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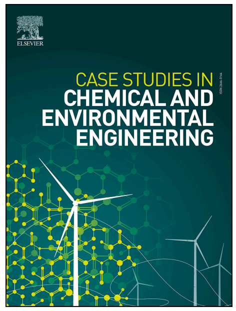

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Yaghoub Mohammadzadeh, Hadi Shahir, Gholamreza Asadollahfardi

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An Experimental Study on Effects of Interactions of Ambient Parameters on Permeability of Geosynthetic Clay Liners

Yaghoub Mohammadzadeh[1], Hadi Shahir[1], Gholamreza Asadollahfardi[1*]

1- Civil engineering Department, Faculty of Engineering, Kharazmi University, Karaj, Iran

Yaghoob_civil@yahoo.com, shahir@khu.ac.ir, fardi@khu.ac.ir

Abstract

Geosynthetic clay liners (GCLs) play a crucial role in landfills, making their hydraulic evaluation essential. This paper focuses on measuring the permeability of GCLs to various permeant liquids, specifically leachates from municipal solid waste landfills (MSWLF), under different ambient conditions. It aims to assess the individual and interactive effects of ambient parameters on GCL permeability. To achieve this goal, a parametric analysis was conducted to evaluate the impact of GCL type, GCL area density, permeant solution, confining pressure, hydraulic head and gradient, and the interaction of these parameters on GCL permeability. The tests were performed on two types of GCLs with varying area density percentages, providing insights into GCL permeability measurements. The findings revealed a direct correlation between hydraulic head and effective stress on the specimen. Under variable hydraulic head conditions, an increase in stress was found to elevate permeability. Conversely, with a constant hydraulic head, there was an inverse correlation between effective stress and permeability. Distilled water exhibited the lowest permeation, while treated MSWLF leachate displayed the highest. Ethanol demonstrated higher permeation than NaCl, and an increase in permeant solution concentration led to a rise in the permeability coefficient.Notably, at hydraulic gradients above a certain level, GCL-II (with a larger area density) exhibited a larger permeability coefficient compared to GCL-I (with a smaller area density).

Keywords: geosynthetic clay liner, MSW leachate, permeability, permeameter

Introduction

Landfills are mainly used for the disposal of municipal solid waste in underlying soil layers to minimize its possible health threats. However, toxic gases released from landfill leachates may pose serious implications, *e.g.*, air pollution and groundwater contamination (Paiooh et al., 2016; Zhang and Surampalli, 2016). Groundwater resources account for a significant portion of drinking and agricultural water. Therefore, we must protect groundwater resources from contaminants. Contaminants with the potential to infiltrate groundwater resources originate from a diverse array of sources, *e.g.*, landfall leachates, which may release toxic pollutants. To prevent contamination of subgrade soil and groundwater, we must isolate the landfill bottom and implement a leachate collection system. In other words, an isolation system at the bottom of solid waste landfills prevents the penetration of toxic contaminants into groundwater resources. Several barrier systems are used below the waste in landfills, *e.g.*, compacted clay liners, geomembranes, and geosynthetic clay liners (GCLs) (Tchobanoglous, 1991). GCLs are a barrier system that has been highly popular compared with other barrier systems (Saheli and Rowe, 2016; Suzuki et al., 2017). Furthermore, geosynthetics are increasingly employed in environmental geotechnics due to their wide range of applications (Weerasinghe et al., 2021).

First introduced in the late 1980s, GCLs are composites of bentonite clay and two geotextiles with satisfactory long-term shear strength for transferring shear forces from the lining layer across the bentonite layer to the core layer. GCLs then became a new sealing element in geotechnical and hydraulic engineering applications and were used all over the world in a short time. In general, initial GCLs would be employed for hydraulic and environmental applications, *e.g.*, mining waste landfill facilities in lining systems, substrate layers of composites, transportation facilities, storage tanks, moisture isolators in construction engineering, infrastructural applications, and single-layer liners of canals, basins, and shallow ponds (Rowe and Li, 2020).

GCLs have several advantages over compacted clay liners, including a much smaller volume and higher freeze-thaw and wet-dry cycle resistance, easy implementation, and significant savings in construction costs upon the reduced quality control/quality assurance (QC/QA) ratio on the site. GCLs have lower permeability than compacted clay liners to liquids and chemicals. GCLs have higher settlement resistance and greater self-healing (Daniel, 1993). Low-permeability sodium bentonite is a geosynthetic composite product with a clay core between two geotextiles with a geomembrane-connected adhesive. This product is used in several applications, *e.g.*, hydraulic barriers to reduce leachate contamination into the surrounding in waste landfills and mining waste dams, resistance to hydrocarbon leaks in secondary control applications, and cut-off walls, such as irrigation canals. They are also effectively used in gas and vapor sealing as a moisture isolator, construction, and water control facilities such as dams and ponds (Jo et al., 2005; Rowe, 1998).

Advances in the attributes of GCL products help overcome the existing limitations. In this respect, the hydraulic performance of GCLs has been improved from 10^{-7} to 10^{-12} m/s in the past two decades (Petrov et al., 1997; Weerasinghe et al., 2021).

Several recent studies have demonstrated that compacted clay liners are still popular as natural materials (Musso et al., 2014). Nevertheless, the conservation of natural resources should also be considered. More than one million square meters of GCLs have been used worldwide, saving nearly one million tons of natural clay. In other words, the use of GCLs in place of compacted clay liners with a thickness of 0.5 m avoids the excavation of nearly one million tons of natural clay (Heerten, 2016).

Several studies have explored the utilization of Geosynthetic Clay Liners (GCLs) in landfills. A few examples include Ganghi et al. (2016), who reported that a single-liner system of GCLs had remarkably higher performance than single- and double-layer hydraulic barrier systems for dangerous waste landfills while reducing clay consumption. Aldaeef and Rayhani (2015) found that daily thermal cycles could substantially influence the hydraulic performance of GCLs. GCLs favor waste landfills due to their form, availability, easy implementation, very small hydraulic conductivity, and self-healing effect. However, the design of hydraulic barrier products according to the requirements of various applications has become a major challenge to GCL manufacturers. Therefore, many studies have been conducted to improve the overall hydraulic performance of GCLs while maintaining the optimal capacity during the use of the hydraulic barrier (Daniel et al., 1997; Egloffstein, 2001; Mazzieri et al., 2000; Rowe, 2020; Weerasinghe et al., 2021). Furthermore, hydration has a major influence on GCL performance (Rayhani et al., 2011).

Dickinson and Brachman (2010) studied the permeability of GCLs at different pressures and thicknesses for a variable head. The results showed that GCLs with a thickness of up to 2 mm would increase permeability. Bannour et al. (2016) reported that not only the granulometric distribution of bentonite but also mass per unit area could affect the hydration process and flow rate evolution through GCL specimens.

Ali-Asgar et al. (2016) demonstrated that the bentonite form (e.g., powder versus granular) could affect the hydraulic performance of needle-punched GCLs, depending on gravimetric water content. Budihardjo (2016) found that GCL hydration using an ionic solution reduced the swell of bentonite particles and increased the hydraulic conductivity of hydrated GCLs. Liu et al. (2015) demonstrated that an increase in the acid concentration (ionic strength) raised the hydraulic conductivity of GCLs. They argued that pre-hydration (50-140% water content) and an effective stress of 35-200 kPa could improve the performance of GCLs. Weerasinghe et al. (2021) evaluated the effects of the confining stress on GCLs. They found that the stress and hydraulic conductivity had an inverse correlation, depending on the permeant. They also developed a model to estimate the hydraulic conductivity of GCLs as a function of confining stress, depending on whether the GCL is pre- or post-hydrated, and the permeant liquid passing through the GCL.

Liu et al. (2023) conducted the GCL permeability test on different salt solutions at several permeant liquid concentrations under wet-dry and freeze-thaw cycles. The results showed that an increase in the permeant concentration raised the permeability. For fewer wet-dry cycles, the permeability coefficient increased at a larger rate and then became stable.

A literature review indicates that there are no proposed methods, based on a permeameter and ASTM 6766 (ASTM, 2012), for measuring the permeability of Geosynthetic Clay Liners (GCLs) to leachates from Municipal Solid Waste Landfills (MSWLF). Additionally, there has been a lack of investigation into the impact of area density on GCL permeability. Previous studies did not assess the effects of hydraulic head on confining stress and permeability, nor did they examine their correlations. This study was designed to address these gaps in research. ASTM D5887 introduces flexible-wall permeameters as the standard testing device to measure the hydraulic conductivity of GCLs (ASTM, 2009). The standard permeameter cell is a basic-scale experimental method that can evaluate GCL specimens with a diameter of 100 mm.

This study evaluates effective stress as one of the multiple factors that affect the control of flows through GCLs. Many studies evaluated the impacts of effective stress (Petrov et al., 1997; Rowe et al., 1998; Shackelford et al., 2016). They reported a remarkable decline in the GCL hydraulic conductivity upon an increase in the confining stress, and smaller void ratios were probably the explanation (Bouazza, 2002; Rowe, 1998). Furthermore, the effective stress was studied under full hydration or hydration during the test (Rowe, 1998). Bouazza (2002) analyzed the effects of low, medium, and high stresses affecting the hydraulic conductivity of a GCL product. A wide set of permeability cell results over a range of low pressures to pressures over 250 kPa was collected. They reviewed a significant set of experimental works in the literature and concluded that the hydraulic conductivity reduced as the overburden confining stress increased.

A limited number of previous studies have focused on structural and conditional parameters to enhance the performance of GCLs. Ozhan and Guler (2016) showed that needle-punched GCLs had higher internal erosion resistance than unreinforced GCLs; however, considering the advantages of GCLs, we must evaluate the permeability measurement of GCLs to a variety of permeant liquids and MSWLF leachates. Furthermore, the area density can influence the permeability of GCLs and should be studied. Confining stress on a specimen in the cell has an inverse correlation with permeability; however, the hydraulic head effects on this correlation have not been analyzed yet. The quantity of waste in a real-life landfill increases over time, increasing the confining stress. At the same time, the MSWLF leachate changes the hydraulic head. Furthermore, the treatment process may reduce the head in the landfill. Therefore, the confining stress and hydraulic head have interactions, and we must evaluate their interaction and the effects of a change in the hydraulic head on the confining stress and permeability and their inter-correlations. As a result, this study aimed to measure the permeability of GCLs to a few permeant liquids and MWSLF leachate and evaluate the effects of the area density on GCL permeability, the effects of the hydraulic head on the confining stress and permeability, and their inter-correlations. A parametric analysis was conducted to capture the effects of the GCL type, GCL area density, permeant type, confining stress on the specimen, hydraulic head and gradient, and the interactions of these parameters on GCL permeability.

Table 1. Brief description of available studies and their results

References	Description of the research	Penetration fluid	Results
Petrov et al. (1997)	The results of confined swell, consolidation, and hydraulic conductivity tests on a needle-punched geosynthetic clay liner (GCL) are reported	distilled water, aqueous single salt solutions withconcentrations between 0.01 and 2.0 M NaCl, and a syntheticmunicipal solid waste (MSW) leachate	concluded that the hydraulic conductivity reduced as the overburden confining stress increased.
Rowe et al. (1998)	The parameters affecting the throughput and service life of GCLs in landfills have been discussed	Distilled water NaCl Solution synthetic MSW leachate	concluded that the hydraulic conductivity reduced as the overburden confining stress increased.
Shackelford et al. (2000)	Fundamental factors and testing considerations affecting the evaluation of the hydraulic conductivity of geosynthetic clay liners (GCLs) permeated with non-standard liquids (i.e., liquids other than water) are discussed and supported with test data.	Distilled water 0.6 M NaCl 0.0125 M CaCl2	Results show that non-standard liquids containing both high concentrations of monovalent cations (e.g., 0.6 M NaCl) as well as low concentrations of divalent cations (e.g. 0.0125 M CaCl2) can cause significant increases (⩾1 order of magnitude) in hydraulic conductivity provided the test is performed sufficiently long to allow for exchange of adsorbed cations.
Bouazza (2002)	Analyzed the effects of low, medium, and high stresses affecting the hydraulic conductivity of a GCL product	Distilled water	Concluded that the hydraulic conductivity reduced as the overburden confining stress increased.
Dickinson and Brachman (2010)	Studied the permeability of GCLs at different pressures	Distilled water	It was noted from this study that the soil type and gradation had significant effect on the long-term permeability variation.
Rayhani et al. (2011)	The hydration of different GCLs from the pore water of the underlying foundation soil is investigated for isothermal conditions at room temperature.	Water	The obtained results include the amount of natural moisture percentage of the sample, the amount of final hydration and the swelling index of bentonite in GCL, which increases swelling causes a decrease in permeability.

Table 1. Continue

References	Description of the research	Penetration fluid	Results
Liu et al. (2015)	The effects of ionic resistance, pre-hydration and overhead pressure have been .investigated	Sulfuric acid solutions	They argued that pre-hydration (50-140% water content) and an effective stress of 35-200 kPa could improve the performance of GCLs
Bannour et al. (2016)	Investigating the hydraulic behavior of GCL with different structural conditions	Distilled water	Reported that not only the granulometric distribution of bentonite but also mass per unit area could affect the hydration process and flow rate evolution through GCL specimens.
Ali-Asgar et al. (2016)	The influence of the initial moisture percentage of the bed and the type of bentonite on the hydraulic behavior of .GCL has been investigated	Distilled water	Demonstrated that the bentonite form (e.g., powder versus granular) could affect the hydraulic performance of needle-punched GCLs, depending on gravimetric .water content
Budihardjo (2016)	The effects of hydration with artificial leachate (different ionic solutions) on the hydraulic behavior and permeability of GCL have .been investigated	Distilled water NaCl	Found that GCL hydration using an ionic solution reduced the swell of bentonite particles and increased the hydraulic conductivity of hydrated GCLs
Shackelford et al. (2016)	The objective of this study was to evaluate the hydraulic conductivity (k) and diffusion behavior of a GCL in the limit as the salt (KCl) concentration increased to the extent that any observed membrane behavior was destroyed.	DIW and solutions of KCl	The results showed that the membrane behavior observed for GCL essentially disappeared when the average KCl concentration in the GCL sample, Cave, reached 200 mM KCl, and the permeability increased dramatically.
Ozhan and Guler (2016)	In this study, the type of GCL structure and the type of bentonite present in it and the level of geosynthetic surface density in the hydraulic behavior of GCL have been .investigated	Distilled water	Showed that needle-punched GCLs had higher internal erosion resistance than unreinforced GCLs; however, considering the advantages of GCLs, we must evaluate the permeability measurement of GCLs to a variety of permeant liquids and MSWLF leachates

Table 1. Continue

References	Description of the research	Penetration fluid	Results
Parastar et al. (2017)	The main objective of the present study is therefore to enhance the performance of GCL structures. By changing some structural factors such as clay type (sodium vs. calcium bentonite), areal density of clay, density of geotextile, geotextile thickness, texture type (woven vs. nonwoven), and needle punching density a series of GCL samples were fabricated.	Distilled water	It was found that higher Montmorillonite content of clay, overburden pressure, needle punching density and areal density of clay poses better self-healing properties and less hydraulic conductivity, meanwhile, an increase in water pressure increases the hydraulic conductivity.
Wireko and Abichou (2020)	Effect of Organic Matter on Index SwellProperties of a Conventionaland Bentonite–Polymer GCL	DI water NaCl $CaCl_2$ Na– Humic substances Ca- Humic substances	SI of Na–B was higher with the NaCl solutions containing HS than the SI with thepure NaCl solutions at Na+concentrations ≥20 mM. This suggests that in a sodium-rich leachate the presence of HS may enhance the hydraulic compatibility of the Na–BGCL.
Weerasinghe et al. (2021)	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.	Distilled water	Concluded that the hydraulic conductivity reduced as the overburden confining stress increased.
Weerasinghe et al. (2021)	They also developed a model to estimate the hydraulic conductivity of GCLs as a function of confining stress, depending on whether the GCL is pre- or post-hydrated, and the permeant liquid passing through the GCL.	Distilled water	They reported that an increased overburden pressure would reduce the permeability at a constant hydraulic head. This finding is in good agreement with the results reported by Ozhan and Guler (2016).
Liu et al. (2023)	Conducted the GCL permeability test on different salt solutions at several permeant liquid concentrations under wet-dry and freeze-thaw cycles.	Solutions containing ions: Ca, Mg, K, Al, Li, Na, Si, Sb & Sr	The results showed that an increase in the permeant concentration raised the permeability. For fewer wet-dry cycles, the permeability coefficient increased at a larger rate and then became stable.

Table 1. Continuation

References	Description of the research	Penetration fluid	Results
Present work	This paper focuses on measuring the permeability of GCLs to various permeant liquids, specifically leachates from municipal solid waste landfills (MSWLF), under different ambient conditions. It aims to assess the individual and interactive effects of ambient parameters on GCL permeability. To achieve this goal, a parametric analysis was conducted to evaluate the impact of GCL type, GCL area density, permeant solution, confining pressure, hydraulic head and gradient, and the interaction of these parameters on GCL permeability.	Distilled water, leachates from municipal solid waste landfills (MSWLF), NCL 10%, 15% and 20% Ethanol 10% and 70%	It was shown that filtered natural leachate has far greater results on GCL permeability, so that solutions with very high percentages are not comparable to it, so it is necessary to check the permeability of samples with it. It was shown that contrary to the idea in the past researches, one parameter such as confining stress does not work alone and should be investigated together in the interaction of the set of parameters. In previous researches, it has been mentioned that the permeability decreases with the increase of confining stress, but here it was shown that with the intervention of head changes, the opposite result may be obtained.

In the studies that were mentioned and the majority of the studies conducted in the field of GCL permeability, it seems that several environmental conditions have not been investigated, which have been discussed in this article in order to simulate the real conditions of the landfill site. First of all, Although previous studies analyzed the permeability of GCLs, synthetic leachates were often used due to the difficult analysis and unpleasant odor of natural MSW leachates, it is possible that the results of GCL permeability with natural leachate may be different from the distilled water of artificial leachate. Therefore, in this article, one of the innovations is The use of natural leachate from the site of Kahrizak and used a permeameter and ASTM 6766 (ASTM, 2012) to measure the permeability of GCLs to natural and treated MSWLF leachates. The second thing is that each of the parameters of the environmental conditions never act separately and independently, if in the previous studies each of the conditions of overhead, temperature, self-healing, infiltration liquid, head and other things were examined separately, but in this study In order to simulate the actual conditions of the site and obtain more realistic results, the interaction of various environmental parameters such as stress, infiltrating fluid and head has been investigated. This is considered a novelty of the present work, which also includes analyzing the effects of the GCL area density on the GCL permeability and permeant liquid and the effects of the interaction of ambient conditions on GCL behavior. The third thing is that the hydraulic gradient varies in real conditions in the landfill, so it is necessary to investigate this phenomenon, which is addressed in this research. The effects of a change in the hydraulic head on the confining stress and permeability and their inter-correlation were also investigated for the first time. This study evaluated the individual and combined effects of various parameters on GCL behavior to identify the natural behavior of GCLs under optimal ambient conditions, And the last item is that when the GCL is applied in the site and its hydraulic work is started, its humidity is not in a saturated state and it is in different humidity percentages, which is also investigated in this study. It should be noted that all the cases examined in this research are for the purpose of simulating the site conditions for GCL under hydraulic load with the aim of obtaining accurate and real results.

Materials and Methods

GCLs

Table 1 illustrates the characteristics of the two GCLs utilized in this study.

Table 2. The characterization of GCLs

Swell index (with leachate)		Swell index (with water)	Permeability (at 100 kPa)	Peel strength	Static puncture strength	Max tensile strength	Mass per unit area	GCL
2.7	4.23	5×10^{-11}	>60	2400	11.20	7	4800	I
1.5	2.19	8×10^{-9}	360	2000	12.12	6	4100	II

Permeant Liquids

The permeant liquids included distilled water, treated MSWLF leachate, ethanol, and NaCl at different concentrations. The MSWLF leachate was obtained from the Kahrizak landfill in the south of Tehran, Iran. The Kahrizak landfill receives nearly 7,000 tons of MWS every day. Table

2 reports the parameters of the permeant liquids collected from the chemical laboratory of the Arian Chimia Tech (ACT) Industrial Group.

Table 3. The parameters of permeant liquids

parameter	Unit	Ethanol 70%	Ethanol 20%	Ethanol 10%	NaCl 10%	NaCl 15%	NaCl 20%	Leachate	Tap water
pH	-	5.8	6.6	6.7	6.2	6.1	6	7.71	8.12
Electrical Conductivity(EC)	ms-Ms	3.25 Ms	5.35 Ms	7 Ms	9200 Ms	12225 Ms	14200	41200	1520
Chemical oxygen demand (COD)	mg/L	87000	56000	45000	1800	2140	2480	16320	0
Total dissolved Solid (TDS)	mg/L	1.25	2.77	3.42	4590	6130	7100	23400	770
Nephelometric turbidity unit (NTU)	NTU	0.58	0.69	0.73	1.53	1.64	2.49	> 1000	1.54
Pb	ppm	<5	<5	<5	<5	<5	<5	< 0.1	0
As	ppm	<2	<5	<5	<5	<5	<5	< 1	0
Cd	ppm	<2	<2	<2	<2	<2	<2	< 0.05	0
Hg	ppm	<1	<1	<1	<1	<1	<1	< 1	0

Panno et al. (2015) stated that in the samples taken from the landfill, the sodium concentration was 4420 mg/L, and the concentration of chloride was 170 mg/L,which means that these concentrations were very low-weight percentages of sodium chloride. Also, Wireko et al. (2020) considered the NaCl concentration range to be 500 mg/L, and Chai et al. (2016) used a solution of 10 g/L of NaCl as an infiltration liquid, all of these percentages for simulating the real condition of the landfill leachate including very low percentages of NaCl solution. In the present work, low percentages are also used, but because the comparison between infiltration liquids is evident, 10%, 15%, and 20% NaCl have been used. We used higher percentages of NaCl than previous researchers to show that even high percentages of synthetic leachate containing a specific ion or heavy metals alone are not a good representative of filtered natural leachate.

Subgrade Soil

Full hydration is not conducted to simulate the site conditions for GCLs. However, ASTM D5887 (2009) requires 48 hours of full hydration, and the saturated specimen undergoes a permeability test. This study did not implement full hydration for site simulation and used the simulated subgrade soil of the Kahrizak landfill. It consists of fine-graded sand with an optimal moisture content (OMC) of 9.7%. According to Table 3, the gradation test was performed under AASHTO T 134 (2019).

Figure 1 depicts the gradation curve of the soil.

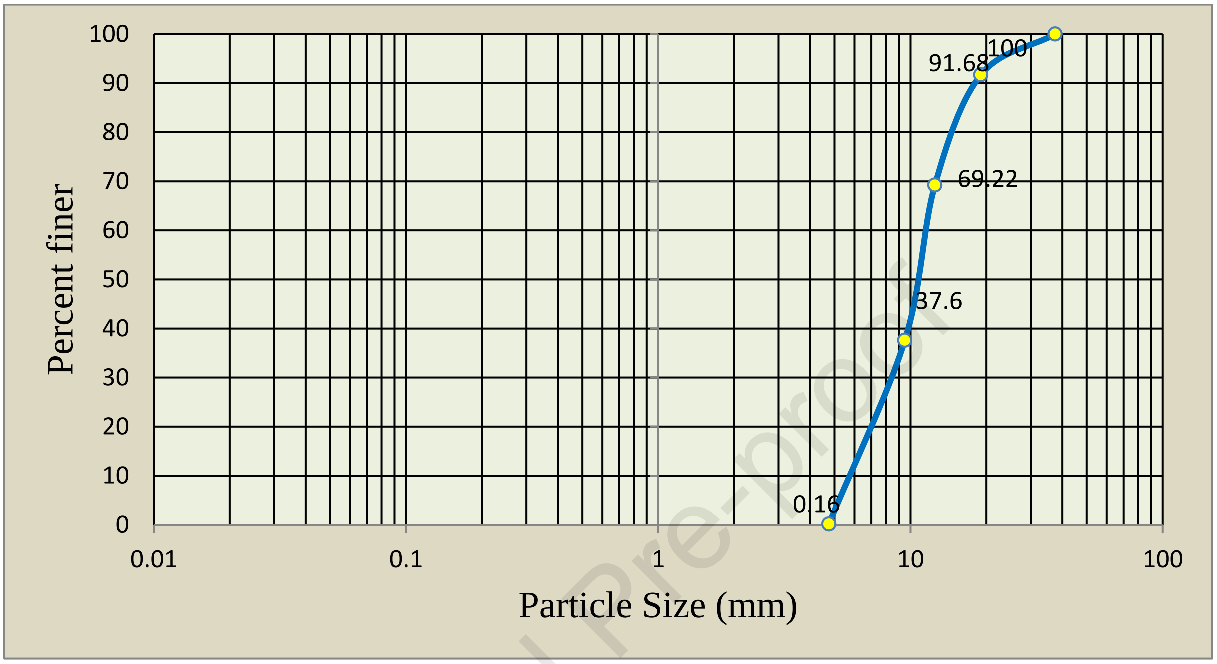

Figure 1. The gradation curve of the substrate soil used for the hydration of the sample

Permeability Test Device

A flexible-wall permeameter cell was employed to measure the hydraulic conductivity and permeability of the GCLs under ASTM D5887 (ASTM, 2009). The permeameter cell applies a controlled fluid pressure using a flexible membrane to the GCL specimen and the confined porous components. It is used to perform the hydraulic conductivity test of GCL specimens subjected to a minimum confining stress of 550 kPa. Figure 2 illustrates a schematic and a photograph of the permeameter (Weerasinghe et al., 2021).

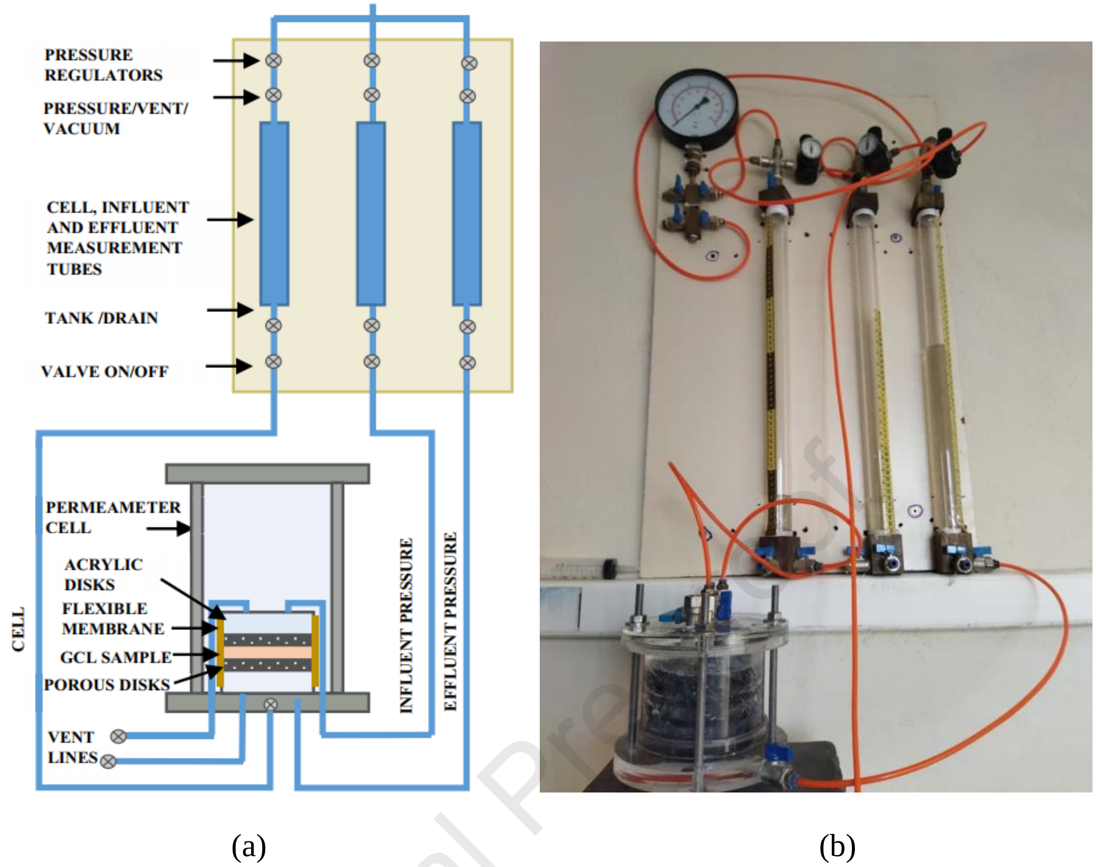

Figure 2. (a) Schematic of the standard permeameter device (ASTM D5887) and (b) photo of the permeameter made for this research.

The permeation testing of distilled water was conducted following ASTM D5887 (ASTM 2009), while ASTM D6766 (ASTM, 2012) served as the standard test method for other permeant solutions.

Experiments

Specimen Preparation

Figure 3 shows the specimen preparation process. In the first step, a GCL specimen with a diameter of 10 was cut so that the bentonite particles would not be lost. Then, the specimen was placed on a porous rock. It was covered with a paper filter on the top and bottom, and another porous rock was placed on the system. Finally, the membrane isolation was applied to the sides, and the GCL specimen was placed in the permeameter.

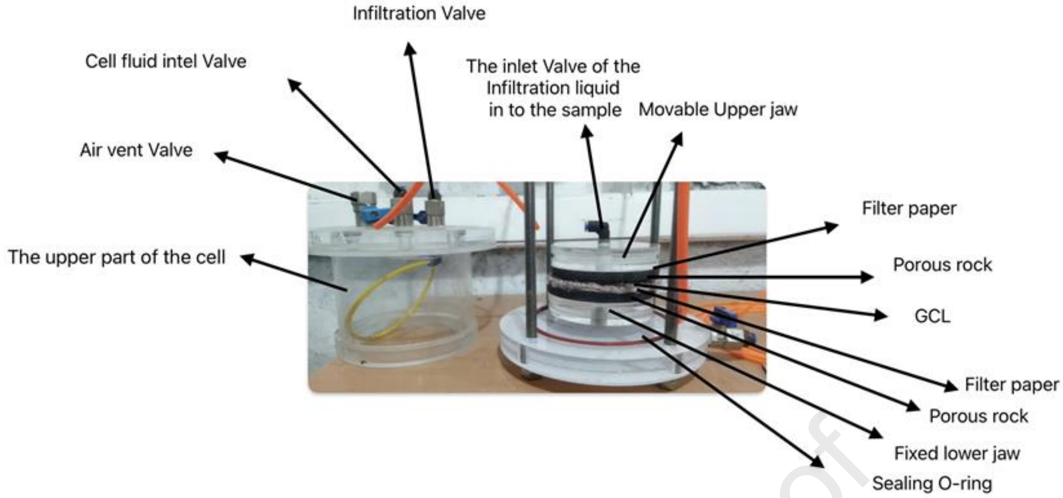

Figure 3. Sampling components in the cylinder of the permeimeter device in the sample preparation process

Landfill standards, including EPA (1999) require *in situ* GCL hydration. However, hydrated GCLs remain on the site to dry. Empirically, drying is finished when MSW is discharged into the landfill. Therefore, full hydration tests were performed before the permeability test to simulate standard conditions.

Hydration

hydration was conducted in two approaches. First, ASDM D5887 (299) was implemented, where the specimen was subjected to a cell pressure of 550 kPa for 48 h. As mentioned, the GCL specimen should be fully hydrated *in situ*; however, this is not carried out in practical applications. The second hydration technique was performed to simulate real-life landfills by natural GCL hydration while considering the leachate liquid in the permeation phase (Figure 4).

Polyvinyl chloride (PVC) cells were fabricated as a sealed column in which GCL could only receive moisture from the underlying layer (Rowe and Li, 2020). The initial subgrade soil had the moisture contents of 5%, 10%, and 15% (Row and Li, 2020). Long-term hydration was performed, and nearly 90% of the GCL moisture was received from the subgrade in the first ten days. The GCL was then separated to measure its moisture. Finally, it was placed in the permeameter to implement the permeability test.

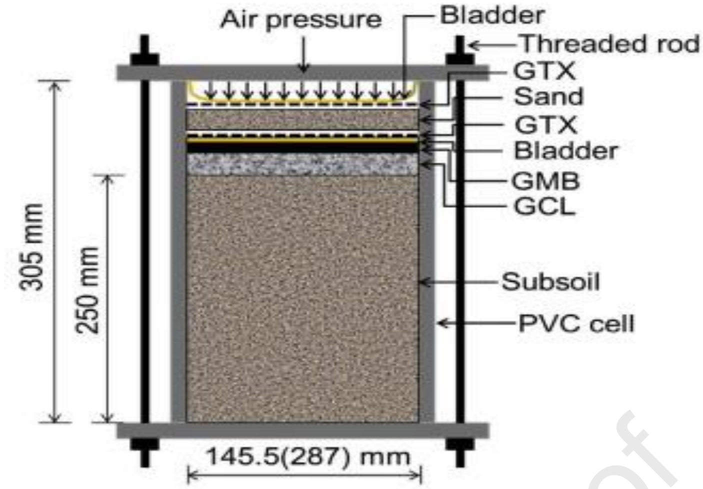

Figure 4. The schematic view of the hydration cell configuration in the permeability test

Permeameter Test

The GCL specimen was prepared under ASTM D5887 (2009). It was isolated to avoid the mixing of the confining pressure with the flow passing through the GCL. The permeant was subsequently deaerated. Furthermore, a treated leachate was used for leachate permeability testing. A confining pressure of 550 kPa was applied to the cell for 48 h, and the input and output pressures remained unchanged during hydration to avoid flows.

An input pressure (bottom) of 350 kPa and an output pressure of 315 kPa were applied, recording the change (increase/decrease) in the input and output heads. Once the test had been completed, the permeability coefficient was calculated. In the second phase, hydration was performed in the cylinder to simulate real-life landfills. The moisture content of the specimen was then measured. Direct permeation was performed within the permeameter, and the permeability coefficient was obtained. An overburden pressure of 27.5 kPa is often applied in permeameter tests. Different overburden stresses and permeant inflow and outflow pressures were used in different tests.

Receiving leachate from the landfill site and using it has limitations, including unsuitable environmental conditions and the need to receive leachate from garbage trucks. In addition, the received leachate has a lot of chemical interactions, therefore, in order to perform the experiment in chemically stable conditions, it is necessary to use old leachate instead of young leachate, which is also taken into consideration in the experiments, and the use of leachate is also due to its negative effects. It is difficult and limited on the device and test tubes, as well as the need for an isolated space due to its unpleasant smell. In addition, in order to prevent the closing of the pores of the test device components, MSW treated Leachate must be used, which is also one of the limitations of the experiment, while purifying the extracted leachate.

Results and Discussion

This study used two GCL types. Figure 5 depicts the permeability coefficients of GCL-II for different permeant liquids. Furthermore, a fixed initial moisture content and an area density of 4100 g/m^2 were assumed. According to Figure 5, the GCLs showed the lowest permeability to distilled water and the highest permeability to the treated leachate. This reflects the use of natural MSW leachate rather than simulated leachate.

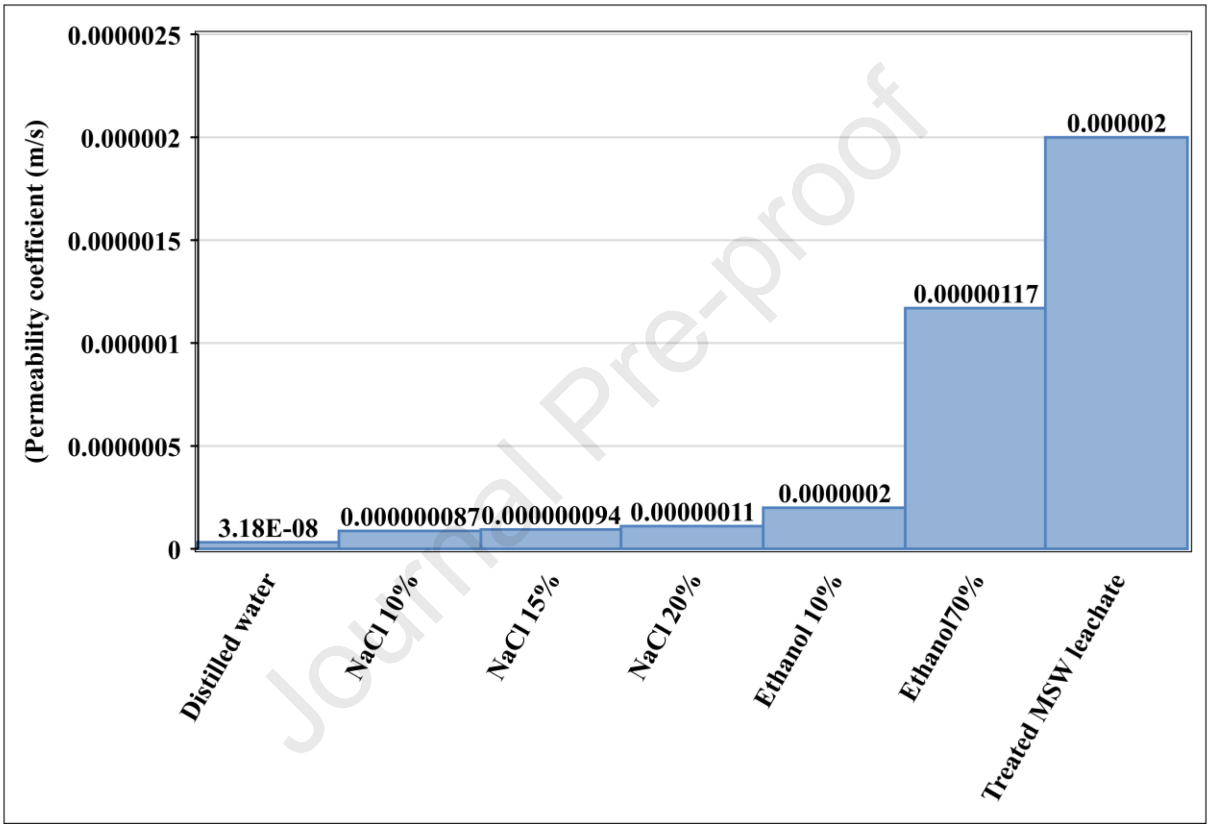

Figure 5. Values of permeability coefficient of GCL sample under different penetrating solutions

Furthermore, the GCLs exhibited higher permeability to ethanol than to NaCl. An increase in the solution concentration increased the permeability. However, the NaCl concentration had a much smaller effect than the methanol concentration on the permeability. This finding aligns well with the results presented by Shackelford et al. (2000). However, they did not analyze MSW leachates containing various components, As mentioned before, they have used artificial leachates with some components of natural leachate. The interaction of all components in the solution also had a major effect on the permeability, which was not examined in previous studies. Although the treated natural leachate did not contain 70% ethanol, the multiplicity of its components substantially increased the permeability. Ethanol may contain a few heavy metals and pose a larger effect on permeation compared with synthetic leachates. Therefore, we must utilize a natural MSWLF leachate to effectively identify the permeability phenomenon in landfills.

GCL-I with an area density of 4800 g/m^2 and different initial moisture contents were tested. Regardless of the permeant solution, an increase in the initial moisture content reduced the permeability. Moreover, the moisture content of the MSWLF leachate had a greater effect than that of distilled water on the permeability. Rayhani et al. (2011) analyzed the effects of moisture content and hydration on GCL permeability. The results align closely with the findings reported by Rayhani et al. (2011). This study evaluated the correlation between the permeability and treated MSWLF leachate (Fig.6), whereas earlier works analyzed synthetic leachates.

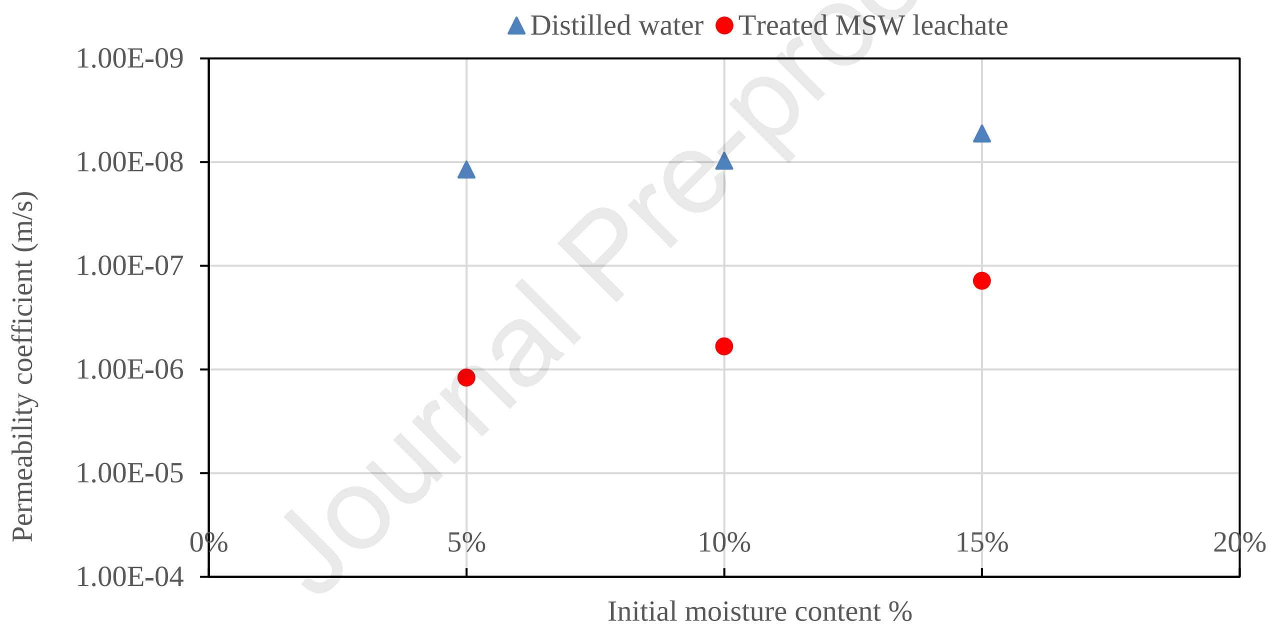

Figure 6. Permeability to distilled water and treated MSWLF leachate at different initial moisture contents

The difference in the permeability of GCL-I to distilled water and treated MSWLF leachate was lower at higher initial moisture contents. In other words, the permeability coefficient to the treated MSWLF leachate had higher sensitivity to the initial moisture content. It increased at a larger rate with the initial moisture content.

The GCL type can affect the permeability coefficient. Thus, two GCLs were studied: GCL-I with an area density of 4800 g/m^2 and GCL-II with an area density of 4100 g/m^2. Figure 7 illustrates the permeability coefficients of GCL-I and GCL-II at different hydraulic gradients.

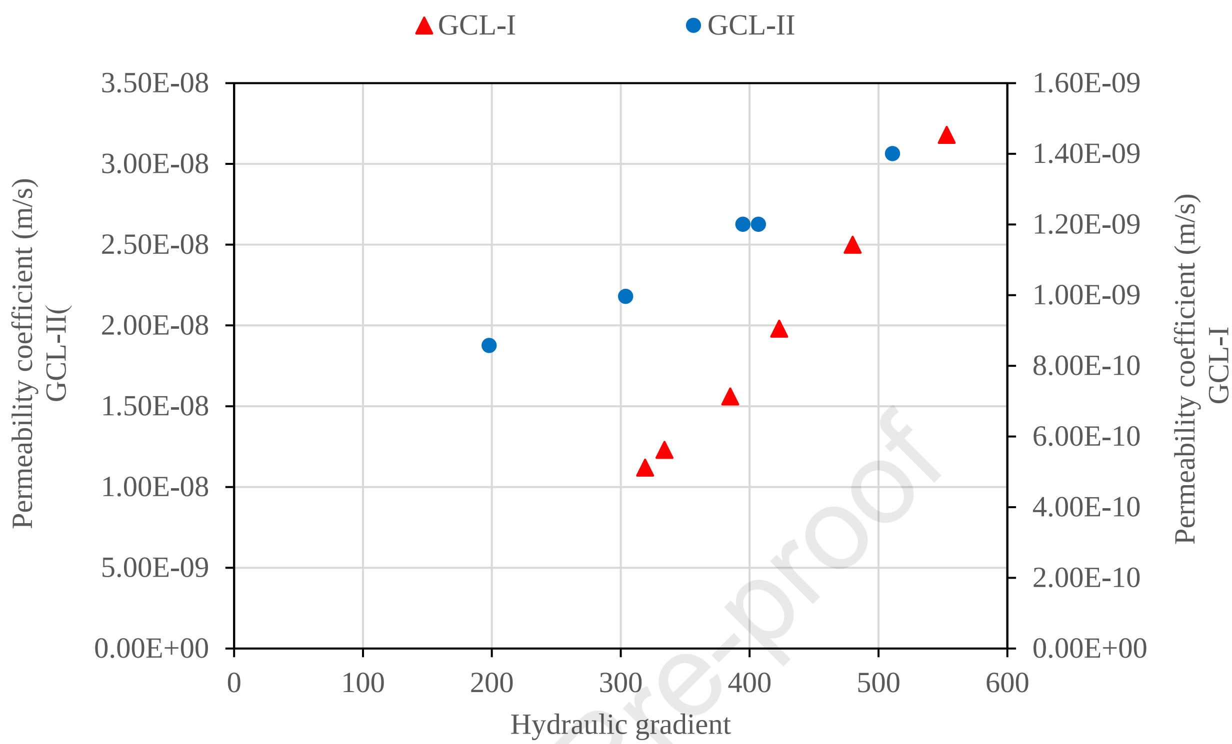

Figure 7. Permeability of GCL-I and GCL-II at different hydraulic gradients

According to Figure 7, a rise in the hydraulic gradient increased the permeability coefficient, regardless of the GCL type. At lower hydraulic gradients, a larger area density resulted in a larger permeability coefficient. However, GCL-II (smaller area density) was more sensitive than GCL-I (larger area density) to the hydraulic gradient; its permeability coefficient rose at a greater rate with the hydraulic gradient. Nevertheless, as the hydraulic gradient exceeded a certain level, GCL-II began to show a larger permeability coefficient than GCL-I. In conclusion, (1) the permeability coefficient is a function of the GCL type, and (2) the hydraulic gradient is a major determinant of GCL permeability since the GCL with a smaller area density showed higher performance (lower permeability) than the GCL with a larger area density over a certain range of the hydraulic gradient. Parastar et al. (2017) argued that the permeability of a GCL was a function of its type, and an increase in the mass per unit area would decrease the permeability coefficient. This study analyzed the combined effect of the hydraulic gradient (as an ambient parameter) and GCL type (area density) and their interaction.

The correlation between the permeability coefficient and effective stress was analyzed for a given GCL type (GCL-I) and a variable cell pressure. Figure 8 plots the effective stress versus the permeability coefficient at different cell pressures for a head of 0.015 m.

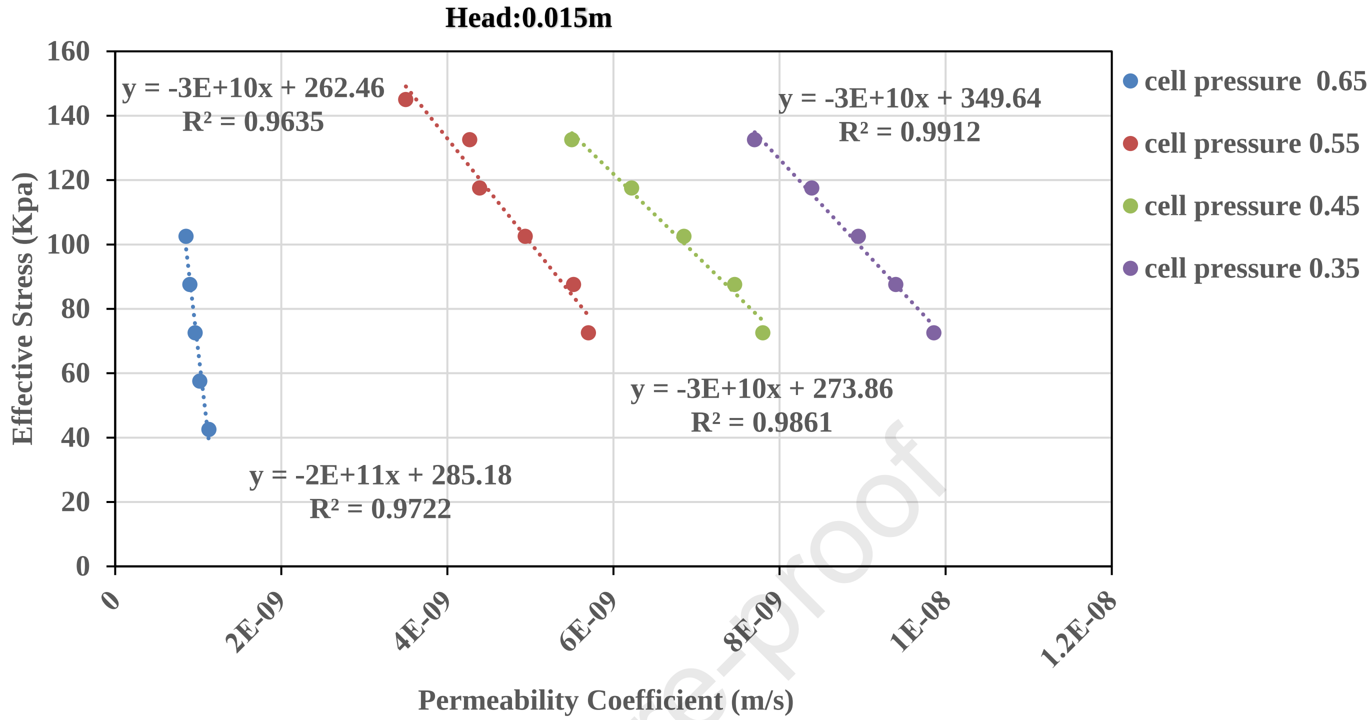

Figure 8. Changes in permeability coefficient of GCL sample versus effective stress in different cell pressures

According to Figure 8, an increase in the cell pressure consistently reduced the permeability coefficient and increased effective stress. Thus, the permeability coefficient and effective stress have an inverse correlation. This finding is consistent with the results reported by Rowe et al. (1998) and Bouazza (2002). They indicated that the permeability reduced as the overburden stress increased. It rose at a larger rate when the cell pressure was higher. The head change may affect not only the change rate of the effective stress but also the correlation between the permeability coefficient and effective stress.

Figure 9 presents the effects of the hydraulic head on the correlation between the permeability coefficient and effective stress. At an increased head, the permeability coefficient increased with the effective stress. In other words, the GCL showed the opposite behavior under a variable head.

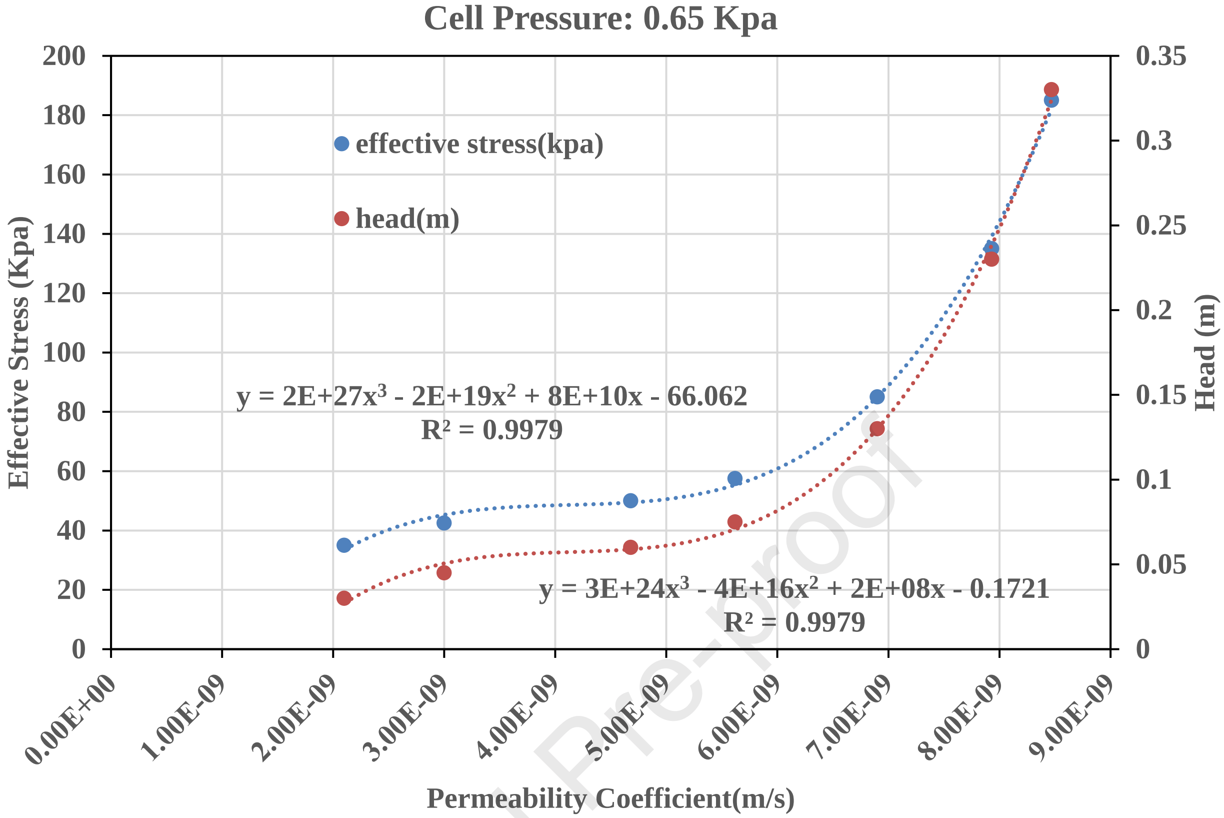

Figure 9. The effects of the head change on the correlation between the permeability coefficient and effective stress

Figure 10 indicates the effective stress versus the permeability coefficient at different heads for a cell pressure of 0.35 kPa. The permeability coefficient and effective stress had a direct correlation as the head increased. Furthermore, the head and effective stress did not have the same change rate. The head was initially divergent and then became convergent, whereas the permeability coefficient and effective stress had a consistently direct correlation.

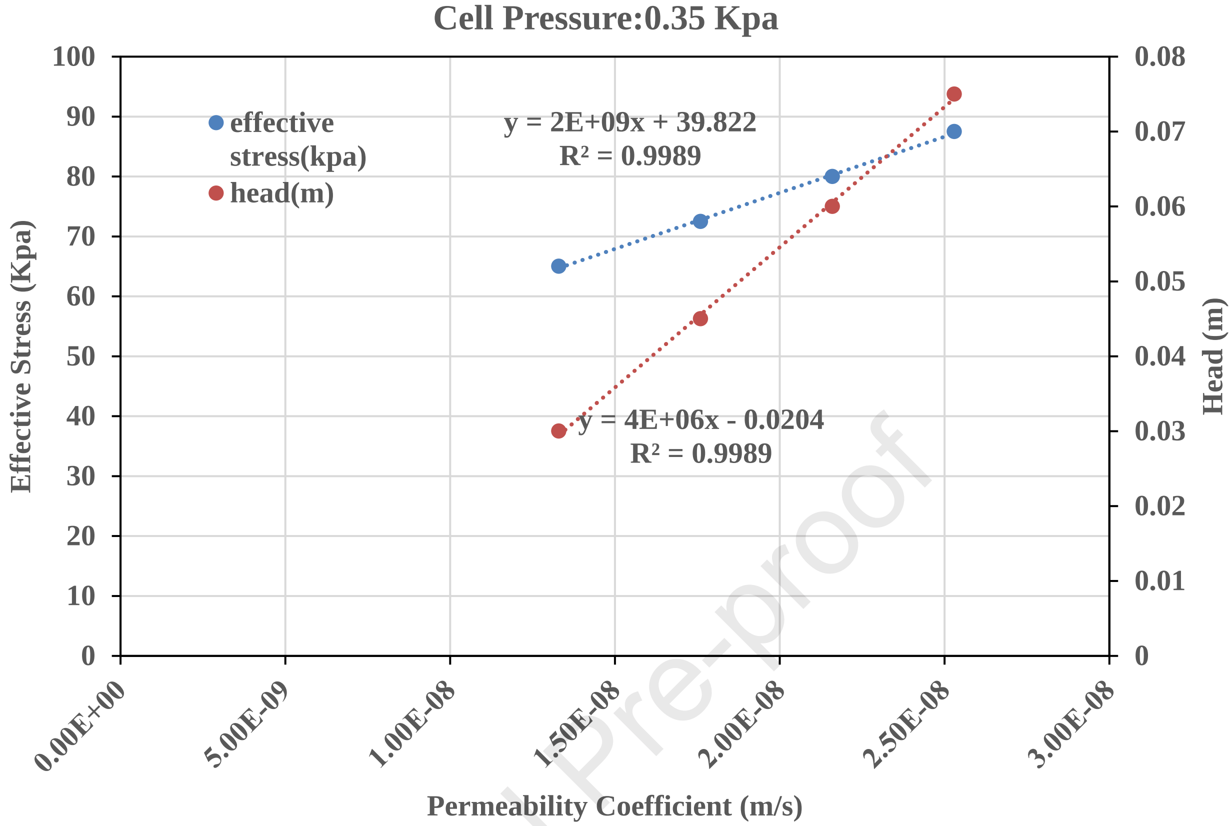

Figure 10. Effective stress versus permeability coefficient at different heads for a cell pressure of 0.35 kPa

The head-stress interaction can change the correlation between the effective stress and permeability coefficient. It is necessary to simultaneously evaluate all effective parameters to analyze GCL performance. Weerasinghe et al. (2021) studied the relationship between the permeability and overburden pressure. They reported that an increased overburden pressure would reduce the permeability at a constant hydraulic head. This finding is in good agreement with the results reported by Ozhan and Guler (2016).

Using the treated MSWLF leachate was a novelty of this research. Although MSW leachates from the Kahrizak landfill were sometimes used in previous studies, this research utilized a treated MSW leachate and incorporated the chemical interactions of the young landfill leachate. The leachate was maintained at the laboratory temperature for a long time to ensure its relative chemical stabilization. Previous studies analyzed the permeation of leachates, whereas the present work investigated leachate effects under various ambient conditions. Many studies reported that an increase in the confining stress reduced the permeability. This study evaluated changes in the permeability under increased confining stresses for a given hydraulic head, and the permeability decreased as the confining stress rose. This finding is consistent with the results of previous studies. However, this was the case only when the head remained unchanged. For a constant head, the permeability consistently decreased as the outflow increased. At the same time, a rise in the outflow reduced the permeability coefficient. Therefore, the permeability coefficient and effective stress had an inverse correlation, and an increase in the cell pressure reduced the reduction rate of the permeability coefficient. Furthermore, at a variable head, the effective stress and permeability coefficient had a direct correlation.

Parastar et al. (2017) studied the type of GCL and the influence of permeate pressure and overhead pressure separately. Wireko and Abichou (2020) used CaCl2 and NaCl solutions and humic acid as infiltration liquids. In addition, Row & Li. (2020) studied the hydration and substrate with deionized water infiltration liquid and artificial leachate. In our research, the investigation results with distilled water for different conditions are similar to previous studies and have a good overlap. Among the innovations of the present work, it can be stated that none of the mentioned previous studies have used natural leachate. In addition, in our results, we show that even higher concentrations of artificial leachate and higher than usual concentrations of different ions have much fewer effects than filtered natural leachate, for example, the normal concentration of sodium and chloride ions in leachate is about 1%, but in our work for a better comparison, even increasing it to 20% did not have a significant effect compared to the filtered natural leachate, or although the concentration of ethanol in natural leachate does not reach 70%, the concentration of 70% of ethanol does not even have an effect like that of filtered natural leachate.

Another novelty of this study is that, for example, Parastar et al. (2017) investigated several environmental parameters on the permeability of GCL and concluded that the permeability decreases with the increase of overhead stress, in the present work it was shown that the interaction of these parameters can bring opposite results. It was shown that in some cases if the head and overhead are changed together, the permeability may increase with the increase of the overhead te tension. Therefore, to simulate the conditions of the site as observed in this research, it is necessary to examine all the parameters together and in interaction with each other.

Conclusion

1. The analysis of permeability to different permeants revealed that the GCLs had the highest permeability to distilled water and the lowest permeability to the treated MSWLF leachate. This suggests that the treated MSW leachate had the highest permeation into the GCLs among other permeant solutions.
2. an increase in the permeant solution concentration increased the permeability coefficient. The permeability to ethanol remarkably increased as the ethanol concentration increased.

3. Regardless of the permeant, the permeability coefficient increased with the initial moisture content. Furthermore, distilled water permeation was higher than treated MSWLC leachate permeation. The permeation of the treated MSWLF leachate had higher sensitivity to the initial moisture content and rose at a larger rate as the initial moisture content increased.
4. GCL-II (smaller area density) had higher hydraulic gradient sensitivity than GCL-I (larger area density), and an increase in the hydraulic gradient resulted in a larger increase in the permeability of GCL-II. At hydraulic gradients above a certain level, GCL-II had a larger permeability coefficient than GCL-I. Moreover, the hydraulic gradient was identified as a major permeability determinant of GCLs.
5. Without considering other environmental parameters and examining the effect of effective stress alone, the permeability coefficient decreases with the increase of effective stress, but considering the interaction of the simultaneous effect of head and effective stress, different results were obtained, and it is possible that changes in head have a positive effect. Neutralize the stress affecting permeability or affect the way it changes.
6. As we know, in the real conditions of the site, with the passage of time, the amount of head, all-round pressure and overhead pressure change, in the condition that the head is constant, the amount of all-round pressure (cell pressure in the test device) will affect the permeability changes affected by the effective stress.
7. One of the limitations in present work was the possibility of air in the permeate liquid, which is mentioned in ASTM D5887 (2009) as a source of error. In addition, a wind pump was used in the device of our research, and the accurate adjustment of input and output pressure simultaneously from a wind pump source creates the possibility of human error and device error. Furthermore, limitations in working with natural leachate received from Kahrizak landfill in the laboratory environment, which makes it difficult to work with due to its unpleasant smell and toxic chemical components. Finally, another possible error in reading the numbers is the decrease and increase of the input and output liquid. We suggest that future researchers are advised to use digital reading devices.
8. None of the previous research applied natural leachate. In addition, we indicate that even higher concentrations of artificial leachate and higher than typical concentrations of dissimilar ions have much fewer impacts than filtered natural leachate.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: