications

The importance of geosynthetic clay liners in various barrier applications such as landfills, mines, ponds and dams are clearly recognised using the comparison of theoretical leakage rates of various barrier systems presented by Giroud et al. (2004). They highlighted the benefit of using the low-permeable clay liner to reduce permeation and improve the service life of a barrier design. GCLs allow the containment facility space to be utilised effectively due to the reduction in thick clay layers in design. Nevertheless, the serviceability of geosynthetic clay liners significantly depend on the hydraulic performance of the installed product.

Historically, the clay used to line a containment facility is sourced locally, and the mineralogy and characteristics of the clay barrier is never the same from one site to another. Often the clay used in the construction of one cell at a single facility is not homogenous. The advantage of using GCLs is that it is essentially the same clay/bentonite used on every project, as the bentonite used to manufacture the GCL would be consistent in each barrier design. Therefore, developing experimental datasets to predict the performance of a generic, application specific geosynthetic clay liner product is identified as important.

The research results of this study address a gap in research data and use the relationships developed to propose a potential method to estimate the effect of overburden confining stress on the hydraulic performance of a specific GCL product depending on the permeant liquid passing through the liner system. The ASTM standard D5887 specifies to apply a total overburden confining stress of 35 kPa on a standard GCL tested for hydraulic conductivity. This does not always reflect the field applications where the overburden confining stress applied on the specimen is different: higher or lower. The authors used the data in literature and results obtained from the experimental study, to observe similar trends in hydraulic conductivity when applying different overburden confining stress conditions. This consistency in trend for each permeant liquid, is hence proposed to be used to predict the hydraulic performance of any given GCL product at the expected overburden confining stress in a given field application. This will allow manufacturers to use these experimental datasets as a knowledge base to determine the expected hydraulic conductivity of a GCL liner system when used in design for a specific application. The method will also benefit the designers/practitioners by allowing them to select the most suitable composite barrier design for the specific application.

7. Conclusions

Geosynthetic clay liners play a major role in overcoming environmental effects such as soil and groundwater contamination, acting as one of the most effective components of the composite barrier system in many geo-environmental engineering applications. The time-consuming nature of experiments and capacity of laboratory facilities has restricted the ability to replicate the field condition of a barrier system. It has been a constant challenge to replicate the expected field hydraulic performance of geosynthetic clay liners using laboratory test results. This research study outcomes allow prediction of the GCL hydraulic conductivity under field conditions using existing laboratory experimental data on product performance by focusing on the effect of overburden confining stress.

Important factors to be considered when using this approach is.

- To identify the type of permeant.
  - o If using water, the hydraulic conductivity when subjected to post hydration confinement is likely to be a factor of 1.5 higher than pre-hydration confinement.
  - o If leachate is the permeant, the hydraulic conductivity when subjected to post hydration confinement is likely to be a factor of 3 higher than pre-hydration confinement.
- Being informed of the overburden confining stress and the permeant liquid passing through the GCL, allows estimation of the hydraulic conductivity of the GCL of a specific application.

These findings will allow designers to determine the contribution of the GCL to improve the hydraulic performance and service life of the composite barrier system.

Declarations

Author contribution statement

Weerasinghe, I. A.: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Gallage, C. & Dawes, L.: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data.

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Data availability statement

The data is owned by Queensland University of Technology and can be shared upon request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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