

Effect of inorganic salt solutions on some geotechnical properties of soil-bentonite mixtures as barriers

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Abstract

The main task in the design and construction of impermeable liners in landfills is to block the migration of pollutants to the groundwater systems or to reduce its rate to a reasonable amount. That is why environmental regulations force governments to construct engineered waste dumps for waste management purposes. These liners are exposed to various types of chemical, biological, and physical processes and are affected by the leachate which is produced from decomposition of waste materials accompanying methane gas. The leachate includes a lot of components such as water and different types of salts. For this reason, the geotechnical characteristics of clay liners which are evaluated in laboratories using distilled water or tap water might be far different from the representative sample of the in-situ conditions. There are some evidences regarding the effect of these salts on the physical and mechanical properties of clay barriers which could affect the long-term performance of these liners. Since the main criterion for impermeable bottom liners in landfills is their hydraulic conductivity, the increase of this parameter could have a considerable environmental impact. This paper embraces the results of a recent study on the effect of three inorganic salts, NaCl, CaCl₂ and MgCl₂ on some geotechnical properties of a common used clay soil in impermeable bottom barrier in Kahrizak landfill, the main waste disposal center of the Tehran Metropolitan. Also the effect of bentonite content by adding different percentage of this special clay mineral, 10 and 20 percent, on these properties was investigated. Laboratory tests like liquid limit, compaction, 1D consolidation and free swell tests were performed for this purpose. Results indicated that all of these salts could have a considerable effect on the geotechnical properties of the mixtures. The main reason of such effects is the changes which occur in diffuse double layer of clay particles.

Keywords: Landfill liners, Inorganic salts, Swelling and consolidation, Hydraulic conductivity, Liquid limit, Compaction characteristics

1. Introduction

Design and construction of sanitary waste dump sites has become one of the most important responsibilities of the governments all over the world.

In sanitary landfills Geosynthetic clay liners (GCLs) and compacted clay liners (CCLs) are the most common materials in construction of impermeable liners. The main reason in using such materials is their low hydraulic conductivity which limits or eliminates the movement of not only the leachate from bottom of landfills but also the generated gases from the final cap of waste dumps.

However, a mixture of locally available soil mainly cohesive fine grain soils like clays and bentonite may be used as landfill

liners. The main mineral in bentonite is montmorillonite which has a large specific surface. This mineral has a large net negative charge which results in adsorption of a large number of hydrated cations as well as adsorption of water molecules, and interlayer separation during hydration [1,2]. The absorbed water molecules and cations may take up a large fraction of the pore space [2-4]; therefore there is a relatively small portion of pore space which is occupied by bulk water [4], which leads to a low hydraulic conductivity of montmorillonite ($\leq 10^{-8}$ cm/s). Bentonite also increases the plasticity index of clay soils [5].

Design guidelines have a framework regarding the geotechnical properties of materials used as barriers in landfills. Such materials should be chosen according to these criteria; thus their geotechnical properties and compatibility with design framework must be evaluated prior to the construction stage. Atterberg limit tests, compaction tests and hydraulic conductivity tests are among tests executed using distilled or tap water. However since liners are exposed to various chemical, biological, and physical processes due to

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leachate production and other chemical compound generation during the biodegradation process, their in-situ geotechnical properties might be different from the ones estimated in laboratories.

It is shown that the Atterberg limits could be used as a representative parameter to estimate clay behavior. Also this factor could be correlated with various engineering properties such as permeability, shrinking and swelling behavior, shear strength, and compressibility of the soil [6-9].

In addition, the evaluation of the consistency limits provides some very basic mechanical data about the soil and also gives a first insight into the chemical reactivity of clays [9]. Basically, the liquid limit and the plasticity index are highly and mainly influenced by the ability of clay minerals to interact with liquids [10], and the hydraulic conductivity tends to decrease when the liquid limit and the plasticity index are increased [11,12].

In recent years, many researches have been focused on the interaction of clay soils and different types of fluids. Hydraulic conductivity is one of the important basic soil characteristics. For barrier soils, the hydraulic conductivity typically required is less than or equal to 10^{-7} cm/s [13]. It is shown that fluids have various effects on geotechnical properties of clays. Mesri and Olson [4], reported that presence of calcium cations in the fluids passing through montmorillonite minerals increases the hydraulic conductivity up to 28 times. Yong et al. [14] concluded that increasing the concentration of salts specifically NaCl, leads to an increase in permeability in a natural soil due to decrease in inter-particle repulsion among negative charged plates.

Gleason et al. [15] showed that water adsorption behavior in two different kinds of bentonite, namely Na-bentonite and Ca-bentonite, when permeated with CaCl_2 in high concentration, was not very much different, due to the high concentration of the electrolyte. Stern and Shackelford [16] concluded that the permeability of sand-bentonite mixtures increases up to 20 times in the case of using 0.5M CaCl_2 solutions. Alawaji [11] evaluated the effect of NaNO_3 and $\text{Ca}(\text{NO}_3)_2$ in four concentrations of 0.1, 0.5, 1 and 4 N on mixtures of sand and 20% bentonite. The results indicated that presence of these salts decreases Atterberg limits of the mixtures considerably. The liquid limit and plasticity index decreased with increase of salt concentration, which reached their minimum value in the concentration of 1N.

Shackelford et al. [17] studied the hydraulic conductivity of GCLs permeated with non-standard liquids such as NaCl, ZnCl_2 , and CaCl_2 stating that an increase in free swell of bentonite causes the hydraulic conductivity to decrease. Jo et al. [18] investigated hydraulic conductivity and swelling of GCLs permeated with single-species salt solutions such as LiCl, NaCl, KCl, CaCl_2 , MgCl_2 , ZnCl_2 , CuCl_2 , and LaCl_3 and confirmed Shackelford et al. [17] findings as Shan and Lai [19] did.

Schmitz and Van Paassen [20] investigated that salt solutions have a more pronounced effect on clays with higher smectite content.

Jo et al. [21] conducted experimental tests to investigate the long-term hydraulic conductivity of a "GCL" permeated with some inorganic salt solutions (i.e. NaCl, KCl, and CaCl_2). Results indicated that in the experiments conducted with 100

mM NaCl and KCl, the hydraulic conductivity increased twice as much in comparison with water.

Sivapullaiah and Manju [22] reported that the liquid limit of low plasticity soil ($w_L = 38\%$) exposed by NaOH solution increases with increasing NaOH concentration which is attributed to the forming of new swelling compounds.

Park et al. [23] studied the effects of electrolyte solutions (NaPO_3 and CaCl_2) on some properties of two soil samples (100% kaolinite clay soil and a mixture of 30% kaolinite + 70% sand). They found that CaCl_2 solution did not affect the liquid limit significantly but decreased the plasticity index of kaolinite soil.

Singh and Parasad [24] studied the effect of aluminum hydroxide and acetic acid which are commonly found in landfill leachate, in controlled conditions in the laboratory, on bentonite. It was shown that hydraulic conductivity decreased by 17% and 12%, and the cohesion of bentonite decreased by 50% and 43%, respectively. Also, the angle of internal friction was not affected by these solutions.

Roberts and Shimaoka [27] investigated the effect of NaCl and CaCl_2 solutions on the hydraulic conductivity of bentonite coated gravel as landfill liner. They showed that when using the proper amount of energy for the compaction of soil, the hydraulic conductivity is considerably low (6×10^{-10} cm/s).

Arasan and Yetimoglu [9] studied the effects of four different salt solutions, NH_4Cl , KCl, CuSO_4 and FeSO_4 on the consistency limits of two different types of clays with low and high plasticity. They concluded that the liquid limit of CL clay increases by increasing the salt concentration; however in the case of high plasticity clay, the liquid limit decreases by increasing the salt concentration. In the case of plastic limit, this factor increases in CL clays with increasing the salt concentration to a certain value; but for CH clays, this factor decreases at low salt concentrations and then increases at high salt concentrations. They found that, in the condition investigated, salt solutions at high concentrations could change the soil class of clays and, CL and CH class clays were transformed into low plasticity silt (ML) and high plasticity silt (MH) class soils, respectively, according to the Unified Soil Classification System (USCS).

Yilmaz et al. [26] evaluated the effect of five different inorganic salts, NaCl, NH_4Cl , KCl, CaCl_2 , and FeCl_3 solutions as permeant fluids on the hydraulic conductivity of two clay soils with different plasticity class, CL and CH. According to their findings the hydraulic conductivity of CH clays increases by increasing the salt concentrations whereas in the case of CL clays, increasing the salt concentrations leads to a decrease in the hydraulic conductivity.

The present study was undertaken to investigate the effect of some components found in the leachate collected from Kahrizak landfill, the main waste dump site of Tehran, the capital of Iran, on some geotechnical properties of clay-bentonite mixtures. Tests were carried out on a clay soil specimen. To evaluate the effect of plasticity, bentonite was added to the soil in the amount of 10 and 20 percent by weight. Three different salt solutions (i.e. Sodium Chloride (NaCl), Calcium chloride (CaCl_2), and Magnesium Chloride (MgCl_2) solutions) were chosen as leachate components in the tests. The tests were repeated at four different values of salt solution concentrations (i.e. 0.01, 0.1, 1 and 2 N).

Test results are compared with those in the literature and have been discussed in detail.

2. Materials and testing procedures

The materials used in this study were commercially available bentonite clay supplied by Iran Barit Falat Company and the typical clay which was collected from Varamin town located in the south of Tehran Metropolitan (referred as Varamin Clay, hereafter) which is used as barrier layers in Kahrizak Landfill.

The main specifications of this clay and bentonite have been represented in Table 1.

Figure 1 shows the grain size distribution of Varamin Clay. According to this graph the soil has 93% clay-silt content and 7% sand content.

A Zeimens diffractogram model D500 was employed for X-ray diffraction (XRD) test. Based on the XRD analysis, the main mineral in Varamin Clay is illite, followed by smectite and chlorite. Also for elemental analysis of this soil, X-ray fluorescence (XRF) was performed and the results are given in Table 2.

Deionized (DI) water as well as three salt solutions, NaCl, CaCl₂ and MgCl₂ has been used. The properties of these three salts are given in Table 3.

Soil mixtures with various bentonite contents were exposed to permeant fluids with various types of salts in different concentrations. Laboratory tests like standard compaction, free swell, liquid limit and 1D consolidation tests were performed. A brief description of each test is presented in the following sections:

Compaction test: In order to investigate the compaction characteristics, the standard Proctor compaction test was

Table 1. The main properties of mixtures components

Spec.	Varamin Clay	Bentonite
Specific Gravity	2.67	2.53
Liquid Limit (%)	34.2	199.4
Plasticity Index (%)	13.66	157.9
OMC(%) / MDD(gr/cm ³)	14 / 1.86	-

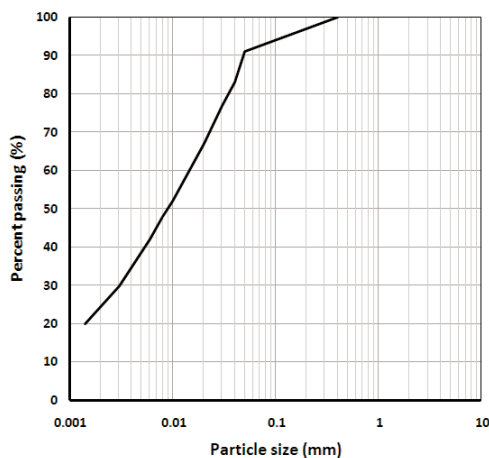


Fig. 1. Particle size distribution curve of Varamin Clay

Table 2. XRF analysis of Varamin Clay

Varamin Clay components	Percent (%)
SiO ₂	1.54
Fe ₂ O ₃	6.90
Fe ₃ O ₄	1.40
Al ₂ O ₃	15.20
MgO	3.20
CaO	1.15
Na ₂ O	1.03
K ₂ O	2.80
SO ₃	0.17
Cl	0.03
CaCO ₃	2.80
LOI*	11.1

* Loss of Ignition

Table 3. The main properties of employed salts

Salt	Chemical formula	Density (g/cm ³)*	Molecular weight (g/mol)
Sodium Chloride	NaCl	1.0387	58.44
Calcium Chloride	CaCl ₂	1.0423	110.99
Magnesium Chloride	MgCl ₂	1.0358	230.30

*given for 1N concentration at 20°C

performed according to ASTM D698 on Varamin Clay with 0, 10 and 20 percent of bentonite content. DI water and fluids which includes NaCl, CaCl₂ and MgCl₂ in 1N concentration were used.

Free swell test: The free swell of bentonite was evaluated according to ASTM D5890 using the proposed modifications by Roberts and Shimaoka [25]. First, samples were dried at 105±5°C; then approximately 40 grams of dried clay were added to 1800 ml of salt solution in a 2000 ml cylinder. Then bentonite was added in increments of 2 grams over a period of approximately 10 min. The samples were settled for 3 hrs until all 40 g of the bentonite was added. After adding the final increment of bentonite, the cylinder walls were washed with the salt solution and brought to the 2000 ml volume. Samples were kept undisturbed for 2 months in which after the changes in swelling were recorded. The pH of the samples was also measured at the beginning and end of the experiment.

Liquid limit test: The liquid limit test was conducted according to British standard BS1377:Part2:1990. The samples were prepared in two proportions of 100:10 and 100:20 (100 is the total weight and 10 and 20 are the weight of bentonite). The used pore fluids were DI water and NaCl, CaCl₂ and MgCl₂ solutions with various concentrations of 0.01, 0.1, 1 and 2 N. The soil mixtures were exposed to the salt solutions then placed in plastic bags to remain for at least 24 hours. After, the liquid limit tests were carried out on the samples. This test has been used by other investigators to determine the hydraulic conductivity of mixtures (for example Abdi et al. [27] used oedometer tests to determine the hydraulic conductivity of fiber reinforced soil samples).

Consolidation test: Consolidation test was carried out in accordance to ASTM D2435 to determine the hydraulic conductivity and compressibility characteristics of the

samples. This test has been used by other investigators to determine the hydraulic conductivity of mixtures (for example Abdi et al. [27] used oedometer tests to determine the hydraulic conductivity of fiber reinforced soil samples samples were performed in the standard oedometer. The consolidation ring had a diameter of 50 mm and thickness of 20 mm. Pore fluids were DI water and NaCl, CaCl₂ and MgCl₂ solutions in two concentrations of 0.1 N and 1 N. To minimize evaporation, the consolidation cell was enclosed within a plastic bag and was allowed to equilibrate for at least 24 hours before executing the test. The samples were initially loaded with a stress of 25 kPa, increasing by an increment ratio of 1 to a maximum stress of 400 kPa.

The hydraulic conductivity of the soil specimens was calculated by the following equation:

$$K = C_v m_v \gamma_w \quad (1)$$

where C_v is the coefficient of consolidation, m_v is the coefficient of volume change and γ_w is the unit weight of the pore fluid.

3. RESULTS AND DISCUSSION

3.1 Compaction Test

In Figure 2 (a) and 2 (b), the effect of bentonite content on the compaction characteristics of mixtures are illustrated. It could be clearly observed that by increasing the bentonite content in

the mixtures, the optimum water content increases while the dry unit weight decreases. The same trend could also be observed in cases where pore fluids included salts. Due to high activity of bentonite, the absorbed water surrounding the clay particles which has considerable volume, leads to an increase in the water content and decrease in the dry unit weight [28].

In Figure 2 (c) the results of Proctor tests on samples with 10% of bentonite which have been exposed to fluids including NaCl, CaCl₂ and MgCl₂ in concentration of 1N are depicted. As shown, adding these salts to DI water leads to an increase in dry density and decreases the optimum water content, although this effect is not much pronounced. In the case of salts with higher cation valence, the increase in the dry density and decrease in optimum water content is larger. The reason is by adding salt to the pore fluid, the thickness of diffuse double layer decreases, therefore using the same amount of compaction energy, the particles pack better together and the dry density increases [24]. The same trend has been illustrated in Figure 2 (d) which shows the results of proctor tests on the samples with 20% of bentonite exposed to fluids with different types of salts. In this set of results, the effect of salts on the level of maximum dry density is clear but the range of optimum water content variation is insignificant.

3.2. Free Swell test

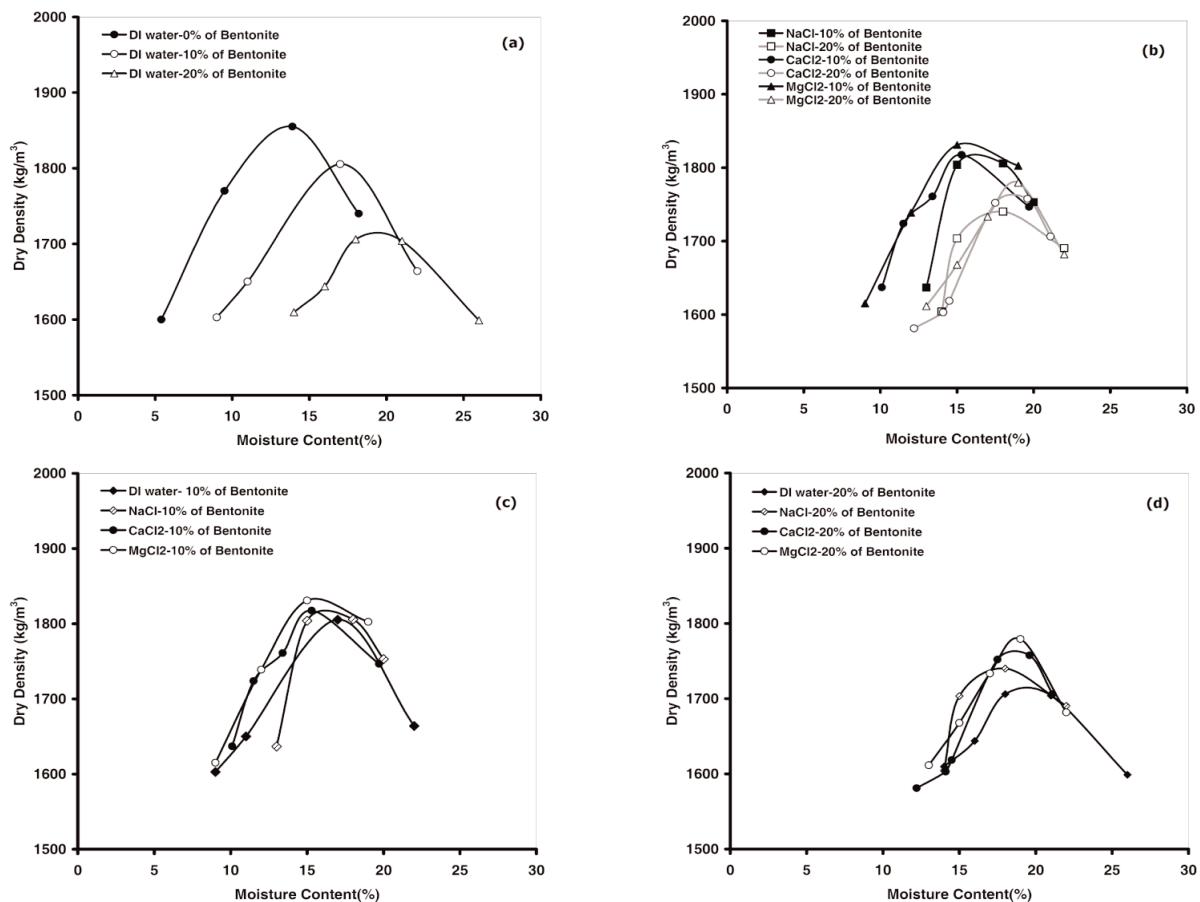


Fig. 2. The results of Proctor tests (a) effect of bentonite content (b) effect of bentonite content with different salt solutions (c) and (d) effect of cation valence on the maximum dry density and optimum water content

Figure 3 shows the results of free swell tests carried out on bentonite. NaCl, CaCl₂ and MgCl₂ in two concentrations of 0.1 and 1 N were used to evaluate the effect of solution type and its concentration on this parameter. As shown in this figure, when using DI water, swelling volume magnitude is the highest. By adding the salts to DI water, the level of swelling volume decreases. Increasing the salt concentration and cation valance also led to a decrease in swelling volume. Increasing the cations in the bulk solution, results in a gradient of free energy which forces water to leave the interlayer region [29].

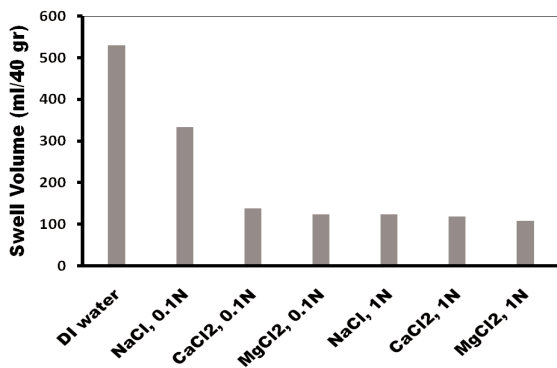


Fig. 3. The effect of various salt solution with different concentration on the swelling volume

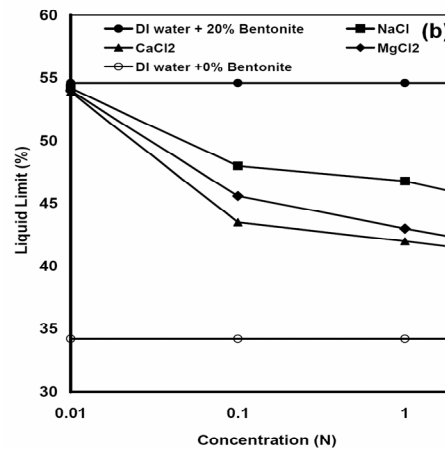
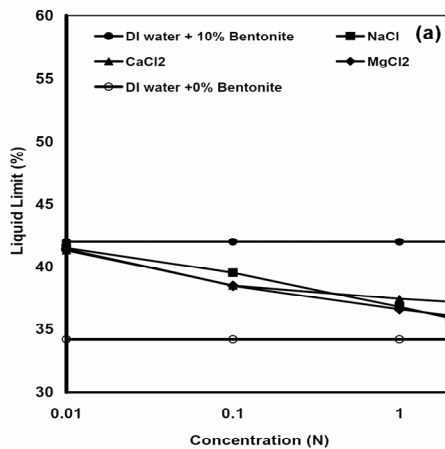


Fig. 4. The effect of different salt solution with different concentration on the liquid limit of mixture with (a) 10% of bentonite and (b) 20% of bentonite

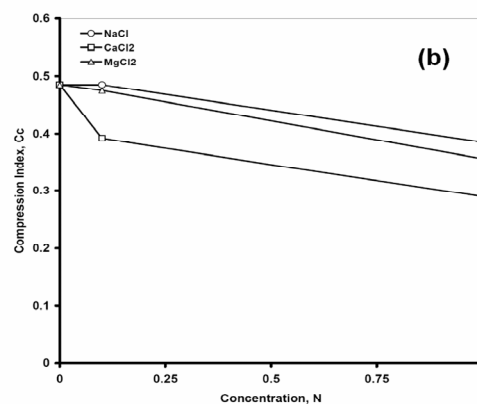
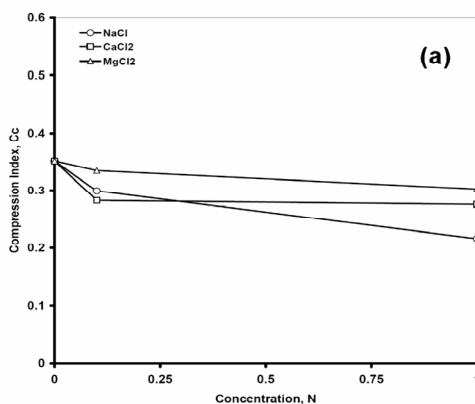


Fig. 5. The effect of various salt solution with different concentration on compression index of soil-bentonite mixture with (a) 10% of bentonite and (b) 20% of bentonite

The PH of the specimens during the tests showed that this factor is in the neutral range and did not have any effect on the swelling volume.

3.3. Liquid Limit test

The results of liquid limit tests are illustrated in Figure 4 (a) and 4 (b). The effect of bentonite content on the liquid limit is evident. Adding 10 and 20 percent of bentonite to the base clay soil leads to an increase in the LL, approximately 22 and 60 percent, respectively. The reason is the high activity of bentonite and its tendency to absorb water.

The results indicate that using salt solutions as pore fluids decreases the liquid limit of the mixtures. Furthermore by increasing salt concentration in both mixtures, the liquid limit decreases. Also it could be concluded that with increasing cation valance the decrease in the liquid limit will be higher especially in the case of mixtures with 20% bentonite. Increasing the salt concentration and the cation valance decreases the inter-particle repulsion which results in particles moving more freely in lower water contents, thus the liquid limit of the mixtures decreases [30].

3.4. Consolidation Tests

Figure 5(a) and 5(b) represent the results of consolidation tests on samples with different bentonite content which are prepared with different type of salt solutions, in the form of

variation of compression index, C_c , against salt concentrations. It is clear that the compression characteristic of samples is dependent on the type of cation and also salt concentration. By increasing the salt concentration, the C_c value decreases. The reason of such a tendency might be because of the reduction in diffuse double layer thickness due to employing salt solution in sample preparation [31]. It was also concluded that by increasing the bentonite content of mixtures, their compressibility increases.

In Figure 6 (a) to 6 (f) the variation of hydraulic conductivity,

resulting from consolidation tests, against the concentration of salt solution is presented.

As could be observed, the hydraulic conductivity of the samples increases by adding salt to the pore fluid and increasing its concentration. This finding is in agreement with most of other research results [17,21,26,29,32]. The reason of this trend could be attributed to the decrease in the thickness of diffuse double layer, resulting in flocculation of clay particles. Based on Quigley [33], clay mineral in contact with certain chemical might undergo large interlayer shrinkage. This event could be accompanied by

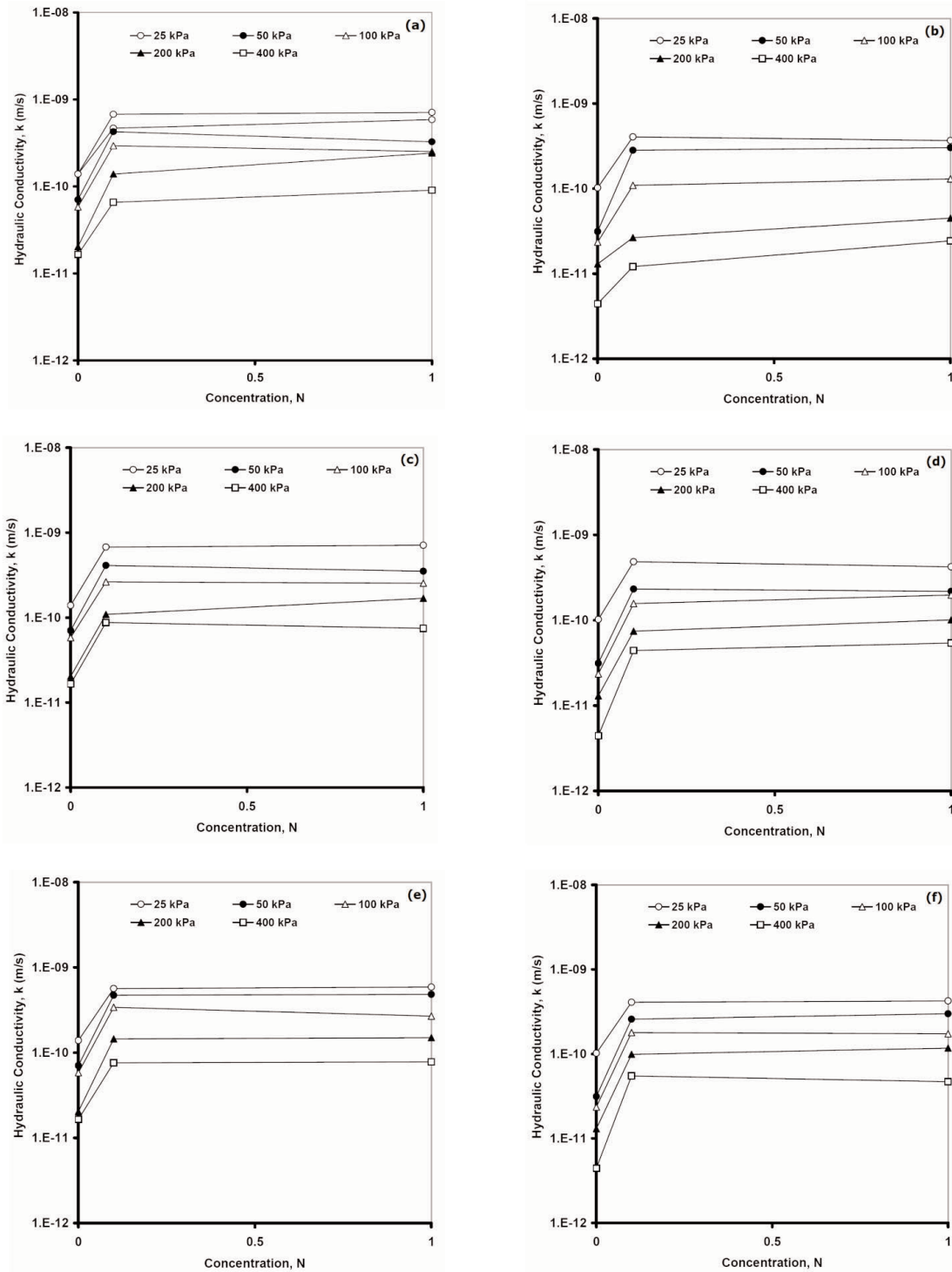


Fig. 6. The effect of the concentration of salt solution on the hydraulic conductivity of the mixtures (a) NaCl-10% of bentonite (b) NaCl-20% of bentonite (c) CaCl₂-10% of bentonite (d) CaCl₂-20% of bentonite (e) MgCl₂-10% of bentonite (f) MgCl₂-20% of bentonite

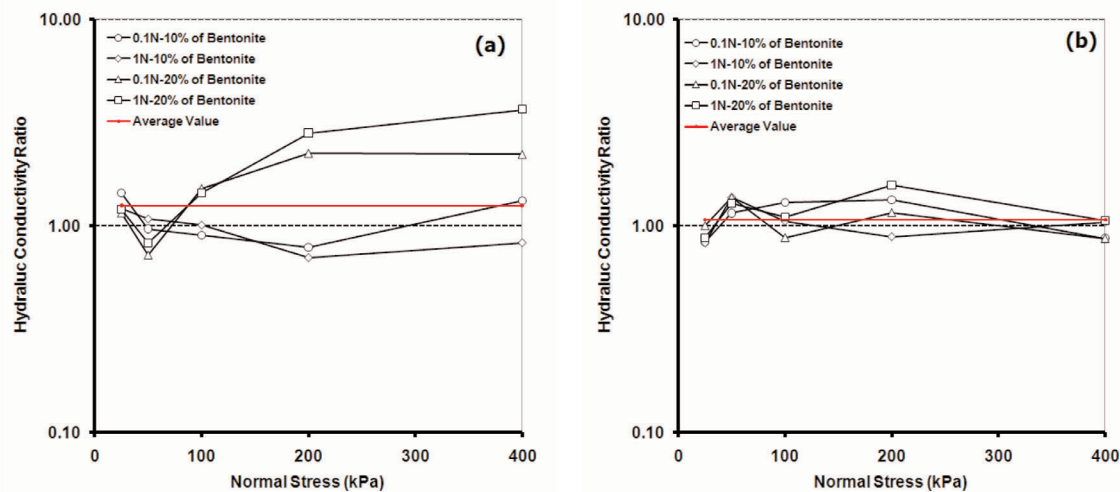


Fig. 7. The effect of cation valence on the hydraulic conductivity of mixtures (a) CaCl_2 to NaCl and (b) MgCl_2 to NaCl

considerable reduction in the thickness of diffuse double layer, potential cracking and increase in hydraulic conductivity values. Also according to the Gouy-Chapman theory by increasing the ion concentration, the thickness of diffuse double layer decreases which leads to flocculation of the clay particles, creating large pore channels which flow can occur [2,15,26].

During this study it was concluded that another factor that could affect the hydraulic conductivity of samples is cation valence. In Figure 7 the ratio of the hydraulic conductivity of CaCl_2 and MgCl_2 to NaCl against normal stress, in different conditions, is seen. According to these graphs the average increase in hydraulic conductivity caused by CaCl_2 salt solution is around 25% higher in comparison to the hydraulic conductivity caused by NaCl . In the case of MgCl_2 this value is around 7%. Based on Shackelford et al. [17] and Jo et al. [18], the effects of divalent and trivalent cations on bentonite are different from those of monovalent cations.

4. CONCLUSIONS

A study has been conducted to investigate the effect of three different inorganic salt solutions (as permeant liquids) on the compaction characteristics, liquid limit, free swelling, consolidation characteristics and hydraulic conductivity of two types of clay-bentonite mixtures. The three different inorganic salt solutions used were: sodium chloride (NaCl), calcium chloride (CaCl_2) and Magnesium chloride (MgCl_2). Bentonite clay in two proportions of 10% and 20% by weight were added to a clay soil with low plasticity.

In these tests, distilled water was used as the reference liquid and salt solutions (at four concentrations varying between 0.01 and 2 N) were used as permeant liquids.

The following conclusions, based on the test results in this study, are drawn.

1. Salt solution increases the maximum dry density and decrease the optimum water content of mixtures. Higher cation valence leads to higher increase in the maximum dry density and higher decrease in optimum water content as well. The decrease of the diffuse double layer's thickness is the source of this trend.

2. By increasing the salt concentration and cation valence the swelling volume decreases.

3. Using salt solutions as pore fluids decreases the liquid limit of the mixtures. Higher cation valence and salt concentration cause higher decrease in liquid limit.

4. It is illustrated that by increasing salt concentration, the compression index (C_c) decreases, however the effect of cation valence is not pronounced.

5. The hydraulic conductivity of the samples increases by adding the salt to the pore fluid and increasing its concentration. Increasing the cation valence also increases the hydraulic conductivity.

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