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Application of nanoclay and nanofiber filters to reduce soil permeability and leachates from landfill liners: A Review

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ABSTRACT

This study aimed to provide a comprehensive review study of the nanoclay and nanofiber filter application in landfilling stage for solid wastes to control the leachate leakage from landfill liners. The filtering is a key element in landfill liners that prevent the leachate from seepage which is the main factor in groundwater pollution. In this regard, providing new methods that are more adaptable to environmental conditions can be efficient. The presented paper is prepared as a review study on nanotechnology application in geotechnics that is used for preventing leachate leaks from landfills body specifically nanoclay and nanofibers.

1. Introduction

Waste and scrap can be introduced as the greatest human achievement in urban areas which has become a global concern in the field of environment engineering (Nanda and Berruti, 2021). Wastes cause widespread pollution in water and soil and the release of their leachate and polluted of groundwater and agricultural resources (Das et al., 2019). One of the most important ways to prevent environmental pollution, especially water and soil by waste, is the use of correct and geo-engineering methods in waste disposal which need to act in all stage from site selection to constructions (Khandelwal et al., 2019). In general, there are various methods for waste disposal, including recycling, reuse, conversion, incineration, and landfilling. Landfilling of wastes is the most common approach used in solid waste disposal that has the highest percentage of implementation in urban areas (Azarafza et al., 2015). Landfilling is actually the last resort with solid waste that is not recyclable and cannot be reused that is usually done in traditional or unsanitary ways (Teng et al., 2021). Sanitary-material landfilling is establishing of landfilling operations along with the arrangements that concluded layers and covers of waste that the infiltration of pollution, especially leachate from the decomposition of materials to the surrounding soils and groundwater (Costa et al., 2019). The landfill should be equipped with various systems and arrangements such as preventing water from entering the landfill, collecting leachate, preventing leakage and possible tracking, collecting and discharging the resulting gases and other measures. It should be noted that engineering landfills also require special arrangements for the disposal of hazardous toxic wastes and nuclear materials (Nanda and Berruti, 2021).

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When wet-waste (usually containing organic matter and hydrocarbons) is piled up, the fermentation and biological decomposition of the waste releases a viscous liquid that contains many chemical elements and is generally toxic is called 'leachate'. The main constituents of leachate are mainly ammonium, organic matter, toxic compounds and heavy metals. Leachate flows into the landfill through the rubbish and accumulates on the floor of the landfill, and a large volume of this very dangerous liquid comes into contact with the soil of the landfill bed (Costa et al., 2019). The volume of leachate collected in the landfill depends on the amount of waste and the initial moisture of the landfill, rainfall, surface-water, evaporation rate, and landfill's transpiration (Miao et al., 2019). The collected leachate begins to penetrate and move between the soil layers due to various mechanisms, and in the absence of an impermeable layer, it enters the groundwater aquifer along a path. The presence of leachate in both short-term and long-term affects the permeability of soil layers and increases the permeability and decreases soil retention conditions by subsidence. In the short-term, it is effective due to the greater viscosity of the leachate than water and the production of gas from the leachate during infiltration, and in the long-term, due to the leachate contact with the soil and physical and chemical changes in the soil. Increasing the concentration of these substances in groundwater may exceed the permissible limits and existing standards and cause widespread pollution of groundwater (Das et al., 2019).

In the last two decades, the spread of traditional solid waste landfills and unsatisfactory hydromechanical conditions and structures in the landfill site have caused leachates to spread easily in the surrounding environment, causing environmental pollution, ecosystem degradation and the spread of various diseases in organisms (Azizpour et al., 2020). To this end, geotechnical and environmental engineers have tried to apply new engineering and management methods to improve the existing conditions. In the meantime, although the first step is proper location based on the principles of geotechnical engineering; but, the implementation of liners can be introduced as the main pillar and front against the spread of leachate in landfills (Luo et al., 2020). The main purpose of landfill construction is to prevent contamination of water and soil resources and this responsibility is provided by liners (Debnath et al., 2013). In general, layers that prevent direct waste contact with soil and prevent leachate from penetrating into the soil are impermeable layers or liners (Katsumi et al., 2001). In landfills, these layers are designed and implemented as wall coverings in the body and floor of the landfill to prevent surface water, rain and runoff from entering the landfill and to prevent the leakage into groundwater (McBean et al., 1994). Fig. 1 shows a schematic of a single-line landfill. The liners can be implemented as single-liner and double-liner in the landfill body which is structured based on nature of the materials, their holding power and their permeability are also very important points in leachate control. Site conditions and geotechnical and hydromechanical properties of landfill host soils as well as leachate conditions play a very important role in the multiplicity of liner construction in landfills (Vesilind et al., 2002). Fig. 2 shows a schematic of the structure of single-line and double-line systems.

The materials used in the liners must have very low permeability and high capacity to absorb pollutants, good flexibility against changes in humidity, settlements for landfill, and also these materials must have sufficient strength against forces and loads. The most optimal materials that meet the above conditions are clay materials (Pazoki and Ghasemzadeh, 2020).

In cases where the local clay as a material used in these coatings is not of sufficient quality and the transportation of clay with suitable conditions is costly; improving soil conditions by adding suitable additives or synthesizing existing materials is cost-effective and changes some properties such as reducing the permeability coefficient and eliminating some problems in the soil (Pazoki and Ghasemzadeh, 2020). Clay is a very wide range of minerals with different types, and depending on the type of clay minerals, the amount of exchange cations in the soil varies. The higher the amount of these exchange cations is belonging to the bentonite or montmorionite (McBean et al., 1994).

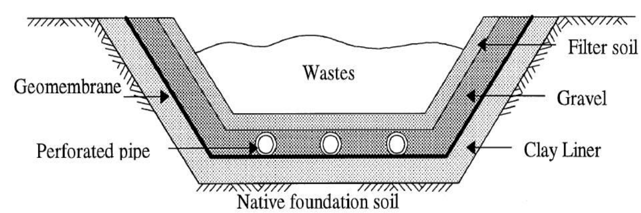

Figure 1. Scheme of a single-line landfill building (Vesilind et al., 2002)

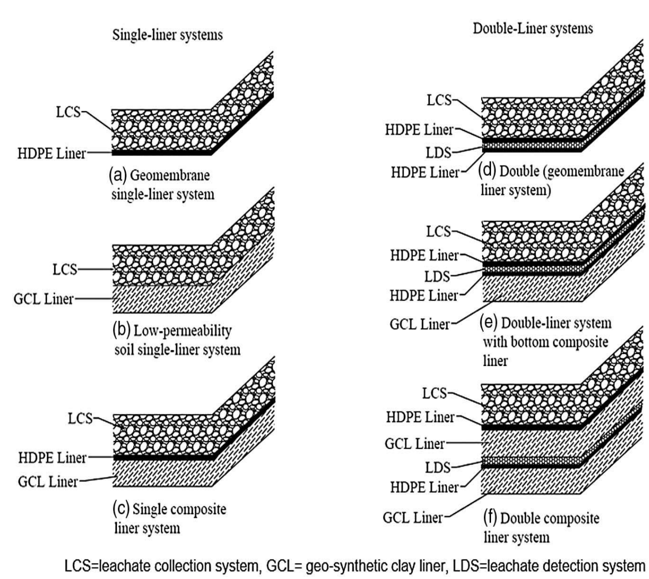

Figure 2. Schematic of single-line and double-line systems (McBean et al., 1994)

The combined use of synthetic materials such as bentonite in combination with geosynthetics in landfill liners has different effects on the ecosystem of the area depending on the environmental conditions and is generally considered as an environmental concern. Despite the fact that the use of these materials is effective in reducing the permeability of the burial body and prevents the transfer of leachate to the soil under the bed, but also has several environmental problems (Sharma and Reddy, 2004). However, newer approaches that have similar capabilities and performance and at the same time are more environmentally friendly have been considered by researchers.

2. Nanotechnology in Geotechnics

In the field of geotechnics, one of the most successful technology that used to contaminate the leachate is clay nanomaterials. Nanoclays are silicate nanoparticles that are generally made from montmorionite, bentonite and smectite clays. The problems that artificial additives are causd in the soil is environmental pollution; while nanoclays have favorable effects on environmental degradation processes and are considered as compatible materials (Krishna and Gupta, 2008). 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).

The use of nanoclays in soil stabilization is technically and economically appropriate, and these materials, due to their natures, have an environmentally friendly structure. On the other hand, the permeability of nanoclays is much lower than conventional clay layers and they are a strong barrier against leachate development (Abbasi et al., 2017). The use of nanoclays in combination with soil causes positive changes in geotechnical conditions and soil strength parameters which has the most positive effect in terms of quantity and quality in soil (Krishna and Gupta, 2008). Investigation of the effect of nanomaterials on the geotechnical properties of fine-grained soils including compaction, Atterberg limits and compressive strength on fine-grained soil samples and the combined percentages of nanoclays show the most positive effect on strength of soil samples. Addition of nanoclay to the base soil due to the high specific surface area and suitable cation exchange capacity reduces the soil divergence potential and reduces the consolidation coefficient and increases the uniaxial strength and soil hardness and improves the soil strength (Khodary et al., 2018).

The use of nanoclay inhibits swelling and reduces the potential for damage in soils, and perhaps the most important advantage of using these nanoclays is the reduction of hydraulic conductivity in soil (Azarafza et al., 2018). Addition of nanoclay to the soil increases the fine-grained fraction and the placement of these fine particles in the space between the coarse soil particles, and this action reduces the useful porosity of the soil and thus reduces the hydraulic conductivity.

On the other hand, hydration and expansion of nanoclay in the presence of water causes the filling of empty space between soil grains and prevents the movement of water between soil grains, and as a result, the hydraulic conductivity of soil is further reduced. Also, the use of nanoclay to improve soil properties due to the origin of these particles is a natural soil; it does not cause environmental pollution (Ng and Coo, 2014).

Although the use of nanoclay materials in liners seems to have the ability to reduce leachate diffusion, but corrosion of materials in leachate, environmental changes and displacement of fluid levels or executive defects and changes in soil properties, cause microcracks and reduce the resistance of liners in It is equal to leachates (Ng and Coo, 2014). Leachate from waste decomposition is very toxic and dangerous and if it penetrates into the surrounding soils and groundwater, it causes severe environmental damage to various species of living things and the environment (Luo et al., 2020). This problem is mostly due to the mentioned reasons, damage to liners and landfills and the landfill should be constantly monitored to prevent leachate from penetrating out of the landfill in case of damage (Das et al., 2019).

The best idea to solve this problem is to use nanocomposites reinforced with nanofibers (Krishna and Gupta, 2008). In fact, clay nanocomposites are hybrid nanostructured materials that are composed of an inorganic material with a nanofiber polymer structure that contains between 2% and 9% by weight of the nanoparticles. In the polymer sector, it seems that natural biopolymers such as cellulose can be used, which are environmentally friendly and do not cause degradation. Nanocelluloses have a high potential, because cellulose is the most abundant organic raw material in nature and can be produced on a micro to nanometer scale (Abbasi et al., 2017).

In general, nanocelluloses can be prepared in two main forms of nanofibers (CNFs) and nanocrystals (CNCs), the main difference being the extraction method and appearance. Nanocrystalline cellulose is extracted mainly by acid hydrolysis, while nanofibers are often separated using mechanical extraction processes such as milling and purification (Yousefi et al., 2011).

The use of such a structure changes the permeability of conventional liners in landfills. In fact, the liner can be expressed as part of engineering landfills, which is responsible for controlling the release of leachate from the landfill body to the environment, especially groundwater. This part plays a significant role against the settling and strength of the body and the impermeability of the buried wall parts. Therefore, it must have an engineering structure and at the same time be compatible with the surrounding environment (Langaroudi and Mohammadi, 2018).

3. Application of Nanomaterials in Landfills

Hermann et al. (2009) used fine-grained volcanic ash (bentonite) to investigate the hydraulic conductivity of a mixture of volcanic ash and sewage sludge in Sweden. In his study, the effect of density, moisture content, volcanic ash ratio, freezing-drying and biological activities on the hydraulic conductivity of volcanic ash mixture and sewage sludge was investigated. The aim was to identify the factors affecting hydraulic conductivity and how to minimize hydraulic conductivity. The results of the study showed that the hydraulic conductivity of the volcanic ash mixture with sewage sludge was between 1.2×10^{-11} m/s and 1×10^{-4} m/s. Based on the results, the hydraulic conductivity can be maintained between 1.7×10^{-11} and 8.9×10^{-10} m/s. Kananizadeh et al. (2011) conducted an experiment that evaluate nanoclay performance on reducing the permeability, swelling, and uniaxial compressive strength (UCS) of Kahrizak Landfill's dense clay liner in Tehran. The scholars performed a series of soil mechanics experiments to investigate the additive nanoclay effect on soil. The results of the study indicate that by adding 4% nanoclay, the permeability of liner soil from 3.66×10^{-9} to 7.74×10^{-11} in normal condition. In acidic state from 3.66×10^{-9} to 7.9×10^{-10} and in the alkaline state it is reduced from 3.25×10^{-9} to 5.24×10^{-10}, which is a significant decrease in soil permeability. On the other hand, soil resistance increases by about 36.28% compared to the baseline condition, which also emphasizes the improvement of soil quality conditions. In general, by adding nanoclay to the mixture, the penetration of heavy metals into it is reduced. The obtained results justify the construction of clay barriers with nanoclay in order to prevent leachate penetration and thus reduce operating costs. Fig. 3 shows the result of changes in soil permeability with nanoclay additives and Fig. 4 shows the result of changes in liner soil strength by adding different percentages of nanoclay.

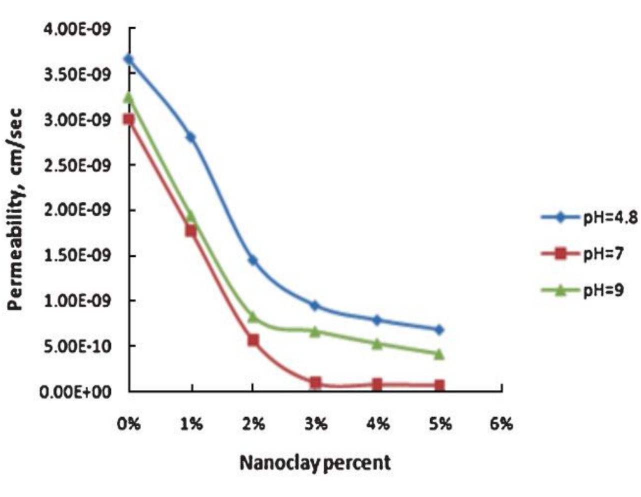

Figure 3. Graph of changes in permeability of liner soil to changes in nanoclay values (Kananizadeh et al., 2011)

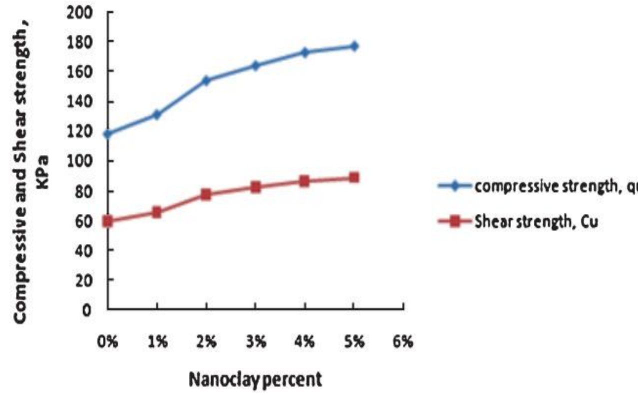

Figure 4. Graph of changes in liner soil resistance to changes in nanoclay values (Kananizadeh et al., 2011)

Debnath et al. (2013) attempted to analysis the effects of the nanomaterials usage on various structures. Considering nanomaterials applications in engineering fields, these researchers stated that nanomaterials have useful and different applications in different fields and improve the operating conditions in those projects. A look at the application of nanomaterials in the field of civil engineering has pointed to the ability of these materials to control leachate in landfills. Scholars stated that according to studies conducted at the international level, the nanomaterials is reduces its permeability of soils agents the leachate. Also, some technological advances have been made in the field of mechanics, which shows the inhibitory role in the body of landfills (nanomaterial shields) which shows that nanomaterials have been able to gain a good position in various scientific and engineering dimensions.

Li et al. (2013) examined the effect of leachate contamination on the dense clay's mechanical properties. To do this, they used a clay sample from the Wuhan metro area of China with a combination of pure deionized-water and four samples of this soil with different percentages of leachate and deionized-water. The leachate used was collected from the Wuhan landfill. Samples were prepared during standard density tests with 95% density and 19.5% moisture and various tests such as penetration on the samples were performed. According to the results, due to chemical reactions on leachate-soil and the suspended solids movement and microorganisms in leachate that reduce effective porosity, the hydraulic conductivity of dense clay decreases and with increasing concentration of leachate, the hydraulic conductivity of soil decreases further. Increasing the concentration and leachate penetration duration is leads to decrease in cohesion (C) and increase in the friction angle (ϕ). The compressibility of dense clay increases with increasing leachate and pollution. The maximum reduction in soil porosity due to pollution was estimated to be 9.7%.

Bahari et al. (2016) used clay nanomaterials to reduce the permeability and improve the strength of the body of water storage ponds for agriculture in Abbandan region. The researchers performed a series of permeability experiments with falling load on fine-grained soils, and submerged state tests which the experiments are shown in Fig. 5. Also, authors used the finite element numerical model to evaluate the results that the performance of nanomaterials has improved in reducing permeability. According to the results, soil permeability was reduced from 1.58×10^{-4} to 2.88×10^{-5} by adding 0.5% by weight of nanoclay and soil up to 58% in the physical model and 22% in the numerical model. Jafari and Abbasian (2018) was conducted a study to investigate the soil permeability behavior with montmorionite nanoclay in landfill liners. In this regard, experiments were performed on twenty soil samples containing 0%, 3%, 6% and 9% nanoclay and permeability testing and determination of soil properties were performed on each of the samples containing nanoclay and results were analyzed. Based on the results, with increasing the percentage of nanoclay from 0% to 9%, soil permeability decreases. This value decreases from 3.16×10^{-4} cm/s for soil containing 0% nanoclay to 4.09×10^{-7} cm/s for soil containing 9% nanoclay. This permeability for acidic conditions is 2.12×10^{-5} cm/s, which decreases with increasing the amount of nanoclay to 6.22×10^{-7} cm/s. The obtained results are presented in Figs. 6 and 7.

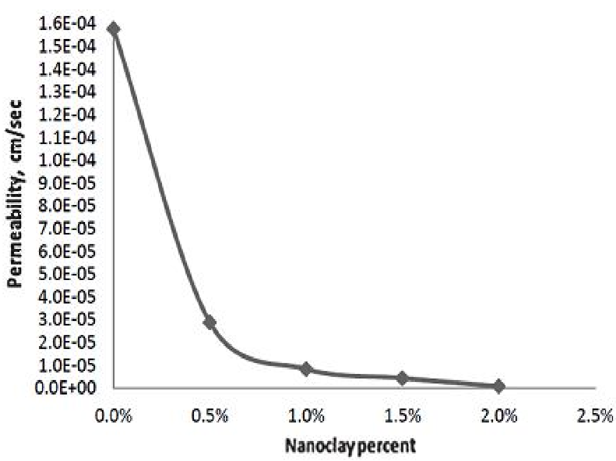

Figure 5. Graph of changes in permeability of liner soil to changes in nanoclay values (Bahari et al., 2016)

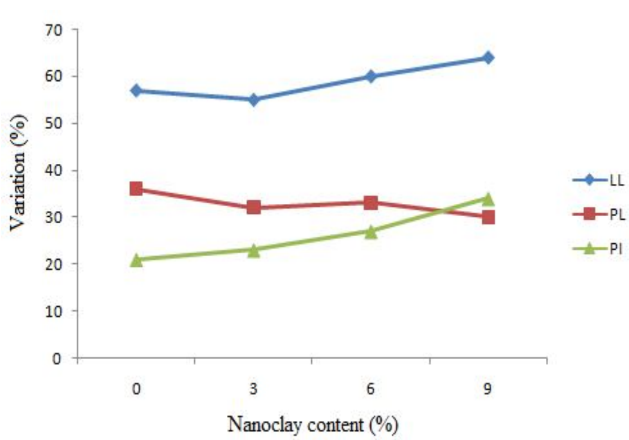

Figure 6. Effect of nanoclay content on the stability of sample particles (Jafari and Abbasian, 2018)

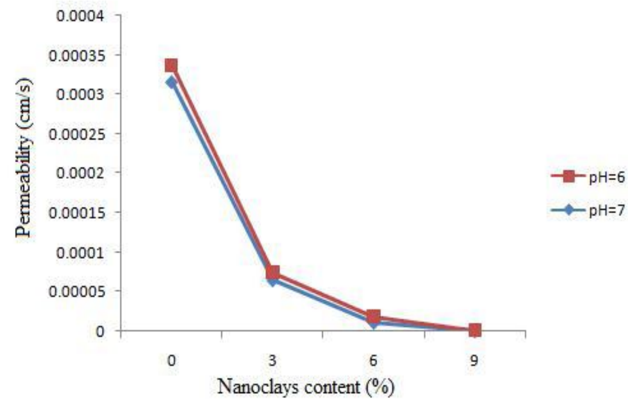

Figure 7. Effect of adding different percentages of nanoclay on permeability (Jafari and Abbasian, 2018)

Derakhshani and Naghizadeh (2018) is state that nanofibers are inexpensive and non-toxic materials with high absorption capacity to remove various contaminants from water. They used high-dose leachate effluent to evaluate their performance in absorbing humic-acid. By considering the effect of various parameters such as pH, leachate contact time, initial concentration of humic-acid and adsorbent dose, these researchers tried to investigate the ability of nanoclay to absorb and retain these contaminants. In the study, the most important issue is the adsorption capacity and thermodynamic adsorption aspects, which are considered as the first and second degree storage of clay nanomaterials. Scholars determined the properties of gravity by analytical methods including field scanning electron microscopy (FE-SEM), Fourier transform infrared spectroscopy (FTIR) and X-ray diffraction (XRD). The results of study showed that the nanoparticles are effective in removing humic-acid from aqueous solutions at pH = 3 and the adsorption capacity increases with increasing humic acid concentration. So, the adsorption capacity of bentonite and montmorionite nanoparticles increased at a concentration of 40 mg of humic-acid and reached 58.21 and 48.20 mg/g, respectively. Figs. 8 and 9 showed that nanofibers are a good adsorbent for the removal of humic-acid from aqueous solutions.

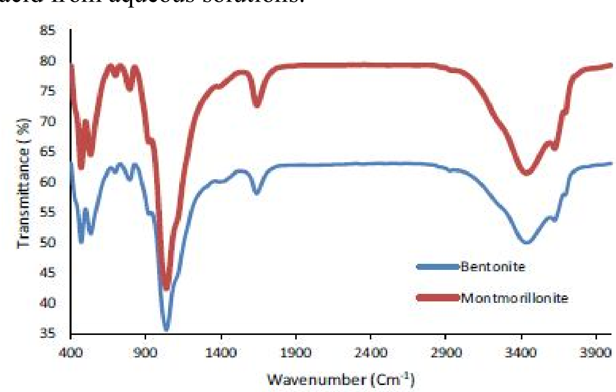

Figure 8. FTIR spectrum corresponds to nanoparticles: bentonite and montmorillonite (Derakhshani and Naghizadeh, 2018)

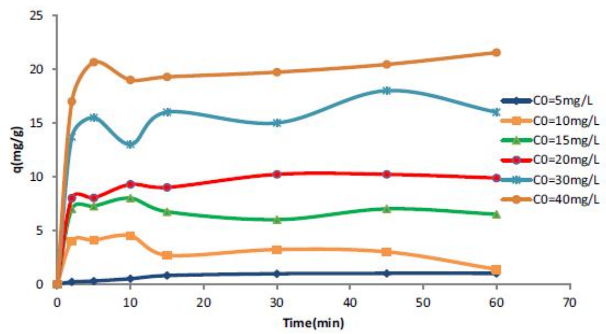

Figure 9. Effect of humic-acid concentration on nanoparticle adsorption capacity (Derakhshani and Naghizadeh, 2018)

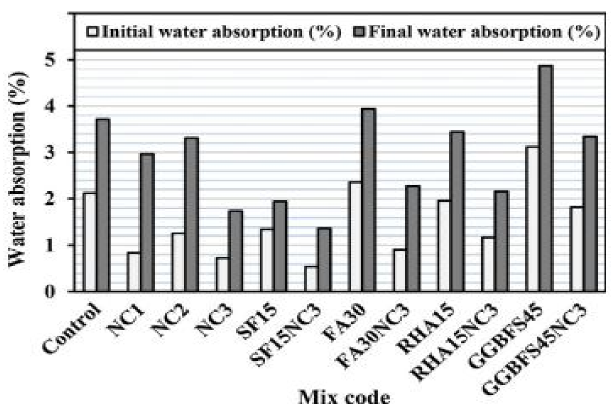

Figure 10. Initial and final values of water absorption in concrete (Langaroudi and Mohammadi, 2018)

Langaroudi and Mohammadi (2018) conducted a study to investigate the concrete properties by adding nanoclay. The researchers investigated the effects of additive nanoclay on the performance properties (e.g., flow drop and ability to pass box test), mechanical (e.g., tensile strength and mechanical strength) and durability (e.g., water absorption, water penetration and electrical resistance) of concrete. In the study, amounts of 1%, 2% and 3% of nanoclay were added to cement as additives. The result was found that adding 3% of nanoclay to cement significantly improves the durability performance but its effect on mechanical properties is limited. Also, adding a small amount of nanoclay can effectively improve the properties of concrete. The contribution of their research is shown in Fig. 10. Falamaki et al. (2018) was investigated the dicalcium phosphate effect on the permeability, cohesion and friction angle of a sand-bentonite liner to prevent the contaminants. Dicalcium phosphate with 0.2% dry weight was added to the sandy soil. It was then combined with water and artificial leachate to evaluate compatibility, permeability and shear strength. The permeability coefficient of soil increased from about 10^{-4} cm/s to less than 10^{-7} cm/s. As a result, the permeability of the soil decreased by about 1000 times. The experimental also showed that dicalcium phosphate increases the compatibility of the sand-bentonite mixture and leachate has less effect on this type of liner. As bentonite increases by up to 6% in the base material coating, the internal friction angle first decreases and then remains almost constant. Therefore, a compacted clay liner with a layer of dicalcium phosphate-containing soil was proposed to reduce the impact of leachate-contaminated soil containing heavy metals.

Almasri et al. (2018) evaluate the performance of clay-based nanocomposites fiber to prepared using a simple wet-moisture synthesis method. The researchers' study on assessing the impact of groundwater contamination with arsenic and the role of the prepared nanocomposite in the inhibition and uptake of arsenic (As^{III}). Using pure montmorionite and hydroxypyrene nanofiber, leads to increase adsorption capacity of arsenic-contaminated groundwater. In this regard, a set of X-ray diffraction (XRD), X-ray fluorescence (XRF), Fourier transform infrared spectroscopy (FTIR), BET surface analysis, calorimetric analysis, scanning electron microscopy (SEM) and transmission electron microscopy (TEM) tests are used. The results showed that the nanocomposite used was more than 55% effective in arsenic adsorption and quality improvement of water conditions, which is 5 times the usual use of iron oxides in arsenic adsorption. Optimal adsorption was performed at pH 6 to 7. The presented results can be used for groundwater, drinking water or arsenic contaminated wastewater. Fig. 11 shows a schematic representation of the contamination process by the prepared nanocomposite.

Dlamini et al. (2019) by preparing mixed (fibrous cellulose based cellulosic composites) attempted to analysis the performance for water treatment of effluents. The researchers used clay-based nanofibers as ultrafiltration (UF) membranes to purify salt and distill salt water. For purify water from salt-containing effluents used nanofiltration (NF) membranes is conducting fiber-based nanocomposites (usually illite and montmorionite) which is mixed with soils.

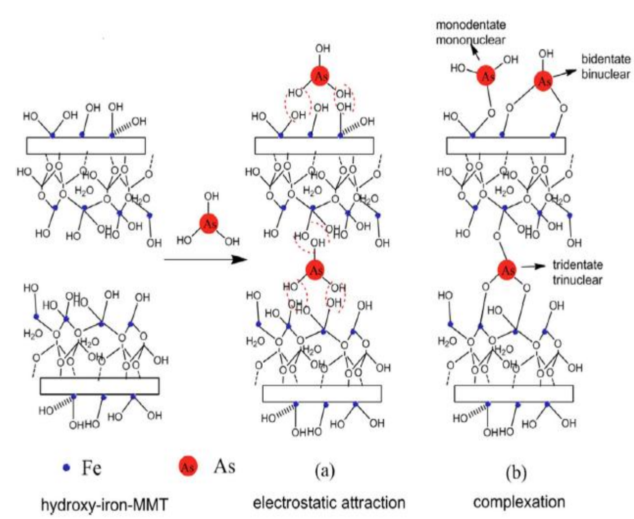

Figure 11. Schematic arsenic adsorption representation mechanism on the HeyFe-MMT nanocomposite (Almasri et al., 2018)

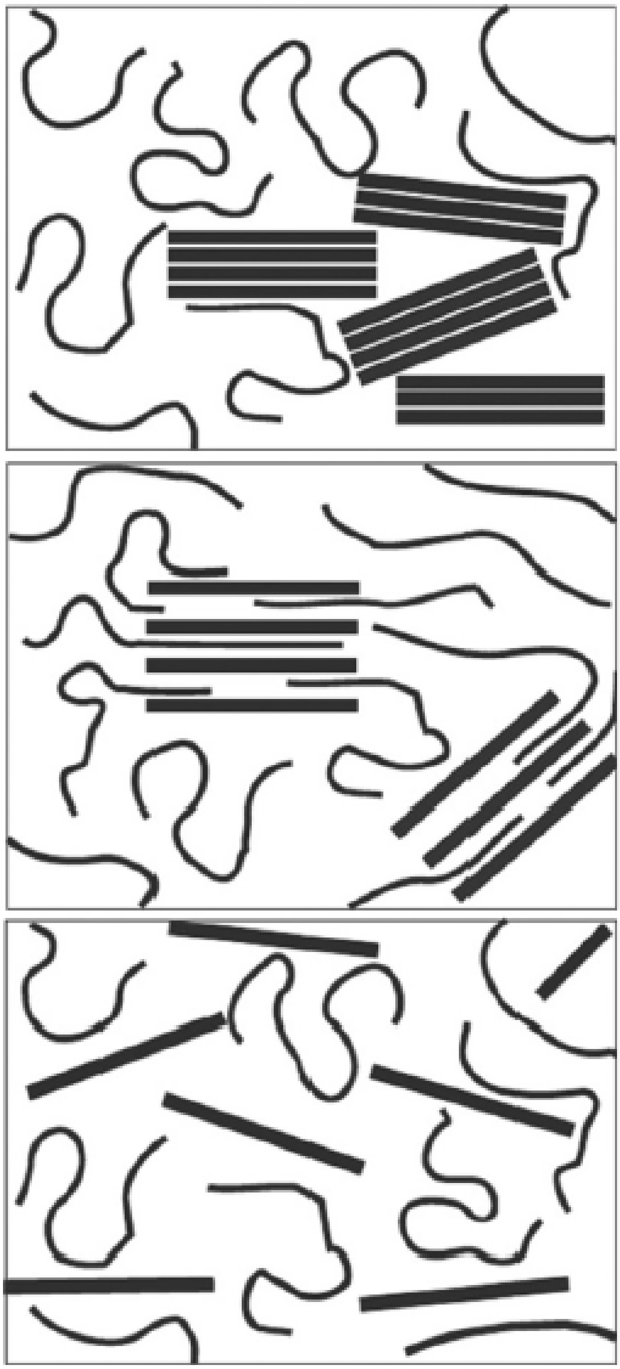

Figure 11. Schematic of the process of mixing cellulose nanocomposites with mineral clay (Dlamini et al., 2019)

To repel salt, the repulsion mechanism and negative charge of clay ions are used and by increasing and then decreasing the water flux in the path of the filter layer. This can be justified by considering the fact of dimensional dimensions between water particles and clay sheets. Fig. shows the mixing status of nanocomposites and threads in the filter body. 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 in Maragheh. For this purpose, a laboratory model was designed to evaluate the performance of nanoclay filters to reduce soil permeability. In this study, samples containing 0%, 3%, 6% and 9% nanoclay were used to create filters used in the permeability tests. The results showed that the permeability coefficient decreased from 3.18×10^{-4} cm/s for 0% nanoclay to 7.71×10^{-7} cm/s for 9% nanoclay and this indicates the ability the function of nanofilters is to reduce the permeability coefficient. The results of these researchers can be seen in Figs. 12 and 13. Qasaimeh et al. (2020) investigated the effects of bentonite nanomaterial additives to reduce environmental impact in the region. Soil samples were prepared from Al Akaider city. The compressive strength, consolidation and permeability tests were performed on soil samples with different percentages of nanoclay added in the range (0.1% to 1.2%) of soil weight. Addition of nanoclay by 0.6% increases soil strength up to 315 kPa and the potential for swelling is significantly reduced by the addition of nanoclay. The optimum percentage of nanoclay was 0.6% and the inherent permeability of the modified soil was 6.03×10^{-15} cm/s. The results of the studies were also used to evaluate the performance of bentonite nanoclay in reducing the swelling of liners.

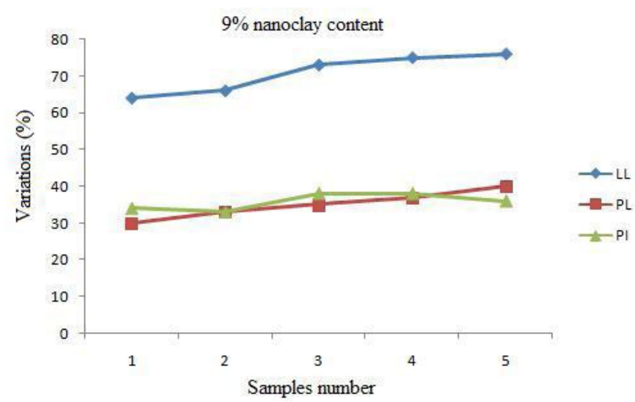

Figure 12. Atterberg limits changes for the studied soil (Jafari and Abbasian, 2019)

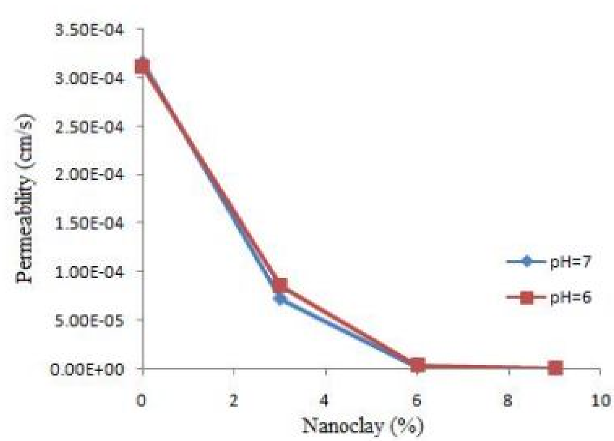

Figure 13. Permeability of samples to different percentages of nanoclay (Jafari and Abbasian, 2019)

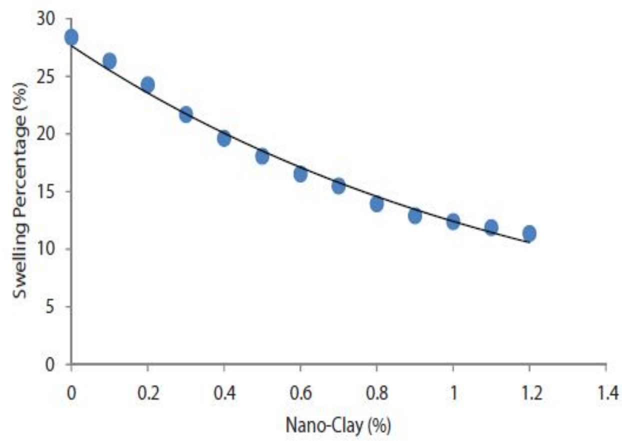

Figure 14. Variation graph relative to bentonite nanoclay changes (Qasaimeh et al., 2020)

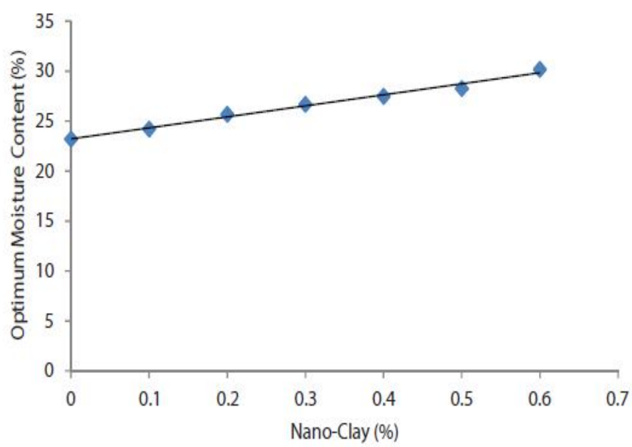

Figure 15. Variation graph soil moisture retention due to changes in bentonite nanoclay (Qasaimeh et al., 2020)

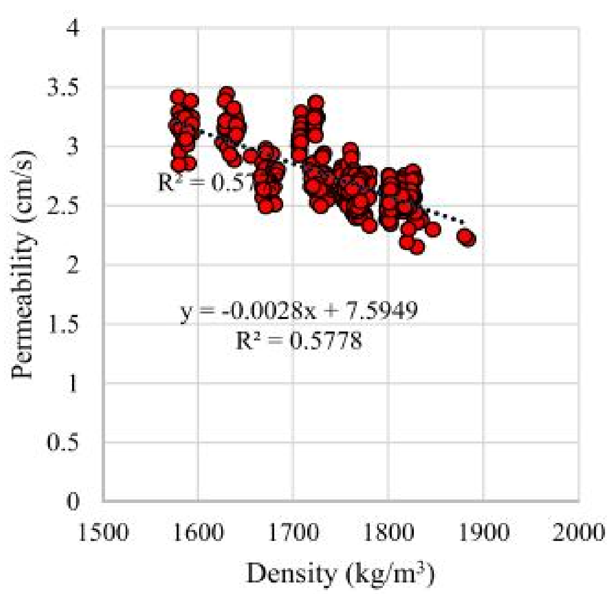

Figure 16. Relationship between permeability and soil density (Mehrabi et al., 2021)

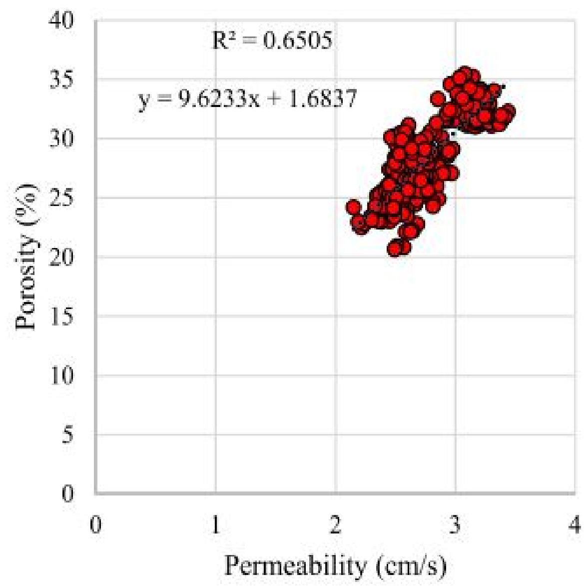

Figure 17. Relationship between porosity and permeability (Mehrabi et al., 2021)

Based on the results of evaluations, it has been found that the addition of 0.6% nanoclay significantly reduces the swelling and permeability of the liners. As a result, the improved soil examined can be used as a cover barrier at the landfill. These findings can also be generalized to landfills with similar conditions. Figs. 14 and 15 show the results of the study. Mehrabi et al. (2021) did about the effect of additive nanoclay on the strength and permeability of concrete. In this regard, amounts of 1% to 3% nanoclay were added to the concrete and measured the compressive strength, voids, density, permeability parameters. These experiments were performed on 7791 samples. The results showed an increase in strength and a decrease in permeability in the samples. According to research, additive nanoclays to concrete can be used as a practical solution to improve its strength and permeability. The results of the experiments can be seen in Figs. 16 and 17.

4. Conclusion

The landfill is the last thing that is done with comprehensive waste that cannot recycle and reuse. When some waste is accumulated, fermentation and biological degradation of waste causes the production of leachate. Formers are much environmental pollution, especially soils and underground waters. To prevent the release of leacers (the most important products in traditional urban waste depot), various industrial and scientific plans have been implemented; depending on environmental conditions, have different biomedical effects. Meanwhile, the use of geometrial, which is less important than artificial materials, is important. In recent years, the use of nanotechnology in improving the physical and mechanical conditions of the soils along with new engineering techniques is considered as one of the new approaches in geotechnical engineering and the use of nanomaterials such as nanoparticles due to environmental compatibility and functionality cheap and availability in focusing on this attention. However, the chemical properties of leachate and the impact of environmental conditions may cause liquid microscopes in the liner body and the release of leachate to the surroundings. For this purpose, the use of nanoparticles in combination with clay materials in addition to the creation of a natural dam in fluid influence; will increase the physical strength of the material. In this regard, in the present treatise, we have tried to investigate the functional role of using nanoparticles in order to reduce soil permeability and prevent the spread of leachate and its combination with nanofibers, in order to strengthen and prevent cracking of landfill lines.

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