Original Article: Compacted Kerman Clay Liner: Different Permeants and Different Additives

Majid Dousti*[1] | Alireza Firoozfar[2]

[1]*Department of Civil Engineering, University of Zanjan, Iran*
[2]*Assistant Professor, Department of Civil Engineering, University of Zanjan, Iran*

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ABSTRACT

This study investigated the feasibility of using Kerman collapsible clay excavated in an urban project as landfill liner material. Several technical requirements must be addressed for a material to be used as liners among which low hydraulic conductivity and high compressive strength are the most important. To achieve this goal, a set of laboratory tests were conducted on the prepared samples. Sample preparation was done and the soil was tested in pure form as well as in lime, bentonite and Nanoscale treated forms. Two different methods were used to determine the permeability of the specimens, falling head (with a direct method), and consolidation (with an indirect method). The results indicated that overall, the hydraulic conductivity obtained from the consolidation test was lower than those of falling head tests. The falling head method was conducted for all specimens using municipal and synthetic leachate instead of water. Samples with 0.4% Nano silica and 8% lime under municipal waste leachate met the EPA permeability requirements. The same procedure was carried out under the synthetic leachate. The results showed that only the specimen with 0.4% Nano silica met the EPA regulation standard. The unconfined compression strength values exhibited a considerable increase in addition of lime and Nano silica and a gradual decrease with adding bentonite. This study showed that Kerman clay can be used as a liner material when supplemented with lime and Nano silica.

Introduction

Landfilling with sanitary waste is a common practice worldwide. As landfilling is less costly, simple to construct and can accommodate a wide range of wastes in comparison to other waste handling options, it is anticipated that landfills will continue to serve as a major waste disposal option [16]. In general, potential migration of leachate through the soil and pollution of groundwater is a main environmental concern of landfills [15,28].

***Corresponding Author:** *Majid Dousti, (dousti.explore@alumni.znu.ac.ir)*

Among diverse types of liners, clay compacted liners (CCL) are characterized by low hydraulic conductivity, higher contamination adsorption capacity and lower cost [17,32]. This ideal property has made CCLs very common particularly in arid and semiarid regions where the clayey soil is abundant and groundwater level is relatively deep [31] According to EPA 1995, the hydraulic conductivity (K) of materials used in the liners is restricted to 1e-9 m/s or less. However, most of the recommended criteria are not met by the available soil types. In this context, natural and artificial materials are used to improve the properties of the soil. To this aim, a wide range of studies have been done over the past decades examining various different materials such as lime, cement, bentonite, fly ash, and Nanomaterials [8,13,21, 24,19]. The effect of lime on soil properties is widely studied. Significant improvement in soil properties, such as reduction of plasticity and increase in unconfined compressive strength is observed by the addition of different percentages of lime [1,9,10] Previous studies on soil lime stabilization show that the reaction types of the lime with soil can be categorized as short- and long-term ones. Short-term reactions (modifications) consist of cation exchange and flocculation which occur fast in the soil causing a rapid increase in soil PH levels. As cation exchange proceeds, the plasticity of the clay decreases. By reducing the plasticity of the soil, the workability of the soil increases [9,25]. Long-term reactions (stabilization) consist of pozzolanic and carbonation reactions, which are slow and controlled mainly by time, temperature and moisture factors. During the pozzolanic reactions, calcium aluminate and calcium silicate gels are produced. These gels change the physicochemical properties of the clay mineral surfaces and facilitate the development of new minerals through pozzolanic reactions responsible for the formation of the cementing agents. These agents gradually cause an enhancement in strength and durability of the mixture. Carbonation reaction is a disruptive reaction that reduces the free ion content in the mixture for the cation exchange and pozzolanic reaction [10]. There is no global agreement on the influence of the lime on soil permeability. In some studies, using falling head method show that by the addition of lime, the hydraulic conductivity of the soil samples increases [7,30]. On the other hand, other studies report that the addition of lime decreases the hydraulic conductivity [2]. There is a third group of researchers who believe that hydraulic conductivity increases with the addition of lime until a specified percentage is reached and then a reverse trend is observed [10,23]. Sodium bentonite (abbreviated as bent), as another alternative for improving mechanical properties of the on-site soil, is used for the construction of compacted soil liners. This material has a large specific surface area and high cation exchange capacity allowing contaminants like heavy metals to be immobilized through adsorption [27]. Bentonite has been severally explored as an additive for reducing the hydraulic conductivity (K) of the mixtures [3,18,29]. It is reported that in some cases, the Atterberg limits and unconfined compression strength of the soil are enhanced linearly by the addition of bentonite [26,35]. The addition of nanoparticles, which are not cementitious material, enhances the mechanical behavior of the soil by reducing the interparticle voids and further Nano-reinforces it [8]. Iranpour (2016) investigated the effect of different nanomaterials on stabilization of collapsible soil and showed that nanomaterials decreased the collapsibility of the soil significantly. The influence of nanosilica on the permeability of the soil stabilized with cement was investigated using falling head method. The addition of nanosilica was found to advantageously decrease the hydraulic conductivity of the mixture [5]. The permeability of the CCL layers is investigated by consolidation test as an indirect method constructed by pure and amended clay with micro silica in confronting municipal leachate. Research has shown that an order of magnitude decrease in the permeability of the mixture in comparison with the pure clay [37]. Shariatmadari *et al.* (2011) studied the effect of three different inorganic salt solutions on the permeability as synthetic leachate (consolidation method) of two types of clay-bentonite mixtures and reported an increase in the hydraulic conductivity in comparison to tap water.

The main aim of this study was to investigate the permeability of the Kerman pure and amended clay by three different additives usable as liner layer in confronting water, fresh municipal leachate, and synthetic leachate by falling head method for evaluating the permeability of the soil. While some researches have studied the soil permeability by falling head or consolidation as direct and indirect methods, respectively, a comparative study of the performance of these two methods has not been not addressed properly in literature. In this paper, first, the differences between these two methods were investigated. Next, for defining the impact of these additives on the other soil properties, a set of laboratory tests such as, Atterberg limit test, standard proctor test, and unconfined compression strength test were conducted. Finally, the results showing the effect of different additives on several engineering characteristics of compacted clay liners were presented.

Materials

Soil

Soil samples were collected from urban projects in Kerman city, Iran. These excavated soils are potential resources for construction of liner layer. Kerman is located in the south-central part of Iran in a semi-arid region. Geologically, most parts of Kerman plain and the city of Kerman are covered by Alluvial and Aeolian sediments located in the north-west Kerman province (Fig.1) [22]. To determine the physical properties of the soil such as, particle size, Atterberg limits, optimum water content, and maximum dry unit weight, a variety of tests were conducted according to ASTM standards (ASTM, D421; D422; D4318; D2487; D854). Since more than 90% of the soil passed the sieve no.200, grain size distribution curve of the soil was obtained in accordance with ASTM D422 (Fig. 2). According to unified soil classification system (USCM), this soil is categorized in the soil group as low plasticity clay (CL). Physical and chemical properties of the soil are shown in Table.1 and Table.2.

Figure 1. Kerman Province and Kerman city

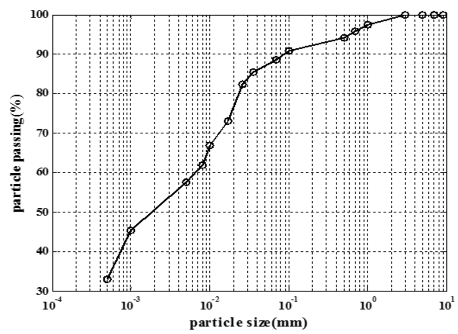

Figure 2. Particle size distribution of the Kerman clay

Table 1. Physical characteristics of the soil used in the tests

Characteristics	Value and Description
Density(gr/cm³)	1.74
Liquid Limit (%)	33
Plastic Limit (%)	21
Clay content (%)	32
Passing no. 200 sieve (%)	90
Specific gravity(G_s)	2.77
Unified classification system	CL

Table 2. Chemical compositions of the soil and bentonite used in the tests

Characteristics	Soil (%)	Bentonite (%)
SiO_2	45.01	55.35
CaO	13.62	1.09
Al_2O_3	11.95	14.07
Fe_2O_3	4.91	2.79
MgO	3.93	3.86
K_2O	2.49	0.21
Other	18.09	15.2

Lime

The hydrated lime used for this project is a product of Lorestan Lime Company. It is a high-quality lime that passes through an 80 (μm) sieve opening with 56.7% of $Ca(OH)$.

Bentonite

Sodium bentonite from Arak Poodr factory is used as another additive in this study. The chemical properties of the bentonite and its physical analysis are shown in Table 2 and Table 3, respectively.

Table 3. Physical characteristics of bentonite

Characteristics	Value and Description
Water absorption (%)	100-110
Absorption of montmorillonite (%)	>75
Liquid limit (%)	230
Plastic limit (%)	110
PH	9
Percent finer than No. 200	99.08

Nano-silica

Silica nanoparticle are purchased from Pasargad Novin Company. The main properties of the Nanosilica are discussed below:

Permeants

Three different kinds of liquids have been used in the experiments: Tap water as the reference liquid, and municipal and synthetic leachate as permeant liquids. Fresh municipal leachate is obtained from a municipal landfill. The chemical analysis results of the municipal leachate are shown in Table 4. The synthetic leachate was selected as it has a composition like the leachate collected form municipal landfill. Synthetic leachate was prepared weekly and the ingredients are shown in Table 4. Na^{+}, K^{+},Mg^{2+}, $Ca^{2+}$and SiO_4^{2-}usually constitute the major inorganic components of the most municipal solid waste leachate. Among these inorganic chemicals, K^{+}, Mg^{2+}, and,Ca^{2+} are the most important, hence, calcium ion is chosen as the chief ingredient of the synthetic leachate [4,33]. These three materials were hand mixed and then one liter of water was added. Next, this compound was mixed with distilled water in the mixer at a speed of 200 rpm for 10 minutes.

Table 4. Chemical analysis of municipal leachate used in the tests

Ingredient	Value and Description (mg/l)
BOD5	30400
COD	27225
Ca	5190
Na	3840
K	1930
S	711
Mg	276
Fe	208
Zn	121
P	103
Si	96.8
Mn	43
Sr	16.3
Ti	1.57
Cr	1.14

Experimental Method

Sample Preparation

To achieve a homogenous soil sample, dry soil and additives were mixed together, and then water was added to the mixture [36]. In this method, soil was air dried at the normal laboratory temperature. Then 3, 5 and 8 percent lime and bentonite were added to the soil with respect to the dry weight of soil and hand mixed to get the combination of soil and additives. The same procedure was followed for the addition of nanosilica. Specific surface area (SSA) is an important parameter in Nanomaterial's reaction with soil. At the nanoscale, a higher ratio of surface to volume causes intense interaction between particles and the solution. Therefore, a low amount of Nanoparticles can induce considerable enhancement to the engineering properties of soil [19,36].

Atterberg limit Test

To determine the influence of additives on liquid limit and plasticity index of the soil, Atterberg limit test was conducted in accordance with ASTM D 4318.

Compaction Test

The relation between water content and dry unit weight of the natural and mixed soil was studied in accordance with the standard test (ASTM D698).

Permeability Test

Consolidation

All the samples were compacted at optimum moisture content and at the maximum standard proctor dry unit weight. Consolidation study was based on the Terzaghi theory of consolidation and the oedometer test was used (ASTM D2435). During consolidation test and with each pressure unit increment, the thickness of the sample decreased. The losses were measured by dial gauge reading. Additionally, the change in the void ratio related to the pressure increase was calculated. The coefficient of permeability was calculated using Eq.1.

(1) $$K(m/s) = \frac{C_v\, a_v\, \gamma_w}{1+e}$$

Where $C_V\left(cm^2/s\right)$is the coefficient of consolidation.

By using Casagrande log time method, C_V was calculated using Eq.2.

(2) $$C_V = \frac{T_{50} \times H_{50}^2}{t_{50}}$$

Where T_{50} is time factor at $U = 50\%$ which is 0.197, $H_{50}$is the height of drainage at $U = 50\%$ and t_{50} is the time at $U = 50\%$. Using the Eq. 3, the compressibility coefficient a_V was calculated as:

(3) $$a_V = \frac{e_0 - e}{\sigma - \sigma_0}$$

Falling Head Test

The falling-head method is suitable for fine-grained soils where (K) is expected to be less than $1e-7(m/s)$ or soil contains 90% or more particles passing the 0.075 (mm) sieve (no.200). Therefore, the falling-head method was selected in this study. The cylindrical compaction mold with an inner diameter of 101 (mm) and height of 131 (mm) was used to prepare the natural and treated soil samples. The effect of different amount of water content on compacted clay permeability was investigated, showing that the minimum permeability could be obtained in one percent wet of optimum moisture content. Therefore, all the samples were compacted at one percent wet than optimum moisture and at 95% of the maximum standard proctor dry unit weight. The permeameter stand consisted of a metal frame with water tank adjustable to a height of 2 (m). All the samples were saturated by water, municipal, and synthetic leachate to be similar to the real municipal solid waste (MSW) liner. To ensure the complete saturation of the tested specimen, after opening the inlet water valve on top of the cell, outflow was monitored to ensure a steady flow regime. Upon ensuring a continuous flow, the value of (K) was calculated as:

(4) $$K(m/s) = \frac{a}{A} \times \frac{L}{\Delta t} \times ln\left(\frac{h_1}{h_2}\right)$$

When $a(cm^2)$ is the cross-sectional area of the inlet water valve which is equal to 0.4 (cm^2), $A\ (cm^2)$ is the cross-sectional area of the specimen, $L(cm)$ is the height of the specimen, and Δt is the total amount of time which is needed to drop from the clearly marked graduation h_1 to h_2.

Unconfined Compression Test

Samples for unconfined compression experiments were prepared by pure and mixed additive treated soil compacted by standard proctor energy (ASTM D698). All the samples were prepared with fresh municipal leachate instead of tap water. One of the preferable ways of determining the compressive strength of the cohesive soils is an unconfined compression test. According to ASTM D2166, all the tests were conducted at the deformation rate of $K(mm/min)$. Cylindrical samples were prepared by pure soil and mixed soil with the height and diameter of 104 (mm) and 49.5 (mm), respectively.

Results and Discussion

Atterberg limits

The effect of lime and bentonite on the liquid limit (LL), plastic limit (PL) and the plasticity index are presented in Fig. 3. Plasticity index shows the range of moisture contents in which the soil remains plastic. As shown in Figure 3, with the addition of lime, while the liquid limit is gradually decreased, the plastic limit is slightly increased. Consequently, the plastic index (PI) showed a reduction with the addition of lime. By reducing the PI, the workability of the soil increases. The addition of lime releases Ca^{2+} to the pure water which boosts the concentration of electrolyte of the pure fluid which in turn decreases the thickness of the double layer water, slackening the rate of the LL. Through this process, the viscosity of the pure water increases that leads to a rise in inter-particle shear resistance, and the PL values increase [9]. A linear relationship between bentonite content and LL of the mixtures could be observed. Figure 3 depicts that the higher the bentonite content, the higher the PL and PI levels which is in agreement with the previous reports [18,25]. The effect of nanosilica on Atterberg limits is shown in Figure 3, presenting an experimental test on the mixed samples with different percentages of nanosilica which yield a slight increase in both liquid limit and plastic limit and consequently a slight increase of the PI of the mixture. This phenomenon is attributed to the amount of water surrounded by mixture particles. Consequently, the plasticity parameters of the soil will slightly increase which is in agreement with earlier reports [5,20].

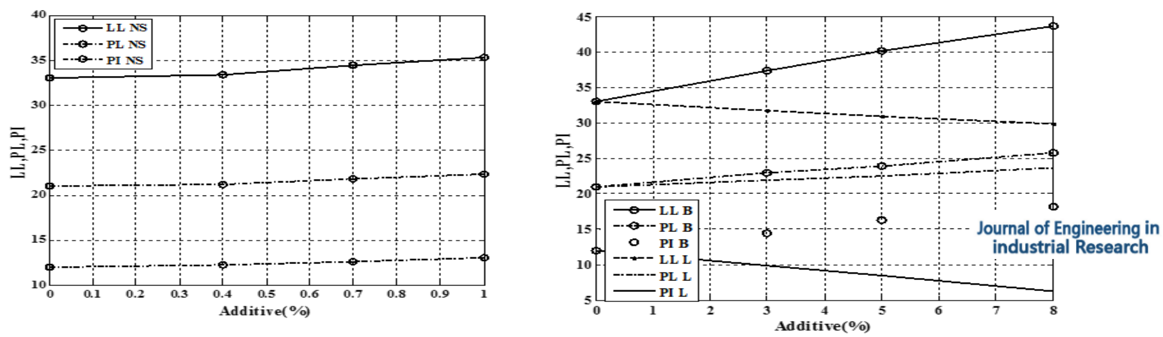

Figure 3. Effect of lime, bentonite, and Nanosilica on Atterberg limits

Compaction

Standard proctor tests are conducted on all the specimens. By the addition of lime to the soil, maximum dry unit weight decreases and the optimum moisture content increases. This trend is presented in Figures 4 and 5. Cation exchange and pozzolanic reactions occur after lime addition and changes in the soil structure by instigating flocculation. This reduction in dry unit weight is attributed to flocculation in the soil, which leads to resistance against compaction. Moreover, lime is lighter than soil and this, in turn, decreases the dry unit weight of the specimens. Soil-lime reactions and also compaction of the flocculated structure need more water; therefore, optimum moisture content is increased. The addition of bentonite to the soil decreases the dry unit weight and increases the optimum moisture content which are shown in Figures 4 and 5. This decrease is attributed to the gel formation around the soil particles as a product of swelling characteristic of bentonite and the increase in the effective size of the soil particles. This increment leads to an increase in void ratio and a subsequent dry unit weight decrease [12,26].

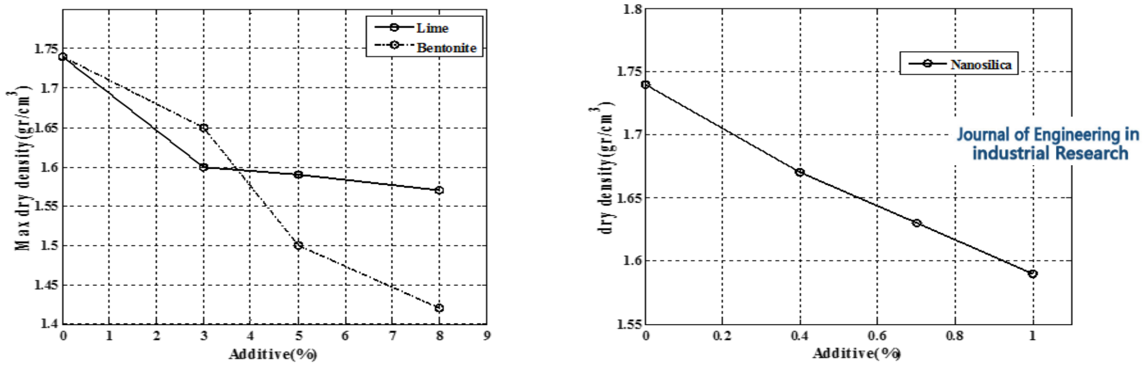

Figure 4. Effect of lime, bentonite, and Nanosilica on maximum dry density

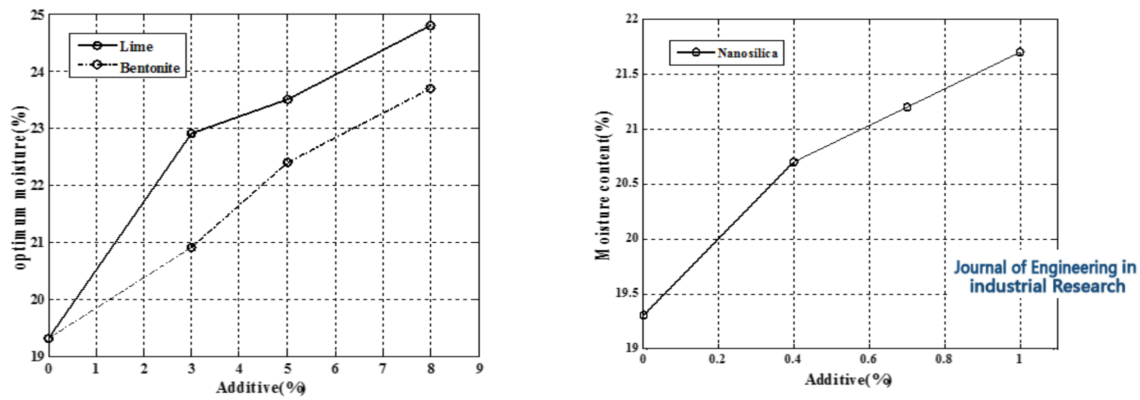

Figure 5. Effect of lime, bentonite, and Nanosilica on optimum moisture content

In a similar condition, the addition of nanosilica to the soil decreases the dry unit weight and increases optimum moisture content, as presented in Figures 4 and 5. This may cause an immediate formation of $C-S-H$ gel at the presence of nanosilica, which may reduce the compatibility, hence, decrease the maximum dry density of the mixture. Also, the addition of nanosilica improves the packing density of the particles, lowers the space between them, and raises the internal friction between solid particles [5].

Permeability Tests

The permeability of the pure and amended soil specimens were evaluated using direct (falling head) and indirect (consolidation) methods, respectively. The intention of compaction was to alter the soil structure from a flocculated structure to relatively dispersed one. When the soil was wet, the clods of the soil were remolded leading to a decrease in hydraulic conductivity. It should be noted that high moisture content tends to decrease the workability and compressibility of the sample, thus, an adjusted optimum amount of water content is very important. The specimens were prepared for falling head tests in a percent wet than optimum moisture content and 95% of maximum dry density. For consolidation tests, all the samples were prepared in optimum moisture content and maximum dry density.

Consolidation test method

All the consolidation tests were conducted using water in indirect method for permeability. In Figure 6, measured hydraulic conductivity (K) values are plotted versus void ratio for all pure and treated samples, indicating that the permeability is higher at higher void ratios simply due to the higher void amount in the particles and space to flow exit in the specimens. Also, it is shown that the sensibility of the permeability value of the pure soil to void ratio is distinctly high. With the gradual increase of lime and bentonite to the soil and in the presence of increasing vertical pressure, the sensitivity of the mixture's permeability to void ratio decreased. By adding 8% lime and bentonite, the sensitivity reached its lowest level. By adding only 0.4% nanosilica, on the other hand, the sensibility reached its lowest value and with further additions, the sensitivity gradually increased, as illustrated in Figure 7. It is apparent that the permeability of the specimens decreases with the drop of the void ratios. At higher void ratios, the permeability is higher due to larger void contents in the particles which are the path to flow exit in the samples. Also, sidewall leakage is possible when using rigid wall permeameter. However, in the presence of vertical loading in rigid-wall cells such as oedometer cells, leakage is typically considered to be minimized. Finally, an increase in the vertical stress also results in an increment in lateral stress that assists in maintaining contact between the soil and the walls of the cells [34].

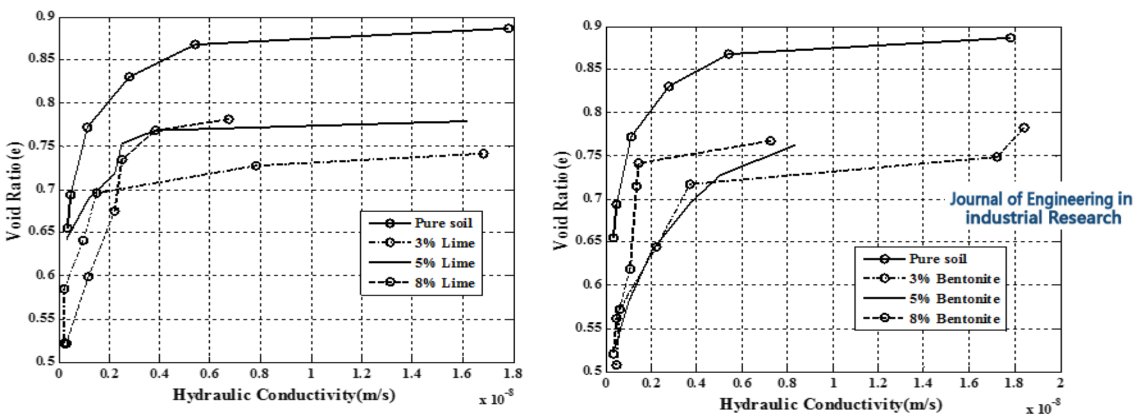

Figure 6. Measured hydraulic conductivity versus void ratio in the lime-soil and bentonite-soil mixtures

Falling head method

The initial hydraulic conductivity value (K) of the compacted untreated soil with water is $4.05e-8\ (m/s)$. The permeability of the lime, bentonite and nanosilica treated specimens are shown in Figure 7. According to this study, we can infer that the effect of lime on Kerman clay is more significant than that of bentonite. This is due to the higher cation exchange and pozzolanic reaction capacity of the lime with the soil, which plays a prominent role in the reduction of the permeability. Furthermore, the decrease in permeability by the addition of lime to the soil is attributed to pozzolanic reactions, dissolving alumina and silica. These released minerals react with calcium and hydroxyl ions to form cementitious gels. Consequently, the pore volume is reduced leading to lower void ratio. Less void ratio means lower permeability [6, 7]. Besides the swelling characteristics of bentonite, the potential of high-water absorption forms a gel to fill most of the pores. Additionally, fine particles of bentonite will be placed in the intergrain pores, thus, will reduce the pore volume. Accordingly, with the addition of more bentonite to soil, the permeability of the mixture decreases [18]. It seems that 8% lime and bentonite are the optimum amount of additives in decreasing hydraulic conductivity. The results of the hydraulic conductivity values K of the nanosilica mixtures are shown in Figure 8. These values decrease drastically with increasing nanosilica content. Nanosilica is known as a pozzolanic material. The reaction between CaO and Al_2O_3 in the soil and nanosilica creates CSH and $CSAH$ gels in the mixture that binds soil particles. By these reactions, the colloidal silica binds to the individual soil particles and also fills the pore spaces that decreases the permeability. It seems that the inclusion of nanosilica reduces the large pores and removes the smaller ones from the soil, which causes the formation of secondary CSH clusters in the mixtures. It also seems that the 0.4% nanosilica is the optimum amount of additive required for decreasing hydraulic conductivity. By adding higher than 0.4% nanosilica, extra water is absorbed and held by a mixture of the nanosilica and water, resulting in a higher conductivity of the specimen shown in the previous investigations [5,19]. In the presence of water, none of the specimens satisfies the EPA requirements. It is realized in this study that the optimum amount of additives in both falling head and consolidation methods are the same. Also, the results of the test with water show that the permeability of the specimens in consolidation method is lower than the falling head, which is compatible with the previous studies [37]. This difference is attributed to the preliminary conditions of the specimens. In consolidation test, all the samples are prepared in optimum moisture content and maximum dry density but specimens in falling head method are prepared in a percent wetter than optimum moisture content and 95% maximum dry density. Additionally, increasing the vertical loading in consolidation test decreases the voids in the specimens, which leads to a lower permeability. Consequently, falling head method is chosen for the rest of the permeability tests with municipal and synthetic leachate.

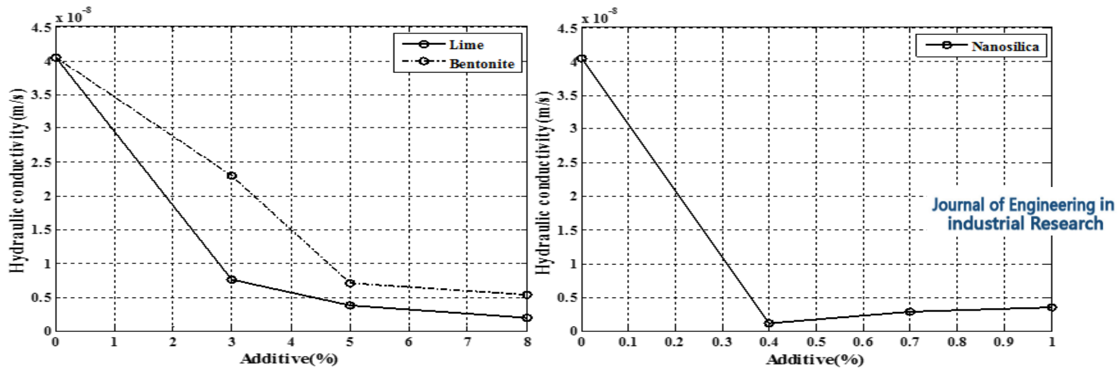

Figure 7. The effect of lime, bentonite, and Nanosilica on permeability of the Kerman clay in the presence of water

Effect of additives on permeability tests with fresh municipal leachate

The initial value of hydraulic conductivity (K) of the compacted untreated soil equals to $1.27e-8$ ($^{m}/_{s}$). The permeability of the lime and bentonite treated specimens are shown in Figure 8. In addition to all aforementioned discussions about the reactions of lime, bentonite, and soil, the effect of fresh municipal leachate is also critical on the decrease of the hydraulic conductivity in the compacted mixtures. With the increase in the concentration of leachate, the permeability of the samples decreases. This phenomenon is attributed to: a) Chemical reaction between leachate and the soil clogging the effective pores in the mixtures, b) using the confining pressure of the leachate, the voids in the specimens decrease and, in some cases, diminish, and c) the chemical contents, suspended solids, and microorganisms in the fresh leachate are absorbed by the soil surface, leading to the blocking of interconnected pores in the samples. Furthermore, the microbial metabolism of the leachate produces materials which decrease the porosity of the mixtures leading to a lower hydraulic conductivity [14,28]. The hydraulic conductivity also highly depends on the chemistry of the solution or the permeant. Dispersion of positively charged (PH 3) and negatively charged (PH 11) soil nanoparticles with variable surface charges lead to the disruption of soil aggregates and the subsequent clogging of the soil pores reducing the permeability [4]. It is important to note that specimens amended with 8% lime and 0.4% nanosilica in presence of fresh municipal leachate meet the minimum amount criterion in the EPA regulations but this is not the case for the bentonite amended specimens.

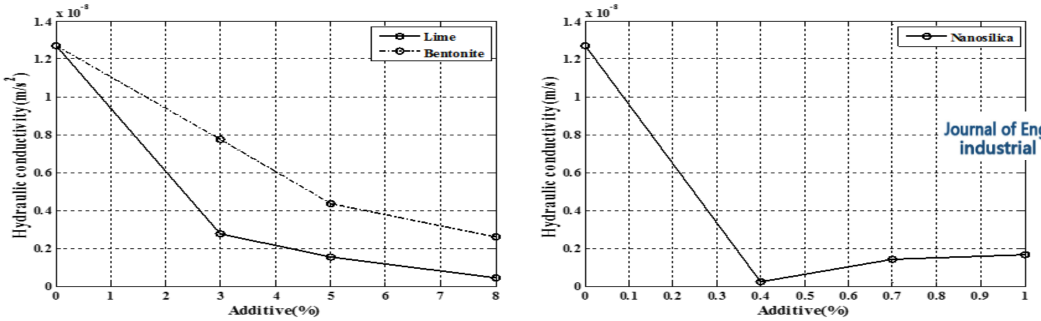

Figure 8. The effect of lime, bentonite and Nanosilica on permeability of the Kerman clay in the presence of municipal leachate

Effect of additives on permeability tests with synthetic leachate

The initial hydraulic conductivity value (K) of the compacted untreated soil with synthetic leachate equals to $3.24e-8\ (m/_s)$. The permeability values of lime, bentonite and nanosilica treated specimens are shown in Figure 9. As mentioned before, the same process takes place with these three additives but changing process is milder. It seems that in both synthetic and municipal leachate, lime and nanosilica are more suitable additive than bentonite for clay liner. In addition to all aforementioned reasoning about the effect of additives on the permeability of the mixtures, the effect of synthetic leachates that are intentionally enriched with Calcium Nitrate ($5000\ ^{mg}/_l$), Sodium Nitrate and Potassium Nitrate ($1000\ ^{mg}/_l$), causing a slight increase in hydraulic conductivity of the specimens in comparison to fresh leachate. This phenomenon is attributed to a double layer contraction and an increase in pore space, resulted from adsorption of divalent cations. The differences in hydraulic conductivity of samples with fresh municipal and synthetic leachate are attributed to the lack of suspended solids and bacterial concentrations in synthetic leachate [4, 33]. It is important to note that in the presence of synthetic leachate, only specimens with 0.4% Nanosilica meet the EPA requirements.

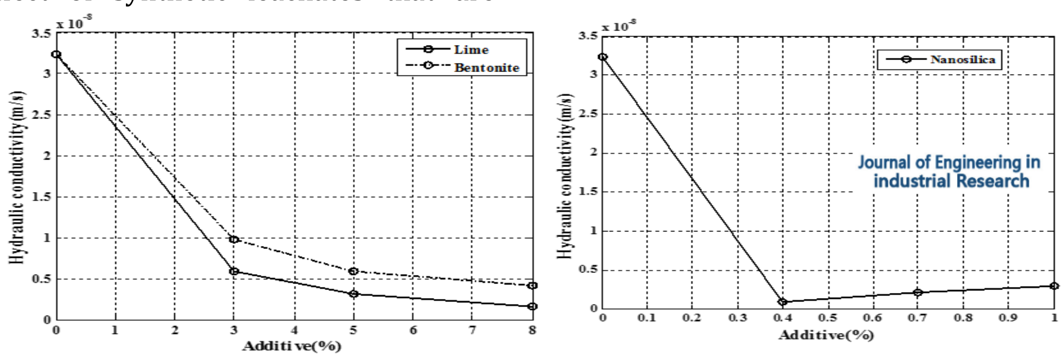

Figure 9. The effect of lime, bentonite, and Nanosilica on permeability of the Kerman clay in the presence of synthetic leachate

The difference in the (K) values in the presence of water in comparison to municipal and synthetic leachate is significant. This increment is attributed to the lack of chemical reactions between soil and leachate, and the suspended solids and bacteria. In the presence of water, none of the specimens satisfies the EPA requirements. In Figure 10, the comparison between EPA minimum requirements and the specimens with the optimum percent of additives under fresh municipal leachate, synthetic leachate and water are presented. It illustrates that specimens amended with 0.4% nanosilica, which are saturated with fresh municipal and synthetic leachate and specimens with 8% lime saturated with fresh municipal leachate, satisfy EPA requirement.

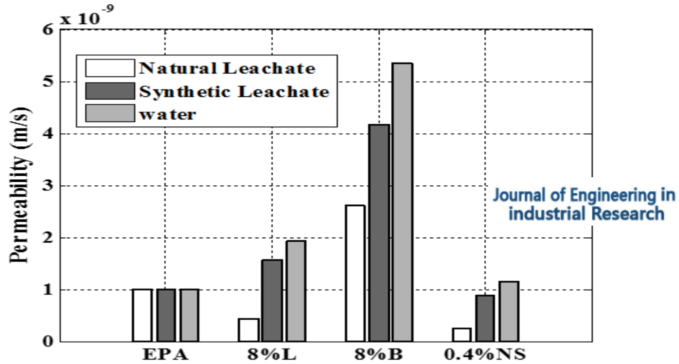

Figure 10. Hydraulic conductivity values by falling head method compared with US regulation (EPA)

The effect of three different additives on the structure of the soil is investigated using the Scanning Electron Microscope (SEM) observation. The SEM observation of the pure soil, as presented in Figure 11, shows conspicuous pores that are the pathways for the fluid. In other words, these pores are the reasons of high permeability of the soil.

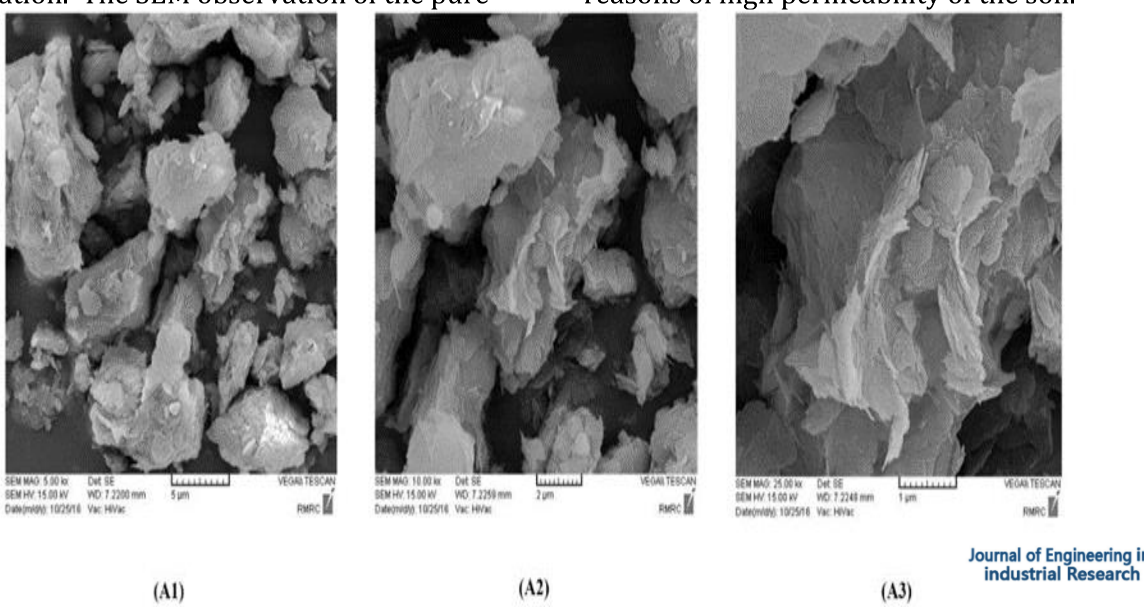

Figure 11. Microstructure observation of pure soil sample at different magnification (A1-A2-A3)

The comparison Figures 11 shows that the porous structure of soil is filled in by flocculation and cation exchange reactions between lime and soil, which visibly decrease the permeability of the specimen. The effect of 8% bentonite on pure soil structure can be observed. It is obvious that although both of bentonite and lime decrease the permeability of the soil, lime creates a more homogenous microstructure, which is more useful in reducing the permeability of the soil.

As it is shown, the effect of 0.4% nano silica on soil structure is so impressive. The inter-particle pores (Fig. 12 (A1-A2-A3)) are filled with CSH gel which is created in the reaction between nano silica and soil. Thus, the permeability of the mixture is decreased. In general, the lime and nano silica are better additives to decrease the permeability of the soil to achieve the minimum permeability stated in EPA.

Effect of additives on unconfined compressive strength test

Unconfined compression strength (UCS) tests are conducted on pure soil and soil additive mixtures with different percentage of lime, bentonite, and nanosilica. All of the specimens are compacted with a water content more optimum moisture content and with fresh municipal leachate as permeant. Lime amended mixtures are cured for 18 days at constant laboratory temperature. The results of unconfined compression strength test on lime-soil mixtures are shown in Figure 11.

The results of unconfined compression strength test on lime-soil mixtures are shown in Figure 11. The study conducted on Kerman clay by Firoozfar and Khosroshiri (2016), using the same tests with water, shows that the brittleness of the mixtures decreases slightly, and in the current study, the unconfined strength values of the lime-treated mixtures increases mildly. However, the cracking problem is not solved and it should be considered in the design of the liners with lime-amended soil. A remarkable rise in the compression strength of the mixtures is achieved by the addition of the lime. The increase in compression strength may occur due to two factors: The highly time dependent pozzolanic reactions which flocculate the soil particles and cause interparticle bonding leading to higher compression values; and the municipal leachate which decreases the void ratio and blocks the interconnected pores in the samples along with the reactions of the lime, leading to an increase in the unconfined compression test. The results of the experimental tests on the bentonite soil specimens are shown in Figure 11, showing a significant decrease in the compression strength and an expansion in the strain rate compared with the lime-amended specimens. This phenomenon is attributed to the increase of plasticity of the mixture by the addition of a different bentonite percentage to the soil which changes the soil behavior to a ductile one. Also, the results of unconfined compression strength tests with fresh municipal leachate shows a minor increase in both compression and strain rate when compared with water, which can be attributed to the impact of fresh leachate on the soil structure. The unconfined compression strength tests are conducted on the soils amended with nano silica. The results are shown in Figure 11. The nano silica is a very effective additive for enhancing the strength of the specimens. With the addition of 0.4% nano silica, the compressive strength of the stabilized mixture is 68% higher than untreated soil. The influences of the municipal leachate and nano silica in decreasing the void ratio and the impact of Nano silica in strengthening the bonding between grains via the pozzolanic reactions is believed to be the major cause of the increase in the unconfined compressive strength. However, further addition of nano silica particles to the soil has an adverse effect on unconfined compressive strength, which is shown in the previous study by Bahmani *et al*. (2014).

Conclusion

This study explores the feasibility of using Kerman clay as a liner layer material in landfills. Thorough sets of experiments with water, fresh municipal leachate, and synthetic leachate are conducted and based on the results obtained the following conclusions are made:

a) The optimum moisture content values are increased by the addition of lime, bentonite and nano silica significantly, and the maximum dry density is reduced;

b) The results drawn from consolidation and falling head permeability tests show that the optimum amount of lime and bentonite are 8% and for nano silica 0.4%. In the presence of water, none of the specimens meets the minimum requirement of the EPA;

c) The results of falling head tests conducted with fresh municipal leachate show that the specimens with 8% of lime and 0.4% nano silica met the EPA requirements. Results from same tests with synthetic leachate indicate that only the samples amended with 0.4% nano silica reach the mentioned regulation minima. It can be concluded that lime and nano silica are the favorable additives for Kerman clay as a municipal liner layer; and

d) The addition of lime with 18 days of curing and nano silica with 2 days of curing increases the UCS of the soil significantly so that the strength is increased 3-fold. However, soil-bentonite mixtures experience a flexible behavior regarding the decreasing strength with increasing bentonite content. Furthermore, the highest amount of UCS is achieved in 8% lime and 0.4% nano silica content.

Orcid:

Majid Dousti:

https://www.orcid.org/0000-0001-0000-0000

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