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Application of Nanoclay in Reducing Permeability of Fine-grained Soil: An Experimental Study

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***Abstract*:** Soil permeability plays a crucial role in controlling leachate migration, which is a major environmental concern in landfills. This study presents an experimental investigation to evaluate the effect of fine-grained soil permeability on leachate migration as part of a broader geotechnical research project. For this purpose, 12 untreated soil samples were compared with 12 samples containing 3% nanoclay, 12 samples with 6% nanoclay, and 12 samples with 9% nanoclay. Unlike conventional permeability tests that use water, this study utilized real landfill leachate from the Tabriz landfill site to simulate actual environmental conditions. The primary objective was to assess the impact of nanoclay on soil permeability and its potential for improving landfill liners. To comprehensively analyze soil behavior, Atterberg limits, chemical analyses, and X-ray diffraction (XRD) tests were performed alongside permeability measurements. The results demonstrated that increasing the nanoclay content significantly reduced permeability, with values decreasing from 10^{-6} m/s in untreated samples to 10^{-9} m/s in samples with 9% nanoclay. This reduction indicates that nanoclay enhances the impermeability of fine-grained soils, making them more effective barriers against leachate infiltration. These findings suggest that nanoclay-modified soils could serve as an efficient and sustainable material for landfill liners, reducing the environmental risks associated with leachate migration. The study provides valuable insights into the application of nanotechnology in geotechnical engineering, particularly in waste management and soil stabilization projects.

Keywords: Nanoclay, Permeability reduction, Fine-grained soil, Experimental study, Soil stabilization.

I. INTRODUCTION

Soil contamination has become a significant environmental concern due to the increasing release of hazardous substances into the environment. Various anthropogenic activities, including industrial operations, agricultural practices, waste disposal, and accidental spills, contribute to the introduction of pollutants into the soil (Nikbakht et al., 2023). Once introduced, these contaminants may migrate through the soil profile, affecting groundwater, ecosystems, and human health. The degree of soil contamination depends largely on the soil's permeability, which governs the movement of pollutants, particularly leachates and hazardous chemicals (Qasaimeh et al., 2020). Understanding the mechanisms of contaminant transport in soil is essential for developing effective remediation strategies (Nikbakht et al., 2022). One of the major sources of soil pollution is landfill leachate, which results from the decomposition of waste materials in landfills (Abbasi et al., 2018). Leachate is a highly toxic liquid containing a mixture of organic and inorganic compounds, heavy metals, and pathogens (Roy and Mishra, 2023). Due to its ability to infiltrate the soil, leachate can migrate deep into subsurface layers, eventually reaching groundwater reservoirs (Arabani et al., 2023). The permeability of soil plays a crucial role in determining the extent of contamination, as highly permeable soils facilitate faster pollutant migration, while low-permeability soils provide a degree of natural containment (Qasaimeh et al., 2020).

Hazardous materials, such as heavy metals, petroleum hydrocarbons, pesticides, and industrial chemicals, pose severe threats to soil quality. These contaminants can enter the soil through direct discharge, accidental spills, or improper disposal methods (Sarand et al., 2022). Once in the soil, they undergo various physical, chemical, and biological processes that influence their mobility and persistence. For instance, heavy metals tend to bind with soil particles, whereas organic pollutants like petroleum hydrocarbons may be subject to microbial degradation or volatilization (Harsh et al., 2023). The permeability of soil is a key factor influencing pollutant movement (Arabani et al., 2023). Coarse-grained soils, such as sand and gravel, exhibit high permeability, allowing rapid infiltration and migration of contaminants. In contrast, fine-grained soils, such as clay and silt, have low permeability and can act as a natural barrier to pollutant migration (Nikbakht et al., 2023). However, the presence of cracks, fractures, and preferential flow paths in clay-rich soils can significantly increase permeability, leading to unpredictable contaminant movement (Nikbakht et al., 2022).

In urban and industrial areas, soil contamination is exacerbated by activities such as underground storage tank leaks, improper waste disposal, and chemical spills (Praveen & Sunil, 2016). Contaminants in these environments may persist for decades, leading to long-term environmental degradation (Nwachukwu & Nwachukwu, 2020). Moreover, polluted soils can lose their natural fertility, affecting plant growth and agricultural productivity (Sarand et al., 2022). Heavy metal accumulation, for instance, can render soils toxic, making them unsuitable for crop cultivation and posing risks to food safety (Azizpour et al., 2020). Groundwater contamination is a critical consequence of soil pollution. When pollutants migrate through the soil, they can reach aquifers, leading to widespread water quality issues (Hajjizadeh et al., 2020). Contaminated groundwater sources are difficult to remediate and may pose serious health risks if used for drinking, irrigation, or industrial purposes (Hashemi et al., 2021). The persistence of pollutants, particularly non-biodegradable substances such as heavy metals and persistent organic pollutants (POPs), further complicates the remediation process (Sarand et al., 2022). Environmental regulations and remediation techniques have been developed to mitigate soil contamination and prevent pollutant migration. Physical containment methods, such as impermeable barriers and liners, can restrict contaminant movement (Hussain et al., 2021). Chemical stabilization techniques, including soil amendments and chemical fixation, aim to reduce the mobility of hazardous substances (Jafari & Abbasian, 2018). Additionally, bioremediation and phytoremediation approaches leverage natural processes to degrade or immobilize pollutants, offering sustainable and cost-effective solutions (Johari et al., 2022).

The role of nanotechnology in soil remediation has gained significant attention in recent years. Nanomaterials, such as nanoclays and iron nanoparticles, have shown promise in reducing soil permeability and immobilizing contaminants. These materials can enhance the adsorption capacity of soil, preventing the leaching of hazardous substances into groundwater. The application of nanotechnology in soil pollution management represents a promising avenue for improving environmental sustainability (Kananizadeh et al., 2011). Preventing soil contamination requires a combination of regulatory measures, sustainable land-use practices, and technological advancements (Zhao et al., 2015). Governments and environmental agencies play a vital role in enforcing pollution control laws and monitoring industrial activities to minimize hazardous discharges. Public awareness and community participation are also crucial in promoting responsible waste disposal and sustainable agricultural practices (Meuser, 2010).

This study aims to investigate the innovative application of nanoclay in reducing the permeability of fine-grained soils through a series of controlled laboratory experiments. The research explores how nanoclay particles, due to their high surface area and unique physicochemical properties, can enhance soil structure, decrease pore spaces, and improve water retention capacity. By systematically analyzing the effects of different nanoclay concentrations, this study seeks to provide a sustainable and cost-effective solution for improving soil impermeability in geotechnical and environmental engineering applications, such as landfill liners, dam cores, and underground construction.

II. LANDFILL LINERS AND LEACHATE

A landfill is a designated site for the disposal of solid waste, where waste materials are systematically buried to minimize environmental impact (Vaverková, 2019). Landfills are an essential component of waste management, which involves the collection, transportation, treatment, and disposal of waste in a controlled manner (Renou et al., 2018). The goal of waste management is to reduce pollution, protect public health, and conserve natural resources through various strategies, such as recycling, composting, incineration, and engineered landfilling. Properly designed and managed landfills prevent uncontrolled dumping, which can lead to severe environmental and health hazards (Crawford & Smith, 2016). Figure 1 is providing a systematic landfill schematic were generally provided to describe a solid waste landfill. Landfills play a crucial role in waste management by providing a controlled and engineered solution for the disposal of solid waste (Nanda & Berruti, 2021). Effective waste management involves a hierarchy of strategies, including waste reduction, recycling, composting, incineration, and landfilling (Warith, 2003). While recycling and waste reduction minimize the amount of waste that reaches landfills, landfilling remains an essential component for handling non-recyclable and hazardous materials (Laner et al., 2012). Properly designed landfills, equipped with liners, leachate collection systems, and gas extraction mechanisms, help mitigate environmental risks such as groundwater contamination and greenhouse gas emissions (Crawford & Smith, 2016).

In fact, waste management strategies vary depending on the type and volume of waste generated (Warith, 2003). Municipal solid waste (MSW) landfills handle household and commercial waste, while hazardous waste landfills are designed for toxic and industrial waste materials (Kamaruddin et al., 2017). Sanitary landfills are engineered to minimize environmental harm by using compacted layers of waste, daily soil cover, and gas collection systems (Laner et al., 2012). These measures help to control odors, limit the spread of waste, and reduce greenhouse gas emissions from decomposing organic material (Vaverková, 2019). One of the most critical environmental concerns associated with landfills is the formation of leachate (Kananizadeh et al., 2011). Leachate is a liquid that forms when precipitation (rainwater or snowmelt) percolates through waste layers, dissolving and carrying with it various contaminants (Sarand et al., 2022). The composition of leachate depends on the type of waste deposited in the landfill, as well as the age of the landfill (Renou et al., 2018).

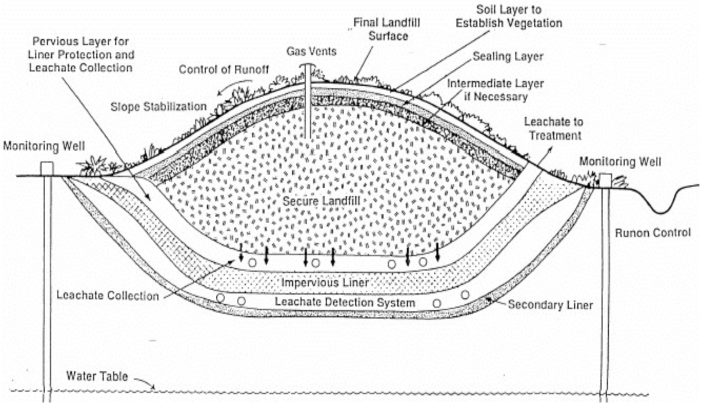

Fig. 1 A schematic view of a landfill (Qrenawi, 2006)

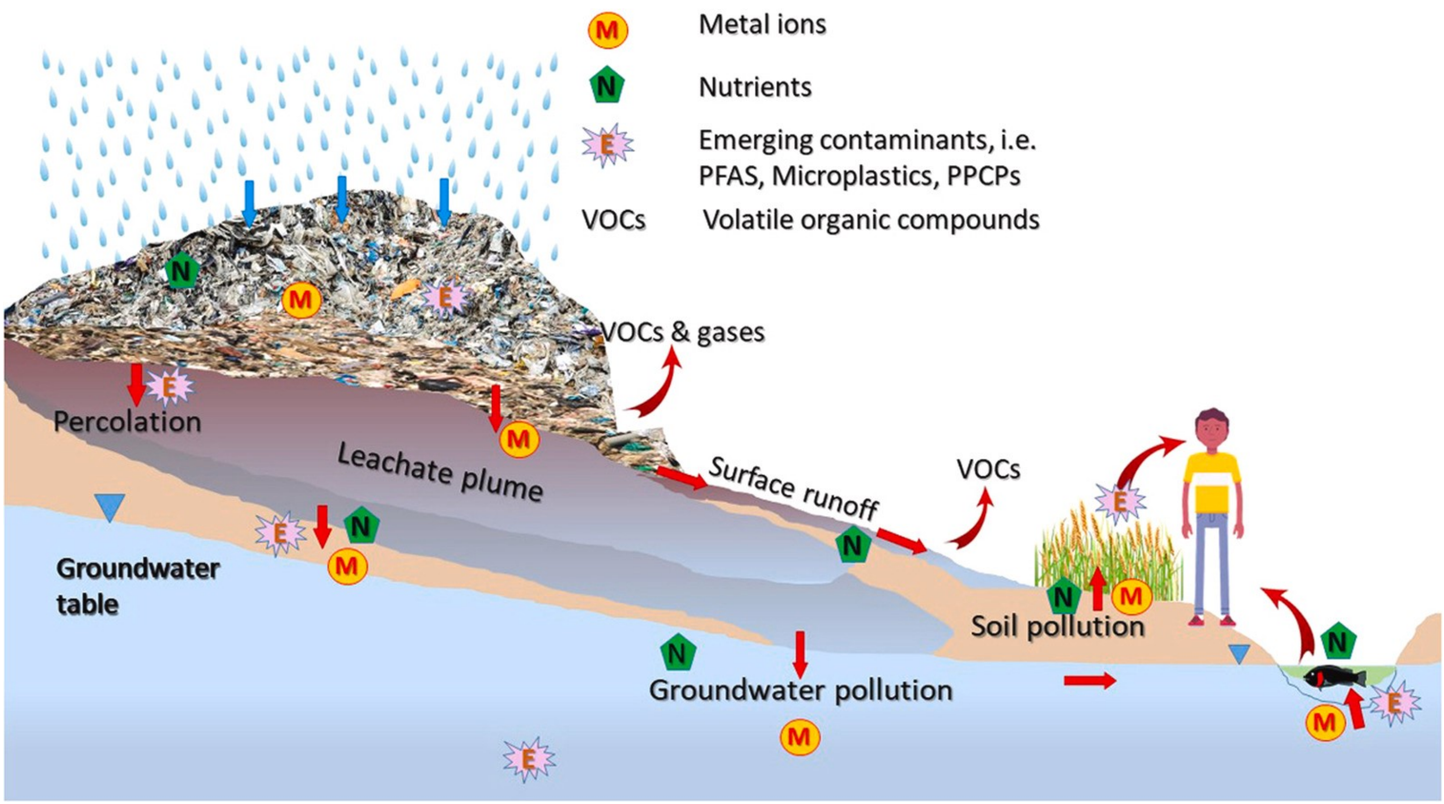

Fig. 2 A schematic view of a leachate transport from landfill to watercourse (Wijekoon et al., 2022)

Freshly generated leachate typically has high organic content, while older landfills may produce leachate rich in ammonia, heavy metals, and hazardous chemicals (Wijekoon et al., 2022). Figure 2 shows the leachate migration and transport in ground. If not properly managed, leachate can pose serious environmental and public health risks (Salem et al., 2008). Contaminants in leachate can infiltrate the surrounding soil, pollute nearby water bodies, and seep into groundwater sources, making the water unsafe for consumption (Christensen et al., 1994). Heavy metals, pathogens, and organic pollutants in leachate can disrupt aquatic ecosystems, harm wildlife, and contribute to the spread of waterborne diseases (Salem et al., 2008). The high biochemical oxygen demand (BOD) and chemical oxygen demand (COD) of leachate can also lead to oxygen depletion in natural water bodies, causing fish kills and ecological imbalances (Fulazzaky, 2013). To mitigate the risks of leachate contamination, modern landfills use landfill liners as protective barriers (Castrillón et al., 2010). A landfill liner is a continuous, impermeable layer placed at the bottom and sides of the landfill to prevent leachate from escaping into the surrounding environment (Jafari & Abbasian, 2018). Liners are made from materials such as compacted clay, geomembranes (e.g., HDPE), geosynthetic clay liners (GCLs), and composite liner systems (Nikbakht et al., 2023). Figure 3 illustrates various types of landfill liners commonly used in landfill constructions. Generally, there are two primary types of landfill liners:

- *Natural Liners*: These consist of compacted clay layers, which have a low permeability and can effectively contain leachate. Clay liners are often used in combination with synthetic liners to enhance containment.
- *Synthetic Liners*: These include high-density polyethylene (HDPE) geomembranes, polyvinyl chloride (PVC) liners, and geosynthetic clay liners (GCLs). Synthetic liners provide superior resistance to chemical degradation and have very low permeability, making them highly effective in preventing leachate migration.
- *Composite Liner Systems*: combine form various lining strategies.

The design and installation of landfill liner systems are paramount to ensuring the long-term environmental safety of landfills. Double-liner systems are often employed, consisting of two layers of liners—typically an HDPE geomembrane and a compacted clay liner—with a leachate collection system sandwiched between them. This setup provides multiple layers of protection and allows for the early detection of leaks. A well-designed liner system is essential for the containment of leachate and the prevention of contamination to the surrounding soil and groundwater. Additionally, landfill liners are critical for controlling greenhouse gas emissions by preventing the escape of methane, a potent greenhouse gas produced by the decomposition of organic waste. Proper maintenance and monitoring of landfill liners ensure their effectiveness, safeguarding both human health and the environment. In modern landfills, composite liner systems are commonly used, combining a synthetic liner (such as HDPE) with a compacted clay layer. This dual-layer system provides enhanced containment and durability, significantly reducing the risk of liner failure. The compacted clay layer serves as a secondary barrier, while the geomembrane prevents leachate penetration. To further prevent leachate accumulation and enhance environmental safety, landfills incorporate leachate collection and treatment systems.

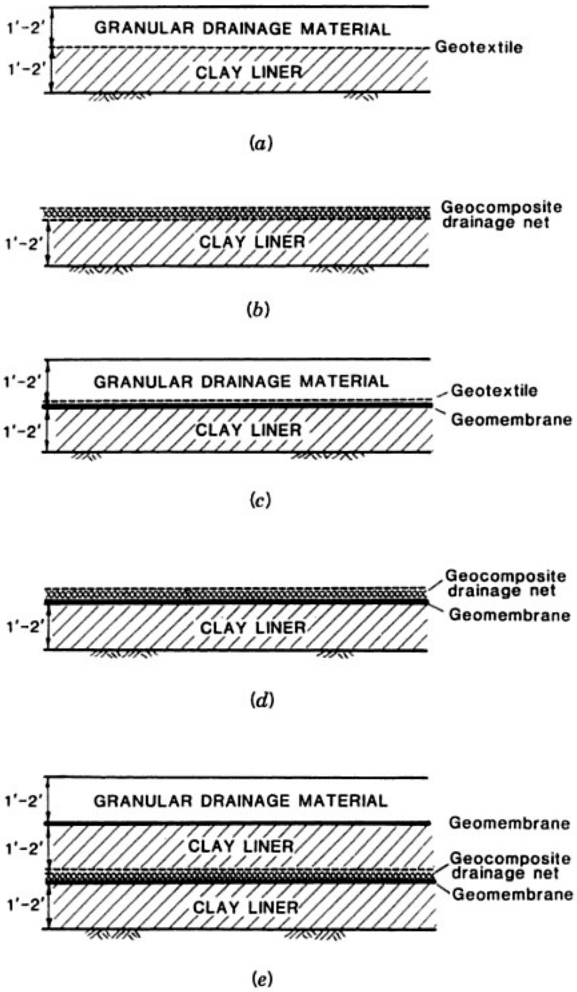

Fig. 3 There are several types of landfill liner systems, including: (a) soil liner with a leachate collection and removal system (LCRS), (b) soil liner with a geosynthetic LCRS, (c) composite liner with an LCRS, (d) composite liner with a geosynthetic LCRS, and (e) double composite liner (Li, 2011)

A leachate collection system consists of a network of perforated pipes, drainage gravel, and sump pumps that actively remove leachate from the landfill base (Castrillón et al., 2010). The collected leachate is then treated through processes such as biological treatment, chemical precipitation, membrane filtration, and reverse osmosis before being safely discharged or reused (Li, 2011). A well-known example of landfill liner implementation is seen in engineered sanitary landfills used for municipal solid waste disposal (Nikbakht et al., 2023). These landfills employ a double-liner system, consisting of a primary HDPE geomembrane liner, a secondary compacted clay liner, and a leachate collection layer between them. This design ensures maximum protection against leachate leakage and enhances long-term environmental safety (Li, 2011).

Landfill liners are essential in controlling leachate, the liquid that forms when water interacts with waste materials in landfills (Özçoban et al., 2022). The primary function of a liner is to prevent the migration of leachate into the surrounding environment, particularly the soil and groundwater, where it could cause contamination (Norouzi et al., 2022). Without an effective liner system, leachate could seep through the landfill base, carrying harmful chemicals and toxins that can endanger public health and damage ecosystems (Nikbakht et al., 2022). By creating a barrier between the waste and the underlying soil, liners help contain leachate, allowing for safe collection and treatment (Sarand et al., 2022). Liners are designed to be impermeable, meaning they prevent the passage of liquids, and this is achieved using materials like HDPE, compacted clay, and geosynthetic clay liners (Varank et al., 2011). These materials are chosen for their low permeability and resistance to chemical degradation, making them effective in containing leachate over long periods (Koerner & Soong, 2000). Additionally, some liner systems are constructed with a LCRS, which captures any leachate that does accumulate, ensuring that it is properly drained and treated before being released into the environment (Li, 2011).

The proper design and maintenance of landfill liners are critical in ensuring their effectiveness (Castrillón et al., 2010). Over time, liners can degrade due to exposure to chemicals in the leachate, temperature fluctuations, and physical wear. Regular monitoring and maintenance are necessary to identify potential weaknesses in the system, and early detection of liner failure can prevent large-scale environmental damage (Ozel et al., 2012). Overall, liners play a crucial role in safeguarding groundwater and controlling leachate, which is essential for environmental protection and public health (Sarand et al., 2022). The environmental importance of landfill liners cannot be overstated (Jafari & Abbasian, 2018). Without liners, leachate can pollute groundwater resources, which provide drinking water for many communities (Zhao et al., 2015). Groundwater contamination by leachate can lead to the spread of harmful substances, such as heavy metals, solvents, and pathogens, into aquifers. This contamination poses significant risks to both human health and wildlife (Wijekoon et al., 2022). Liners act as a critical barrier, preventing these pollutants from infiltrating groundwater, thus protecting valuable natural resources (Li, 2011). In addition to protecting water resources, landfill liners help reduce the environmental impact of greenhouse gas emissions. As organic waste decomposes in landfills, it produces methane, a potent greenhouse gas (Wijekoon et al., 2022). By containing leachate and controlling waste degradation, liners help minimize the release of methane into the atmosphere (Özçoban et al., 2022). Methane is a major contributor to climate change, so by controlling its emissions, landfill liners support global efforts to mitigate environmental damage and promote sustainable waste management practices (Nikbakht et al., 2023).

III. MATERIALS AND METHODS

This study aimed to evaluate the impact of nanoclay on the permeability of fine-grained soils and its potential role in improving the performance of landfill liners. The research utilized a series of experimental tests conducted on soil samples modified with varying concentrations of nanoclay. The methodology is divided into distinct sections, including sample preparation, experimental procedures, testing standards, and data analysis. Figure 4 is illustrating a view of utilized nanolcay in this study. The used nanolcay is classified as montmorillonite clay as known member of smectite group of clay minerals. Table 1 provides the nanolcay specification used in this task.

Fig. 4 A view of used nanoclay in this study

Table 1 Physical-chemical properties of used nanolcay

Properties	Parameter	Unit	Value
Physical	Clay type	-	Montmorillonite
	Particle size	mn	1 - 2
	Density	g/cm^3	0.5 - 0.7
	Specific surface area	m^2/g	220 - 270
	Electrical resistivity	MV	-25
	Inter-particles distance	A^o	60
	Ion exchange coefficient	meg/100 g	48
	Color	-	Pale yellow
	Moisture	%	1 - 2
Chemical	Na_2O	%	0.98
	MgO	%	3.29
	Al_2O_3	%	16.60
	SiO_2	%	50.95
	K_2O	%	0.68
	CaO	%	1.97
	TiO_2	%	0.62
	Fe_2O_3	%	5.62
	LOI	%	15.45

Nanomontmorillonite additives were prepared from Temad Kala/Nano Sadra Company with IDs Closite 15A/MJ-48 and synthesized cellulose nanofibers were also provided from Nanosani Service Company with IDs NS-CNF-001. For this experiment, 12 untreated soil samples were collected from the Tabriz landfill site to represent the baseline soil characteristics. In addition, three modified soil groups were prepared by adding different percentages of nanoclay (3%, 6%, and 9%) to the soils. The grain-size analysis result for Tabriz landfill soil is provided in Figure 5. This soil was the host soil for treatments by nanocaly. Nanoclay was thoroughly mixed with the soil samples to ensure uniform distribution, following ASTM D2487, ASTM D1140 and ASTM D422 to characterize the soils and to ensure proper soil classification for the tests.

The primary objective of the research was to evaluate how nanoclay influences soil permeability, particularly its ability to serve as an effective barrier against leachate migration in landfills. Permeability tests were conducted using constant head and falling head methods in accordance with ASTM D5856. The tests were conducted on both untreated and nanoclay-modified soils, with real landfill leachate from the Tabriz landfill site being used instead of water. This approach was chosen to better simulate the actual environmental conditions under which landfill liners operate. Figure 6 is illustrated the permeability tests scheme were considered in this experimental research.

To assess the behavior of the fine-grained soils, Atterberg limits tests were conducted to determine the soil's plasticity and consistency. This was performed in accordance with ASTM D4318. These limits provide important insight into the workability and behavior of soils under varying moisture conditions, which is vital for understanding the effect of nanoclay on the soil's overall performance as a liner material (see Figure 7). Performing Atterberg limit tests is essential for understanding the behavior of fine-grained soils, particularly when incorporating nanoclay. The Atterberg limits, which include the liquid limit, plastic limit, and plasticity index, provide crucial information about the soil’s plasticity, workability, and its response to changes in moisture content. For this study, determining the Atterberg limits is important because nanoclay can significantly alter the soil's plasticity and consistency, which in turn influences its permeability and stability.

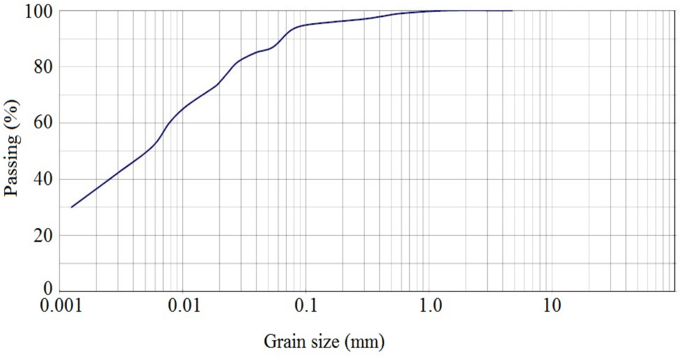

Fig. 5 Grain size distribution result for the host soil samples

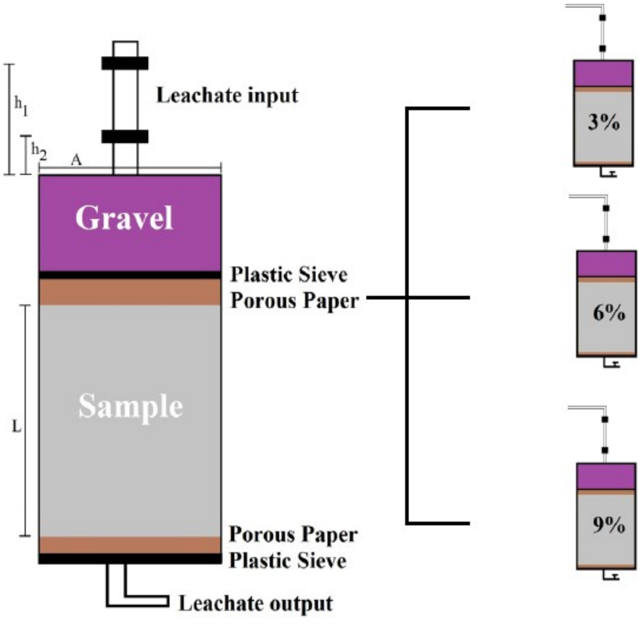

Fig. 6 The permeability tests sequences used in this task

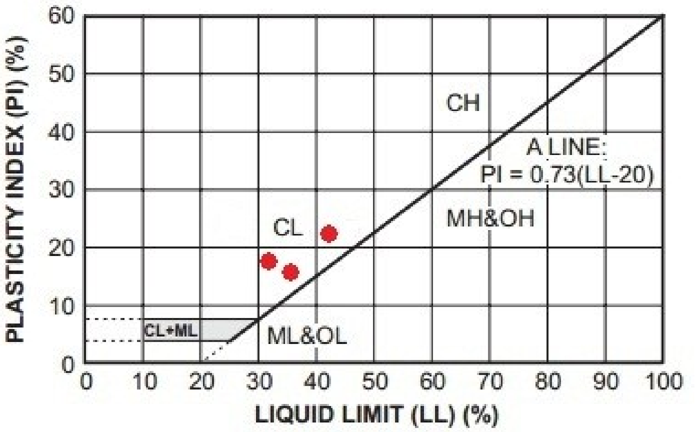

Fig. 7 Atterberg limits results for used soil for this task

In parallel with the permeability tests, chemical analysis of both the untreated and nanoclay-modified soils was conducted to evaluate changes in the soil's chemical properties due to nanoclay addition. The analysis was carried out using methods described in ASTM D5237. The real landfill leachate was also chemically analyzed to identify the specific contaminants present. This helped in understanding the interaction between the leachate and the nanoclay-modified soil samples. To gain further insights into the structural changes within the soil due to the addition of nanoclay, X-ray diffraction (XRD) was used to study the mineralogical composition of both untreated and nanoclay-modified soil samples. The XRD analysis was essential in identifying the type of minerals present and how the nanoclay interacted with the soil at a molecular level, improving its impermeability. This method follows ASTM D6432. Figure 8 is providing the results of chemical analysis of Tabriz landfill leachate.

IV. RESULTS AND DISCUSSION

The soil used in this study is classified as CL clay with low plasticity. This classification indicates that the soil is predominantly composed of fine-grained particles with relatively low cohesion, making it susceptible to permeability when subjected to environmental stressors like leachate exposure. To improve the soil's impermeability, different concentrations of nanoclay (3%, 6%, and 9%) were mixed with the soil, and the effects of these modifications on soil permeability were assessed using various tests including permeability tests, Atterberg limits, chemical analyses, and X-ray diffraction (XRD). The data obtained were carefully analyzed using statistical methods to establish the relationship between the nanoclay content and the soil's permeability. The results from the permeability tests indicate a clear and significant reduction in soil permeability with increasing nanoclay content. Untreated soil samples exhibited a permeability value of approximately 10^{-6} m/s, which is characteristic of the naturally occurring fine-grained CL clay. However, as the nanoclay concentration was increased to 3%, 6%, and 9%, the permeability values decreased substantially, with the highest concentration (9% nanoclay) showing a permeability reduction to 10^{-9} m/s.

This result demonstrates the ability of nanoclay to effectively reduce the permeability of soil, making it more suitable for applications such as landfill liners, where low permeability is critical to minimize leachate migration and prevent environmental contamination. In particular, the reduction in permeability observed in soils modified with nanoclay is particularly significant when considering the potential application of such modified soils as landfill liners. When landfill leachate was introduced into the soil samples, it was observed that the presence of leachate did not reverse the reduction in permeability, which highlights the robustness of nanoclay's effect on soil. This mimics the real-world conditions of landfill liners, where the liners must withstand the long-term presence of leachate without significant degradation in performance. The results from this experiment suggest that nanoclay-modified soils can perform effectively even under the harsh conditions that are characteristic of landfill environments.

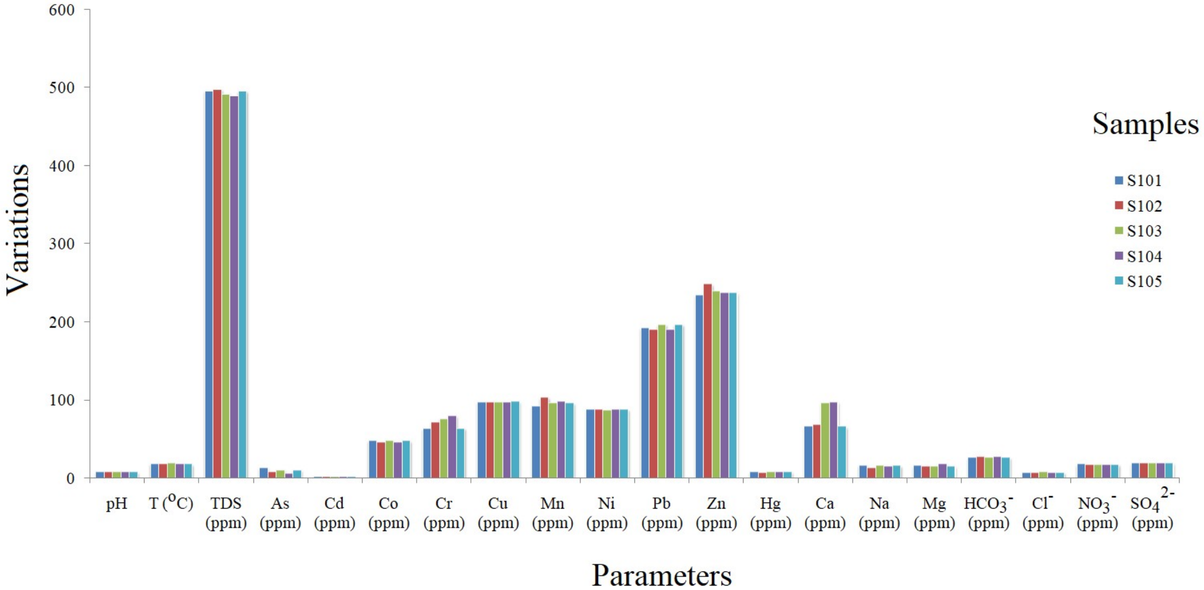

Fig. 8 Chemical properties of used leachate liquid in this study

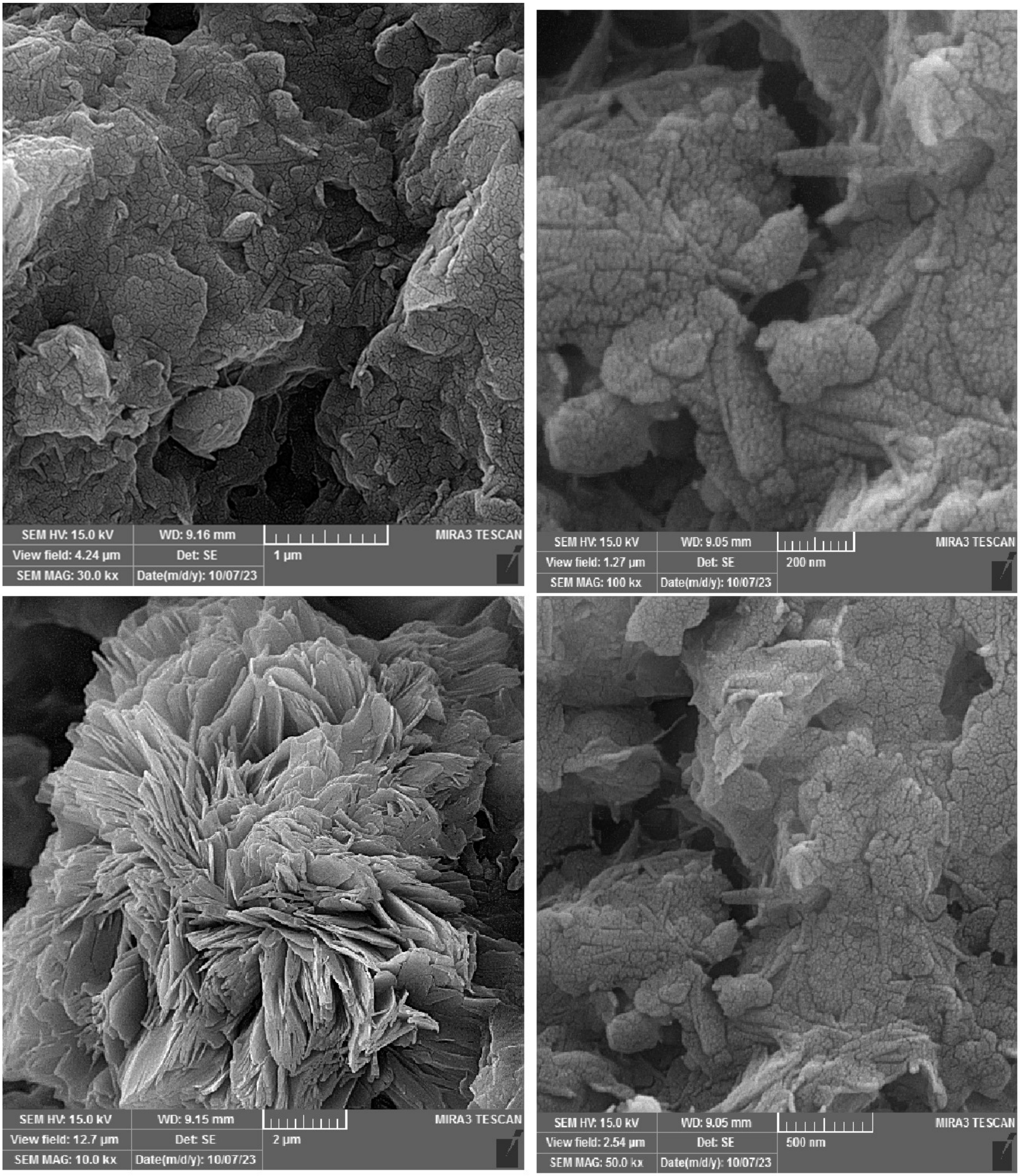

Fig. 9 A view of selected soil samples with nanoclay treatments

The chemical analysis of the leachate revealed that certain elements, such as calcium and magnesium, were present in higher concentrations in the untreated soil samples, which may contribute to increased soil permeability due to ion exchange processes. However, the nanoclay modification appeared to mitigate this effect by enhancing the soil's ion exchange capacity and creating a more stable structure that resists leachate infiltration. This further underscores the role of nanoclay in not only reducing permeability but also improving the soil's resistance to chemical interactions that typically occur in landfill environments. XRD analysis was also conducted to examine the mineralogical composition of the soil before and after the addition of nanoclay. The results showed that the nanoclay particles were well-dispersed within the soil matrix, with the nanoclay contributing to the formation of a more tightly packed soil structure. The presence of nanoclay particles likely promoted the formation of small pores and voids, which significantly decreased the overall permeability of the soil. This observation aligns with previous studies that have highlighted the role of nanoclay in enhancing the microstructure of soils by filling larger voids and reducing the flow of fluids through the material.

When comparing the untreated soil and the nanoclay-modified soil samples, it is evident that the addition of nanoclay significantly improves the impermeability of the soil. The nanoclay-treated samples, especially those with higher concentrations (6% and 9%), demonstrated superior performance in resisting leachate penetration, making them promising candidates for use as landfill liners. The soil's ability to withstand increased permeability challenges posed by the leachate suggests that nanoclay-modified soils could serve as a cost-effective and sustainable alternative to conventional materials used in landfill liner construction. The enhanced impermeability of nanoclay-modified soils not only offers environmental benefits in terms of reducing leachate migration but also presents a sustainable solution in the field of geotechnical engineering. The use of nanoclay as an additive to improve the performance of landfill liners may reduce the need for more expensive or environmentally harmful materials, such as synthetic liners. Moreover, nanoclay-modified soils could offer long-term durability and performance, making them an attractive option for addressing the growing concerns regarding the environmental impacts of landfill leachate. So, the results of this study indicate that nanoclay-modified soils can significantly reduce the permeability of fine-grained soils, making them a viable and sustainable alternative for landfill liners. The findings suggest that nanoclay's ability to enhance soil impermeability holds promise not only for landfill applications but also for other geotechnical uses, such as soil stabilization and waste containment. Future research should focus on the long-term durability and performance of nanoclay-modified soils under varying environmental conditions, as well as their potential use in other applications related to waste management and environmental protection.

V. CONCLUSION

The results of this study underscore the potential of nanoclay-modified soils as an effective solution for improving soil impermeability, particularly for applications such as landfill liners. The CL clay, characterized by its low plasticity, exhibited high permeability in its untreated form, which is a significant concern in environmental management, especially in the context of landfill leachate. The introduction of nanoclay into the soil at concentrations of 3%, 6%, and 9% led to a remarkable reduction in permeability, with the highest concentration achieving a permeability reduction from 10^{-6} m/s to 10^{-9} m/s. This dramatic improvement demonstrates that even relatively low concentrations of nanoclay can significantly enhance the soil's resistance to fluid flow.

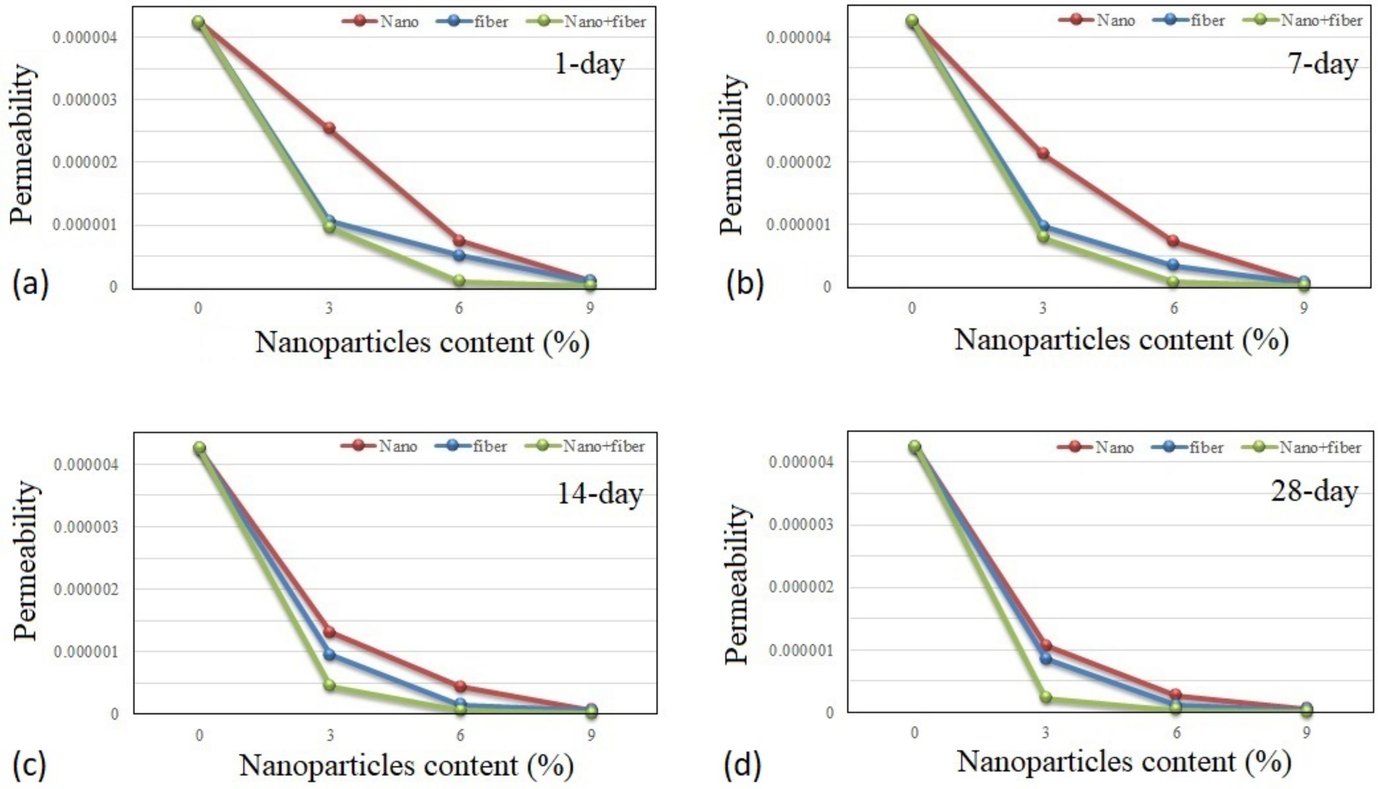

Fig. 10 Changes in the permeability for the soil samples with different nanoclay: (a) 1-day, (b) 7-day, (c) 14-day, (d) 28-day

The incorporation of landfill leachate into the experiment was critical, as it mimicked real-world conditions where the liner would be exposed to leachate over time. The results showed that nanoclay-modified soils effectively resisted leachate infiltration, making them a promising alternative to conventional landfill liners, which are often susceptible to degradation or inefficiency over time. The chemical and XRD analyses further supported the findings, revealing that nanoclay contributes to a more stable soil structure, enhancing both its physical and chemical properties. This study suggests that nanoclay-modified soils offer an environmentally sustainable and cost-effective solution to landfill liner construction. The reduced permeability not only minimizes the risk of leachate migration but also presents a viable alternative to synthetic materials typically used in liner construction. Future research should focus on the long-term durability and performance of nanoclay-modified soils under various environmental conditions to fully understand their potential for widespread application in geotechnical engineering and waste containment. Overall, the use of nanoclay in soil modification holds promise for enhancing the sustainability and environmental performance of landfill liners, contributing to more efficient waste management systems.

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AUTHORS' CONTRIBUTIONS

Mahdi Nikbakht conducted the main data analysis, contributed to the data collection, preprocessing, and interpretation, and was responsible for drafting the initial manuscript. Fariba Behrooz Sarand and Rouzbeh Dabiri assisted in the development of the methodology and performed validation checks, provided supervision, conceptual guidance, and critical revision of the manuscript. All authors read and approved the final manuscript.

CONFLICT OF INTEREST

The authors have not disclosed any competing interests.

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