Advances in Materials Research, *Vol. 13, No. 1 (2024) 19-35*
https://doi.org/10.12989/amr.2024.13.1.019

Assessing the impact of nanoclay on the permeability and geotechnical properties of fine-grained soils in landfill liners

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(*Received February 18, 2023, Revised July 9, 2023, Accepted July 10, 2023*)

Abstract. Presented Article evaluates the effect of nanoclay on permeability, compressive strength, and plasticity behavior of fine-grained soil related to the Tabriz landfill site. In this regard, comprehensive experimental study was performed on taken soil samples (42 specimens) with aim of design high-performance liners for Tabriz landfill. The samples was mixed by 0% (control) 3%, 6% and 9% nanoclay and prepared in 1, 7, 14 and 28 days before testing stage. Index tests like particle-size, permeability, atterberg limits, and uniaxial compressive strength (UCS) was conducted on samples. The results show that studied soil is classified as CL in USCS classification and atterberg limits measured as LL is 37, PL is 20.67, and PI is 16.33 which increase into 75, 45, and 30. The assessment presented the LL was increased about 20.27% based on increasing in nanoclay from 0% to 9%. These variations for PL and PI were 21.77% and 18.37%, respectively. Also, the and soil's compressive strength is increase from 120 kPa to 188 kPa and permeability is estimated as 4.25×10^{-6} m/s which reduced into the 6.34×10^{-9} m/s with respect the naboclay content increases form 0% to 9%.

Keywords: fine-grained soils; landfill liners; leachate control; nanoclay; permeability

1. Introduction

Pass the time due to the population, municipal solid waste (MSW) amount has increased extensively worldwide (Praveen and Sunil 2016, Ghazifard *et al.* 2016, Wang *et al.* 2022). MSW is disposed in different scales in many countries and contain various component regarding standard of living, and degree of urbanization (Nwachukwu and Nwachukwu 2020, Hajjizadeh *et al.* 2020). With respect to the landfilling technologies of each country, MSW are buried under different condition and circumstances (Part *et al.* 2018). Regardless of the engineering capability level of landfills, MSW generate leachate which is related decomposable and putrescible contents (Azizpour *et al.* 2020, Özçoban *et al.* 2022). Leachate is a liquid with high environmental pollution capacity that has dissolved or entrained environmentally harmful substances. Leachate carries a large amount

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http://www.techno-press.org/?journal=amr&subpage=5 ISSN: 2234-0912 (Print), 2234-179X (Online)

of pollutants that are produced from MSW in landfills (Derakhshani and Alipour 2010, Khodary *et al.* 2018). Generally, MSW's leachate from a landfill varies widely in composition depending on the age of the landfill and the waste type that it contains (Part *et al.* 2018, Hussain *et al.* 2021). So, it can be carried different type of pollutants and have extensive environmental impact (Zoriyeh *et al.* 2020).

The most important environmental dangerous events caused by leachates are related to old landfills and traditional waste disposals which those with no engineering or natural barriers between the waste and the underlying geological units (Bethi and Sonawane 2018), leachate is free to leave the waste and flow directly into the ground or surface waters. In such cases, high concentrations of leachate are often found in nearby springs and flushes (Özçoban *et al.* 2022). Leachate high concentrations can enter the environmental and food cycles of animal and plant ecosystems. This issue causes irreparable damage to the environment (Part *et al.* 2018). Regarding to the leachates' high potential for environmental impact, countries are implementing environmental standards and regulations to control and management and treatments (Taghvaei *et al.* 2021).

Liners are play significant role as both a collection device and as a means for isolating leachate within the fill to protect the soil and groundwater below (Amarasiri and Adassooriya 2021) which have to maintain integrity and impermeability over the life of the landfill (Qasaimeh *et al.* 2020). Geotechnically, the liners must have high tensile/compression strength, flexibility, eco-friendly, easily installable, and elongation without failure (Özçoban *et al.* 2022). In perspective of geoenvironmental aspect, liners must have resistance agent's abrasion, resistance agent's puncture, resistance agent's chemical degradation, resist agent's UV light, and withstand temperature variation (Wang *et al.* 2022). There are different types of liners technologies that used to control and collection of leachates (Mahallei and Badv 2021). Using clay-based liners due to the environmental compatibility with the environment, as well as being made of natural materials, have flexibility and a suitable ability to control leachates. The nature of clays has caused it to attract the attention of geo-engineers to design high-performance liners and used clay-based materials (especially montmorillonite) to modify the current liners regarding to leachate leakage (Bethi and Sonawane 2018). In fact, clay is considered as best natural adsorbent layer of environmental pollutants. Specific surface area, high cation exchange capacity and very low permeability are prominent features of nanoclays (especially smectite group minerals) that have led to the use of these materials in environmental projects (Majeed *et al.* 2012).

Several studies have investigated the potential of nanoclay in modifying the permeability characteristics of soils. Nanoclay particles, due to their small size and high surface area, can form a network within the soil matrix, creating a tortuous path for fluid flow. This network reduces the pore size and increases the soil's resistance to the movement of water and other fluids. Research has shown that incorporating nanoclay additives into fine-grained soils can significantly reduce permeability, making them suitable for applications such as landfill liners, containment barriers, and hydraulic barriers. The presence of nanoclay in the soil matrix offers the advantage of minimizing seepage and fluid migration, contributing to improved environmental protection and stability in geotechnical projects (Karumanchi *et al.* 2020, Jung *et al.* 2021, Nikbakht *et al.* 2022a, b).

Nanoclay additives have been found to influence various geotechnical properties of soils. Studies have shown that the inclusion of nanoclay can enhance the shear strength and stability of soils. The interlocking structure formed by the nanoclay particles improves the load-bearing capacity of the soil and its resistance to deformation under applied stresses. Additionally, nanoclay has been observed to improve the plasticity and workability of fine-grained soils, facilitating easier compaction and shaping during construction processes. The modified soil's improved geotechnical properties, such as increased shear strength and reduced compressibility, make it suitable for geotechnical applications requiring enhanced stability and performance (Khalkhali *et al.* 2019, Karkush *et al.* 2020, Mollaei *et al.* 2023).

Selvakumar *et al.* (2021, 2023), Kulanthaivel *et al.* (2021, 2022a, b, c, d), Sivabalaselvamani *et al.* (2022) studies investigate the effects of different additives and stabilization techniques on soil strength and engineering behavior. They explore the impact of nano-silica, sodium silicate, fibers, geosynthetic encasement, fly ash brick bats, ordinary Portland cement, sodium hydroxide, waste eggshell, and bio-cementation on clay soil and sand. Their research yields significant findings: nano-silica and sodium silicate contribute to the strength characteristics of clay soil, while the combination of nano-silica and randomly distributed fibers further enhances its strength. Geosynthetic encased conventional aggregate and fly ash brick bats columns show promising results in improving soft clay conditions. The studies also highlight the positive effects of ordinary Portland cement, sodium silicate, and sodium hydroxide in strengthening clay soil. Additionally, the application of waste eggshell as a calcium source enhances the engineering properties of sand, and bio-cementation with eggshell as a calcium source improves the strength behavior of clay soils. Moreover, machine learning algorithms have been employed to study the engineering strength properties of ceramic waste powder-stabilized expansive soil. Collectively, these studies provide valuable insights and strategies for stabilizing and enhancing the engineering characteristics of soils using various materials and techniques.

Application of clay-based nanoparticles (nanoclays) to modify the liners performance regarding both Geotechnical and geoenvironmental aspects are extensively increases (Hashemi *et al.* 2021). Nanoclays can be considered as natural filters to reduced/prevent the MSW leachates (Naz and Chowdhury 2021). There is various scholars used nanoclay to modify the geotechnical behaviors regarding environmental actions. Hermann *et al.* (2009) used bentonite to analysis of the hydraulic conductivity of a mixture of volcanic ash and sewage sludge in Sweden. The study result was showed that the hydraulic conductivity reduced significantly by using bentonite. Kananizadeh *et al.* (2011) used montmorillonite nanoclay to reduce the permeability, controlling swelling, and increase the strength of dense clay liner for Kahrizak Landfill in Iran. Debnath *et al.* (2013) provide extensive investigation on nanomaterials effects in geo-engineering field. The researchers stated that nanomaterials have useful applications specifically in environmental impact on leachate control in landfills. Azarafza *et al.* (2015) used nanoclay in experimental analysis for permeability reduction in Bonab landfill liner to control the leachate leakage and swelling. The researchers used 3%, 6% and 9% nanoclay percentage and estimate the geotechnical modifications regarding permeability reduction of liner. Bahari *et al.* (2016) used nanoclay to reduce the permeability and improve the strength of the water storage ponds for agriculture purposes in Abbandan, southwest of Iran. The scholar used different percent of nanoclays in fine-grained soils which results shows the nanoclay has improved in permeability reduction.

Jafari and Abbasian (2018) implemented an experimental assessment on soil permeability behaviour with montmorionite nanoclay additive in landfill liners. Researchers used geotechnical index tests to determine the soil’s permeability, strength and swelling improvements. According to the results, by increasing the nanoclay’s percentage from 0% to 9%, soil permeability and swelling capability was decreases. Jafari and Abbasian (2019) investigated the effect of using nanoclay filters to create a natural barrel in order to prevent the spread of industrial effluents in the transmission channels of Kaveh Soda Company. Qasaimeh *et al.* (2020) investigated the effects of bentonite nanomaterial additives to reduce environmental impact in the Al Akaider region regarding permeability and swelling modifications. The results of the studies used to evaluate the performance of bentonite nanoclay in reducing the swelling of liners.

One of the significant advantages of incorporating nanoclay into the soil matrix is the reduction in permeability. Nanoclay particles create a complex network within the soil, resulting in a tortuous path for water flow. This arrangement impedes the movement of fluids through the soil and significantly decreases permeability. This improved impermeability is highly beneficial in geotechnical projects that require minimizing seepage or fluid migration, such as the construction of landfills, dams, or containment barriers. In addition to reduced permeability, the inclusion of nanoclay can enhance the shear strength of the soil. The interlocking structure formed by the nanoclay particles reinforces the soil matrix, increasing its load-bearing capacity and stability. This improved shear strength is particularly advantageous in geotechnical applications where soil stability and resistance to deformation are crucial, such as in embankments, retaining walls, or foundation systems. By incorporating nanoclay, engineers can achieve greater safety and stability in their geotechnical designs. Moreover, the addition of nanoclay can lead to improved plasticity and workability of fine-grained soils. The presence of nanoclay particles alters the particle arrangement and lubrication properties of the soil, making it easier to handle and shape during construction (Majeed *et al.* 2012, Jafari and Abbasian 2019).

On the other hand, one of the primary drawbacks of using nanoclay additives is the cost involved. Compared to traditional soil modification techniques, nanoclay additives can be relatively expensive. The procurement and incorporation of nanoclay into large-scale geotechnical projects may pose financial challenges, particularly for projects with budget constraints. Therefore, careful consideration of the cost-effectiveness and the specific benefits offered by nanoclay is necessary before deciding to use it in geotechnical applications (Bahari *et al.* 2016). Achieving a uniform dispersion of nanoclay throughout the soil matrix can be challenging (Nikbakht *et al.* 2023). Uneven distribution or agglomeration of nanoclay particles within the soil may result in inconsistent performance and compromised geotechnical properties. Proper mixing techniques and quality control measures are crucial to ensure a homogeneous dispersion of nanoclay, which can be labor-intensive and time-consuming, adding complexity to the construction process (Farzadnia *et al.* 2013, Kausar *et al.* 2022). Another important aspect to consider is the potential environmental impact of nanoclay additives (Nikbakht *et al.* 2023). While nanoclay itself is generally considered to have low toxicity, the long-term effects of its release into the environment are still being studied. Proper disposal and management of nanoclay-contaminated soil are essential to minimize any potential adverse environmental consequences. It is important to adhere to recommended guidelines and regulations to ensure the safe and responsible use of nanoclay in geotechnical applications (Kananizadeh *et al.* 2011).

The presented study aimed to provide a comprehensive investigation on the utilization of montmorillonite nanoclay as an innovative additive to significantly enhance the geo-engineering characteristics of fine-grained soil samples obtained from the Tabriz landfill site. This research not only focused on designing high-performance liners but also introduced novel approaches to address the challenges associated with traditional soil modification techniques. To assess the effectiveness of the nanoclay additive, a series of extensive experimental assessments were conducted on 42 soil specimens. These assessments encompassed a wide range of geotechnical parameters, including permeability, Atterberg limits, uniaxial compressive strength (UCS), and direct-shear tests. By modifying the soil samples with varying percentages of nanoclay, this study introduced an innovative approach to tailor the properties of the soil and optimize its performance in diverse geotechnical applications. The findings of this study unveiled several novel insights into the influence of nanoclay on the geotechnical characteristics of fine-grained soil. The permeability tests revealed a significant reduction in hydraulic conductivity, indicating the potential of nanoclay in mitigating fluid flow through the soil. Moreover, the Atterberg limits analysis demonstrated enhanced plasticity and reduced shrinkage potential, showcasing the effectiveness of nanoclay in stabilizing the soil structure. Furthermore, the uniaxial compressive strength (UCS) tests exhibited remarkable improvements in the soil's load-bearing capacity with the addition of nanoclay. The modified soil samples demonstrated higher strength and enhanced resistance to deformation under compression. The direct-shear tests further substantiated these findings by revealing an increased shear strength and improved stability in the soil matrix. These novel insights contribute to expanding the understanding of the geotechnical engineering community regarding the benefits and applications of montmorillonite nanoclay as a pioneering soil additive. The innovative modification techniques introduced in this study have the potential to revolutionize the design and construction of high-performance liners for various engineering projects, offering improved durability, enhanced environmental protection, and cost-effective solutions for geotechnical applications.

While the use of nanoclay additives shows promise in permeability control and soil geotechnics, there are several challenges and areas for further investigation. Some challenges include ensuring a uniform dispersion of nanoclay throughout the soil matrix, addressing cost considerations, and understanding the long-term behavior and environmental impact of nanoclay-modified soils. Future research can explore optimizing the types and concentrations of nanoclay additives, studying the effects on different soil types and conditions, and evaluating the performance of nanoclay in field-scale applications. Additionally, the use of advanced testing methods and modeling techniques can further enhance our understanding of the mechanisms and benefits of nanoclay in permeability control and geotechnical engineering.

2. Materials and methods

The purpose of this study was to develop a clay-based modified filter for landfill liners using nanoclay additives, with the aim of reducing leachate contamination. To achieve this objective, an extensive field survey and sampling campaign were conducted at the Tabriz landfill site, located approximately 10 km northwest of Tabriz, Iran (Fig. 1). Careful precautions were taken during the sample collection process to ensure the integrity of the samples, which were then transported to the geotechnical laboratory. The soil samples obtained from the landfill site underwent a series of ASTM standard tests, including D1140, D2166, D3080, D422, D4318, and D2434. These tests were performed to determine the geo-engineering characteristics of the fine-grained soil, including particle-size distribution, Atterberg limits, unconfined compressive strength (UCS), permeability, and direct-shear behavior. The particle-size distribution test analyzes the proportions of different-sized particles in a soil sample. It involves determining the percentages of course, medium, and fine particles present in the soil. This information is crucial for understanding the soil's engineering behavior, such as its compaction characteristics, permeability, and potential for soil erosion. By knowing the particle-size distribution, engineers can classify the soil according to standardized systems and make informed decisions about its suitability for specific engineering applications (ASTM D422, ASTM D1150). The Atterberg limits tests are performed to assess the soil's plasticity and moisture-related properties. These tests determine the soil's liquid limit (LL), plastic limit (PL), and plasticity index (PI). The liquid limit represents the moisture content at which the soil transitions from a semi-solid to a liquid state, while the plastic limit indicates the moisture content at which the soil becomes non-plastic. The plasticity index quantifies the soil's plasticity range. Understanding

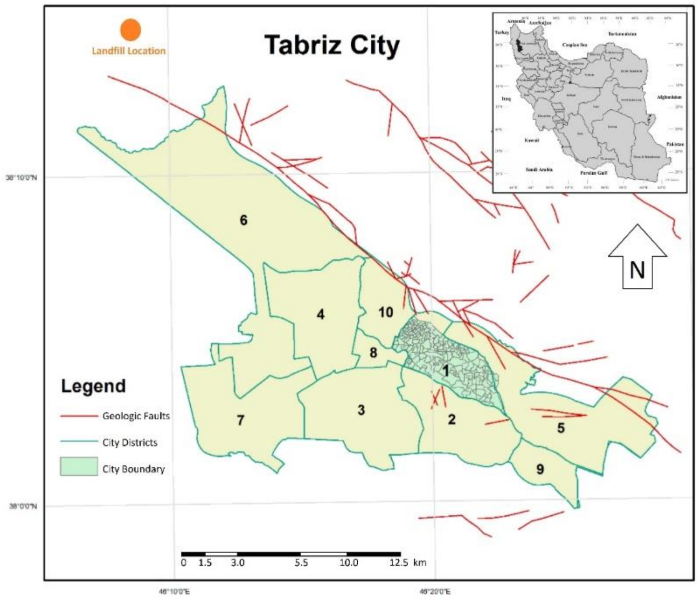

Fig. 1 Location of the Tabriz Landfill

the Atterberg limits is vital for assessing the soil’s workability, shrink-swell potential, and behavior under varying moisture conditions (ASTM D4318). The UCS test is conducted to measure the maximum axial compressive stress that a soil sample can withstand before failure. It provides an indication of the soil’s load-bearing capacity and its resistance to deformation under compression. The test involves applying axial loading to an unconfined soil sample until it fractures or fails. The UCS test is valuable in assessing the stability and strength of soils, particularly for designing foundations, embankments, and other geotechnical structures subjected to vertical loading (ASTM D2166).

The permeability test evaluates the ability of a soil sample to allow the flow of water or other fluids through it. This test measures the soil’s hydraulic conductivity, which determines the rate of fluid flow under a given hydraulic gradient. By quantifying permeability, engineers can assess the soil’s potential for seepage and evaluate its suitability for various applications such as designing landfill liners, drainage systems, or groundwater flow control measures. The permeability test provides valuable insights into the soil’s ability to transmit fluids (ASTM D2434). The direct-shear test is performed to determine the shear strength properties of a soil sample. It involves applying a controlled shear stress to the sample along a specified plane. This test measures the soil’s resistance to sliding or failure under shear loading conditions. By evaluating the direct-shear behavior, engineers can assess the stability and shear strength characteristics of soils for slope stability analysis, foundation design, and retaining wall construction. The test provides critical information for understanding the soil’s response to shear forces and helps ensure the safety and stability of geotechnical structures (ASTM D3080). These tests play a fundamental role in characterizing the geotechnical properties and behavior of soils. By conducting these tests, engineers and researchers gain valuable insights into the soil’s physical and mechanical properties, enabling them to make informed decisions about soil suitability, design considerations, and construction practices in geotechnical projects.

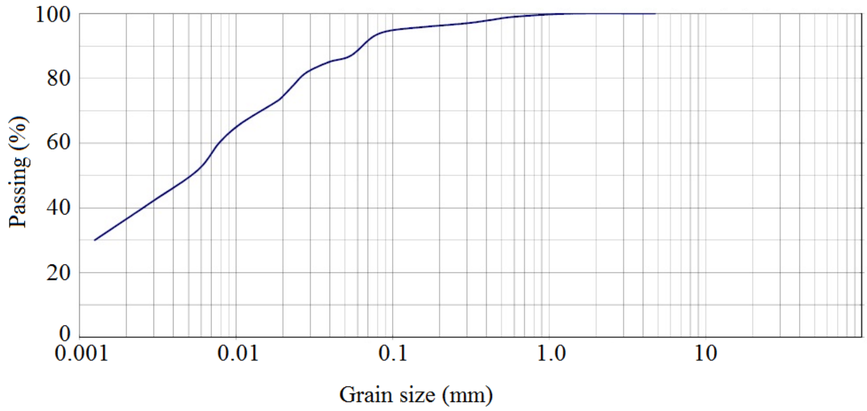

Fig. 2 The grain size analysis results for Tabriz landfill soil

Table 1 Geo-engineering index properties of the studied samples

No.	Parameter	Max.	Min.	Mean	St.Dv.
1	Water content (%)	17	11	14	3.013
2	Specific gravity (G_s)	2.65	2.65	2.65	-
3	γ_d (gr/cm^3)	1.86	1.72	1.79	0.07
4	γ_w (gr/cm^3)	2.14	2.08	2.11	0.03
5	Liquid limit (%)	58	33.66	45.83	12.17
6	Plastic limit (%)	32	23	27.50	4.5
7	Plasticity index (%)	26	20.67	23.33	2.665
8	Activity number	0.71	0.44	0.575	0.135
9	Initial void ratio	0.685	0.641	0.663	0.022
10	Saturated void ratio	0.715	0.711	0.713	0.002
11	Clay content (%)	87	43	65	0.921
12	Coarse content (%)	10	6	8	0.04
13	Silt content (%)	31	23	27	1.39

The Atterberg limits test was particularly useful in assessing the plasticity behavior of the clay particles present in the soil. The grain-size analysis curve and the geo-engineering index properties of the soil are presented in Fig. 2 and Table 1, respectively. Based on the Unified Soil Classification System (USCS), the studied soil was classified as CL, with two samples falling into the ML classification. To address leachate control in landfill liners, montmorillonite, a type of clay, was employed. Montmorillonite is known for its expansive characteristics and low hydraulic conductivity, making it highly effective in environmental protection (Kananizadeh *et al.* 2011). The nanometer-sized particles of montmorillonite, referred to as nanoclay, offer advantages in terms of composition and engineering properties by improving surface integrity. Nano-montmorillonite consists of aluminosilicate layers that are approximately 1 nm thick, surface-substituted with metal cations, and stacked in multilayer structures with sizes of around 10 µm. Depending on the surface modification of the clay layers, montmorillonite can be dispersed within a polymer matrix to form a polymer-clay nanocomposite. In this study, an off-white to cream-colored hydrophilic

Table 2 Chemical characteristics of the Tabriz MSW leachate

Sample	1	2	3	4	5	6	7	8	9
pH	7.22	7.13	7.20	7.22	7.17	7.22	7.13	7.13	7.13
T (oC)	18.1	17.7	18.3	18.0	17.2	17.8	17.7	18.1	18.3
TDS (ppm)	496.12	498.33	492.25	489.36	496.11	490.45	486.7	450.12	476.42
As (pmm)	12.2	7.3	9.9	5.7	9.6	6.3	10.7	9.6	12.2
Cd (ppm)	1.10	1.14	1.06	1.03	0.98	1.17	1.02	0.97	0.97
Co (ppm)	47.6	45.4	47.3	45.6	47.3	45.5	47.3	47.3	45.6
Cr (ppm)	63.14	71.17	75.63	79.64	63.35	17.17	66.37	65.97	71.49
Cu (ppm)	96.83	96.85	97.10	96.37	97.45	96.17	96.75	97.58	96.19
Mn (ppm)	91.3	102.7	95.5	97.3	95.6	91.3	91.7	95.5	97.3
Ni (ppm)	87.30	87.42	85.96	87.74	87.35	86.91	87.5	87.63	87.33
Pb (ppm)	192.1	189.7	196.3	190.0	196.4	196.4	192.5	231.9	238.0
Zn (ppm)	234.7	248.2	239.7	237.0	237.0	235.4	239.1	231.9	238.0
Hg (ppm)	7.47	6.03	7.17	7.41	7.10	6.65	6.85	7.10	6.36
Ca (ppm)	65.71	67.77	65.63	97.12	65.45	67.36	65.22	67.47	65.60
Na (ppm)	15.9	12.5	15.4	14.9	15.2	12.9	14.2	14.9	12.5
Mg (ppm)	15.23	15.03	14.56	14.73	14.81	15.20	14.65	14.71	15.02
HCO_3^- (ppm)	25.41	27.33	25.45	27.12	25.63	27.92	25.40	25.45	27.12
Cl^- (ppm)	6.39	6.35	7.10	6.89	6.33	7.17	6.63	7.25	6.32
NO_3^- (ppm)	17.20	16.96	17.15	17.12	16.85	17.20	16.74	15.56	17.31
SO_4^{2-} (ppm)	18.85	18.63	18.74	18.52	18.25	19.12	18.78	18.45	19.02

montmorillonite nanoclay was used. The nanoclay had a size of 1-2 nm, a density of 0.6 g/cm^3, a specific surface area of 220-270 m^2/g, an electrical conductivity of -25 MV, and an inter-particle distance of 60 A°. This specific nanoclay was employed to control the passage of leachate through the liner in the Tabriz landfill, thus minimizing leachate contamination risks.

By utilizing nanoclay additives in the development of a clay-based modified filter for landfill liners, this study aimed to enhance the effectiveness of leachate control and contribute to environmental protection measures. The unique characteristics of montmorillonite nanoclay, such as its low hydraulic conductivity and expansive properties, make it a promising material for optimizing the performance and integrity of landfill liners.

To assess the chemical composition of the leachate mixtures, several tests were conducted, including atomic absorption spectrometry (ASP), total dissolved solids (TDS), pH analysis, and X-ray fluorescence (XRF) spectrometry. Leachate samples were analyzed to measure the presence of various chemical components. Table 2 provides detailed information on the chemical properties of Tabriz MSW leachate. The results revealed elevated TDS values and the presence of heavy metal elements, indicating potential solute transport and widespread pollution. Consequently, the leakage of leachate from the landfill poses a significant environmental risk to the region's ecosystems, both for biological organisms and human populations. In order to address the issue of leachate leakage, the study employed nanoparticles to modify the soil composition. Different percentages of nanoclay additives, specifically 3%, 6%, and 9%, were applied to the soil. Geotechnical tests were performed

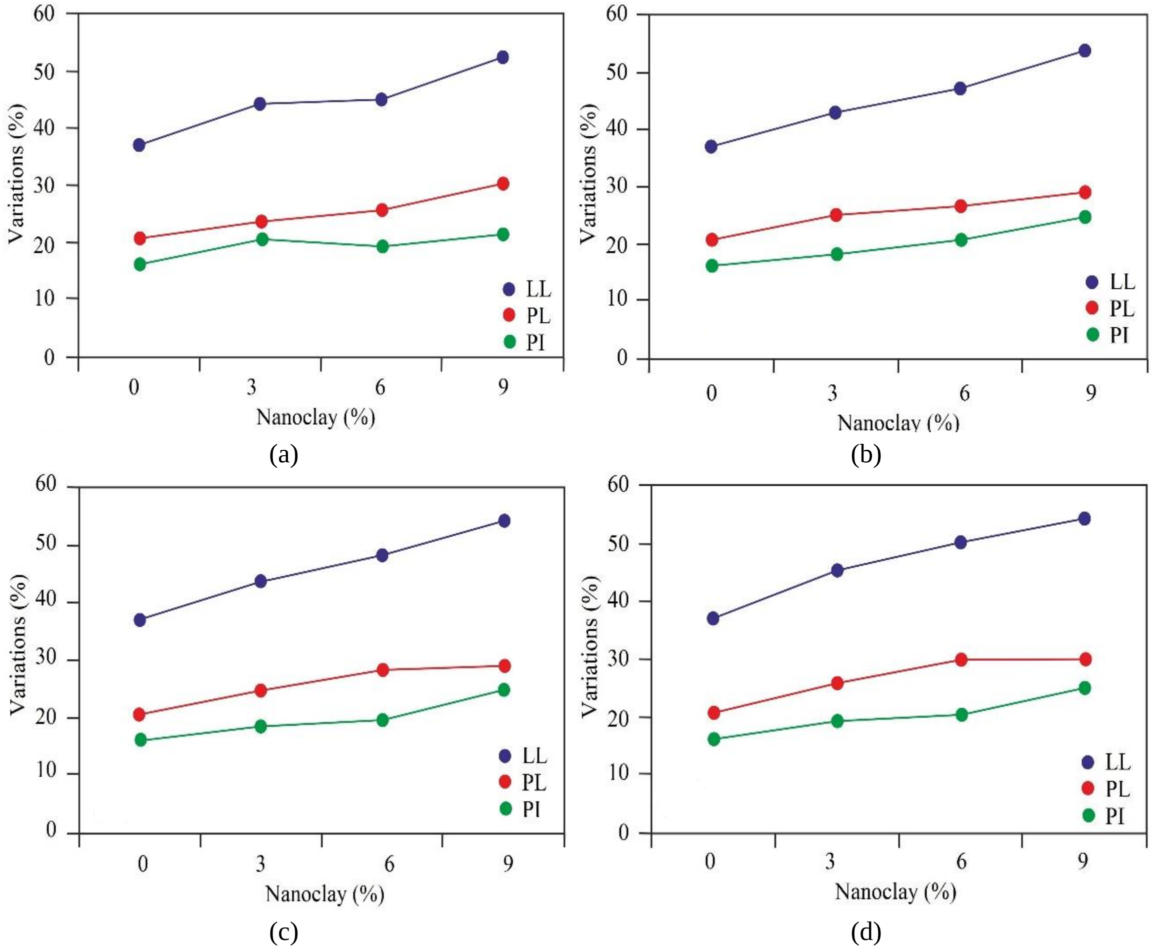

Fig. 3 Atterberg limits variation in soil based on nanoclay content (a) 1 day, (b) 7 day, (c) 14 day and (d) 28 day

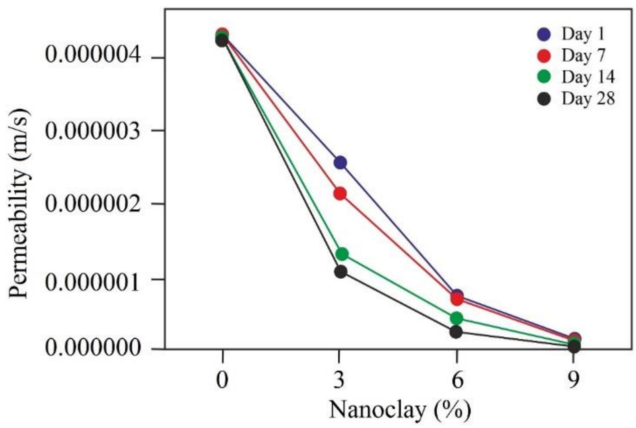

Fig. 4 Permeability variation in soil based on nanoclay content

on four distinct groups: the "control" group without any additives, and the "3% additive," "6% additive," and "9% additive" groups. Comparative analysis of the results and assessment of the modified soil behavior were conducted with respect to the basic control group (without additives).

The performed tests encompassed various categories, including particle-size analysis (ASTM D422), Atterberg limits (ASTM D4318), unconfined compressive strength (UCS) tests (ASTM D2166), and permeability assessments (ASTM D2434). These tests were carried out in accordance with the guidelines provided by the American Society for Testing and Materials (ASTM). Before the tests, all specimens were dried in a heating oven at approximately 110°C for 24 hours to ensure consistent moisture content. The mixing of soil and soil additives was performed manually with great care to achieve homogeneous mixtures. The mixtures were then allowed to rest for 1, 7, 14, and 28 days before the testing stage to observe any time-dependent changes or improvements in the soil properties.

3. Results and discussion

To analyze the effectiveness of nanoclay in reducing permeability and its impact on geo-engineering properties such as liquid limit (LL), plastic limit (PL), and plasticity index (PI), a series of experiments were conducted. The experiments were divided into four groups: the control group with 0% nanoclay additive, and groups with 3%, 6%, and 9% nanoclay additives. Each group underwent a set of geo-engineering tests, and the variations in the test results were recorded. These variations provide insights into the influence of nanoclay content on fine-grained soils commonly used in landfill liners. The impact of nanoclay content on the plasticity of the studied soil samples is illustrated in Fig. 3. The figure reveals that the liquid limit (LL) increased as the percentage of nanoclay increased from 0% to 9%, indicating an enhancement in the plasticity properties of the fine-grained soil. A similar trend is observed for the plastic limit (PL), but with a smoother and gradual increase. Overall, the plasticity index (PI) of the soil increased with the addition of nanoclay. Additionally, when considering the variations in plasticity over the preparation days (from day 1 to day 28), the LL increased by approximately 20.27% with the increase in nanoclay content from 0% to 9%. The variations for PL and PI were 21.77% and 18.37%, respectively. These results indicate that nanoclay has the potential to improve the plasticity behavior of the soil, as evident from the changes observed in the Atterberg limits. The findings of this study suggest that the incorporation of nanoclay in fine-grained soils can positively impact their plasticity characteristics, as demonstrated by the changes in the liquid limit, plastic limit, and plasticity index. These improvements have significant implications for the design and performance of landfill liners, as enhanced plasticity can enhance the soil's ability to retain moisture and mitigate the risk of leachate migration. Further investigation is necessary to explore the long-term effects of nanoclay additives on the geotechnical properties and durability of modified soils.

Permeability plays a crucial role in effectively controlling leachate within landfill liners. To assess the impact of nanoclay additives on permeability reduction, a total of 42 permeability tests were conducted on various soil specimens. Fig. 4 depicts the results of these tests, highlighting the influence of different nanoclay additives on permeability reduction in the soils. The Atterberg limits were estimated for the control group without any nanoclay additives, revealing an average liquid limit (LL) of 37, plastic limit (PL) of 20.67, and plasticity index (PI) of 16.33. However, with the addition of 9% nanoclay additives, these values increased significantly to 75, 45, and 30, respectively. Furthermore, in the control group, the permeability was measured at 4.25×10^{-6} m/s,

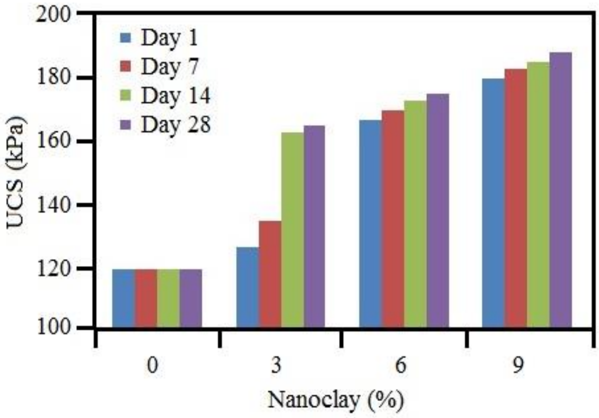

Fig. 5 The nanoclay content impact on UCS

which decreased to 6.34×10^{-9} m/s with the incorporation of nanoclay additives. The results clearly demonstrate that increasing the amount of nanoclay leads to a substantial reduction in soil permeability, thereby enabling the development of high-capacity liners for retaining leachate and preventing leakage in landfill bodies. Additionally, Fig. 5 illustrates the effects of nanoclay content on the uniaxial compressive strength (UCS) of the soil mixtures. The figure demonstrates that the addition of 3% to 9% nanoclay enhances the compressive strength of the studied soil, increasing it from 120 kPa to 188 kPa. This improvement in compressive strength can be attributed to the geotechnical properties of nanoclay, which contribute to the overall stability and load-bearing capacity of the soil. These findings highlight the significant role of nanoclay in permeability reduction and enhancing the geotechnical properties of the soil. By incorporating nanoclay additives, the permeability of the soil is significantly reduced, facilitating effective leachate control in landfill liners. Furthermore, the increase in compressive strength ensures the stability and durability of the soil in geotechnical applications. The results support the potential of nanoclay as a valuable additive for improving the performance and reliability of landfill liners, contributing to enhanced environmental protection and waste management practices.

The results of the permeability tests demonstrate the significant impact of nanoclay additives on reducing the permeability of the soil. The addition of nanoclay led to a substantial decrease in the permeability rate, indicating its effectiveness in controlling leachate migration within landfill liners. This reduction in permeability can be attributed to the unique properties of nanoclay, such as its small particle size and large surface area, which create a network within the soil matrix, hindering the flow of fluids. The formation of this network restricts the movement of water and other solutes, thereby improving the soil's ability to retain leachate and prevent its leakage into the surrounding environment. Moreover, the Atterberg limits provide valuable insights into the plasticity behavior of the soil. The increase in liquid limit (LL), plastic limit (PL), and plasticity index (PI) with the addition of nanoclay indicates an enhancement in the plasticity properties of the fine-grained soil. Nanoclay particles contribute to the modification of the soil matrix, increasing its plasticity and ability to retain moisture. This increase in plasticity is particularly advantageous for landfill liners, as it enhances the soil's capacity to absorb and retain leachate, reducing the risk of leachate migration and potential environmental contamination. In addition to permeability and plasticity, the results demonstrate the positive impact of nanoclay additives on the uniaxial compressive strength (UCS) of the soil mixtures. The increase in compressive strength can be attributed to the improved interlocking and bonding mechanisms between soil particles facilitated by the incorporation of nanoclay. The presence of nanoclay enhances the soil's load-bearing capacity and resistance to deformation under applied stresses. This increased compressive strength is crucial for the stability and performance of geotechnical structures, as it ensures the soil's ability to withstand vertical loads and maintain its integrity over time.

Overall, the findings highlight the significant potential of nanoclay as an effective additive for modifying the permeability, plasticity, and compressive strength of fine-grained soils. The reduced permeability, enhanced plasticity, and increased compressive strength contribute to the development of high-performance landfill liners, offering improved leachate control and environmental protection. However, further research is needed to investigate the long-term effects and durability of nanoclay-modified soils under various environmental and loading conditions. Understanding these aspects will enable more informed and optimized use of nanoclay additives in geotechnical engineering applications.

A microstructural study can provide valuable insights into the mechanisms behind the observed improvements in permeability reduction, plasticity enhancement, and compressive strength increase with the addition of nanoclay additives. The unique properties of nanoclay, such as its high surface area and small particle size, play a crucial role in altering the microstructure of the soil. At the microscale, the nanoclay particles disperse within the soil matrix, creating a network of interconnected particles. This network effectively blocks the flow paths of water and other solutes, reducing the permeability of the soil. The nanoclay particles form inter-particle bonds and bridges, leading to the formation of microaggregates. These microaggregates contribute to the increased packing density of the soil particles, further limiting the movement of fluids. The microstructural changes induced by nanoclay result in a more tortuous and compacted soil structure, which significantly reduces the permeability and enhances the soil's ability to retain leachate.

In terms of plasticity enhancement, the microstructural study reveals that the nanoclay particles act as a filler material within the soil matrix. The small size and large surface area of nanoclay particles facilitate their distribution between soil particles, increasing the contact points and interlocking mechanisms. This improved interparticle bonding and increased surface area promote better water retention and plastic deformation characteristics. The nanoclay particles effectively absorb and hold water molecules, resulting in increased water content and plasticity properties of the soil. Additionally, the microstructural study sheds light on the mechanisms responsible for the increased compressive strength of the soil with the addition of nanoclay. The presence of nanoclay particles reinforces the soil matrix at the microscale. The interlocking of soil particles with nanoclay particles enhances particle-particle contact and bonding. The nanoclay particles act as a strengthening agent, distributing stress more efficiently and preventing particle dislocation or slippage. This improved interparticle bonding and load transfer mechanisms contribute to the increased load-bearing capacity and compressive strength of the soil. Overall, the microstructural study highlights the intricate interactions between the nanoclay particles and the soil matrix. It elucidates the mechanisms behind the observed improvements in permeability reduction, plasticity enhancement, and compressive strength increase. The microscale changes induced by nanoclay additives result in a more interconnected and compacted soil structure, leading to enhanced geotechnical properties. Understanding the microstructural modifications helps in optimizing the design and application of nanoclay additives for geotechnical engineering purposes, contributing to improved soil performance and stability.

The study, like any scientific research, may have limitations that should be taken into account when interpreting the results. One potential limitation is the age and composition of the soil samples used. Soil properties can vary with time due to weathering, consolidation, and other environmental factors (Kannan and Sujatha 2022). Therefore, the representativeness of the soil samples in terms of their age and composition should be considered (He *et al.* 2023). Older soil samples may exhibit different geotechnical properties compared to younger ones (Calitz, 2022), potentially impacting the observed effects of nanoclay additives. Similarly, variations in the composition of the soil samples, such as differences in mineralogy or organic content, could influence the interaction between the soil and nanoclay particles. The testing conditions employed in the study are another potential influencing factor (Chaudhary *et al.* 2023). Factors such as sample preparation, compaction methods, curing duration, and testing equipment can introduce variability and affect the results. Inconsistent or non-standardized testing procedures may lead to biased measurements. To mitigate these limitations, it is crucial to adhere to standardized testing protocols and implement rigorous quality control measures throughout the experimental setup (Kausar *et al.* 2022).

It is important to recognize that some properties of nanoclay-modified soils exhibit time-dependent behavior. Hydration, consolidation, and other time-related effects can influence the soil's geotechnical properties over extended periods (Chaudhary *et al.* 2023). Therefore, the duration of the testing period and the time elapsed since the soil modification should be considered. Long-term effects, such as the durability and stability of the modified soil, may not be fully captured within the scope of the study (Johari *et al.* 2022). Future research could incorporate long-term monitoring to better understand the performance of nanoclay-modified soils over extended periods (Mehrabi *et al.* 2021). Furthermore, it is essential to acknowledge that the study may have been conducted at a laboratory scale, which may limit the direct applicability of the results to real-world field conditions. The behavior of soil under actual field conditions, such as in-situ stresses, environmental factors, and complex loading conditions, may differ from laboratory settings (Krishnan and Shukla 2019). To address these limitations and enhance the reliability of future research, it would be beneficial to consider a wider range of soil samples with different ages and compositions. Incorporating more comprehensive testing conditions that better simulate real-world scenarios, conducting long-term monitoring, and considering scale effects would further enhance the applicability and reliability of the findings.

The practical implications of this study have significant scientific and engineering value. The incorporation of nanoclay additives in fine-grained soils used in landfill liners presents practical benefits for leachate control and liner performance. The observed reduction in soil permeability due to nanoclay addition has direct implications for groundwater protection and environmental preservation. By minimizing the potential for leachate migration, the risk of groundwater contamination and subsequent ecological damage can be effectively mitigated. Furthermore, the enhancement of soil plasticity properties and compressive strength through nanoclay modification has important practical implications for landfill liner design and construction. The improved plasticity characteristics enable the liner to better adapt to changes in moisture content, reducing the likelihood of cracking and maintaining its integrity over time. The increased compressive strength ensures the stability and durability of the liner, enhancing its overall performance and reducing the need for maintenance. These practical implications extend beyond landfill applications and offer potential advantages for geotechnical engineering practices. The insights gained from this study have the potential to inform the design and construction of various geotechnical structures, such as foundations and embankments, by improving soil properties. The utilization of nanoclay additives can contribute to sustainable waste management practices, reducing the environmental impact associated with conventional stabilization methods and offering cost-effective solutions.

4. Conclusions

The objective of this study was to investigate the potential of incorporating nanoclay to enhance the permeability of fine-grained soils commonly used in landfill liners. To achieve this, an extensive experimental study was conducted using soil samples obtained from the Tabriz landfill site. The samples were divided into four distinct groups: the "control" group without any additive, and three groups with varying percentages of nanoclay additives: "3% additive", "6% additive", and "9% additive". The geotechnical properties of each group were assessed through particle-size analysis, Atterberg limits testing, permeability measurements, and unconfined compressive strength (UCS) tests. The results of the study revealed that the studied soil belonged to the CL classification, and its compressive strength exhibited significant improvement upon the addition of nanoclay. The compressive strength increased from an initial value of 120 kPa to 188 kPa with the inclusion of nanoclay additives. Furthermore, the permeability of the soil decreased remarkably, decreasing from an initial value of 4.25×10^{-6} m/s to 6.34×10^{-9} m/s, indicating a significant reduction in fluid flow through the soil. In terms of the plasticity behavior of the soil, the liquid limit (LL) was initially measured at 37, the plastic limit (PL) at 20.67, and the plasticity index (PI) at 16.33. With the increasing concentration of nanoclay additives from 0% to 9%, these values increased to 75, 45, and 30, respectively. This observation indicates that the addition of nanoclay resulted in increased plasticity and enhanced ability of the soil to retain moisture. These findings demonstrate the potential of nanoclay as an effective additive to modify the geotechnical properties of fine-grained soils, particularly those used in landfill liners. By incorporating nanoclay additives, the compressive strength of the soil increased, permeability decreased, and plasticity improved. These outcomes highlight the promising prospects of using nanoclay to enhance the performance and durability of landfill liners, contributing to more effective waste containment and environmental protection.

Acknowledgments

There are no conflicts of interest. This research received no external funding.

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