Geomechanics and Engineering, *Vol. 25, No. 3 (2021) 245-251*
DOI: https://doi.org/10.12989/gae.2021.25.3.245

Ageing effect on compressibility, permeability and shear strength of clayey soils exposed to salt solutions

Emel Çakar[1] and Yeliz Yukselen-Aksoy*[2]

[1]*Department of Civil Engineering, Celal Bayar University, Manisa, Turkey*
[2]*Department of Civil Engineering, Dokuz Eylul University, Izmir, Turkey*

(Received March 1, 2019, Revised April 19, 2021, Accepted April 26, 2021)

Abstract. The present study investigated the ageing effect on compressibility, permeability and shear strength behavior of kaolin and bentonite samples in the presence of NaCl and $CaCl_2$ solutions. The compressibility, permeability and shear strength parameters were determined on the 60, 190, and 250 days cured samples. The results have shown that, the kaolin sample becomes more compressible in the presence Ca^{2+} ions with ageing. Generally, the normalized compression index values of bentonite samples increased at the end of 60 days and 250 days curing time periods. The normalized permeability value of kaolin decreased by ageing in the presence of Na^{+} ions almost twofold. The permeability values of bentonite increased both in NaCl and $CaCl_2$ solutions during ageing. In the presence of Na^{+} ions kaolin had higher max. shear stress value than Ca^{2+} ions. When the max. shear stress values of 0, 60 and 190 days samples were compared, it was seen that NaCl solution had no significant effect on the shear strength of kaolin sample. However, the shear strength of kaolin increased in the $CaCl_2$ solution during ageing. In the presence of Ca^{2+} ions the max. shear stress value of bentonite was higher. The results of this study have shown that ageing has significant effects on the compressibility, permeability and shear strength of kaolinitic and bentonitic clayey soils.

Keywords: ageing effect; salt solutions; kaolin; bentonite; compressibility; shear strength

1. Introduction

Clay liners are effective barrier materials for bottom liners and cover systems at waste containment facilities. Clay liners must perform long-term stability, deformability, and impermeability. However, there may be some physico-chemical changes on the engineering characteristics of landfill liners (composed of natural clayey soils, geomembranes or composite material) with the effect of contaminated leakage water, temperature or pressure with time. The results of previous studies have shown that ageing has some effects on the crystalinity, compressibility-swelling behavior, shear strength and permeability characteristics of soils (Allam and Sridharan 1979; Sridharan 1991, Delage *et al.* 2006, Katsumi *et al.* 2008, Bo *et al.* 2015, Mazzieri 2017). These engineering parameters directly affect the service life of landfill liners. If permeability change, leakage from landfill liners may cause contamination at the underneath layers. The changes at the performance of these landfill liners should observed with respect of economical and environmental concerns.

There are limited studies on the ageing effect on the natural clayey soils especially in the presence of different cations. Generally, the studies on the ageing effect examines the behavior of soils in the presence of water. The studies on the settlement behavior has shown that the structural resistance develops during ageing (Zeng *et al.* 2016).

Shahriar and Jadid (2018) observed that at a specific moisture content, with the increase of ageing period yield stress increase. The increment in rigidity with ageing in soils' deviator stress-strain curves was observed by Allam and Sridharan (1979). The initial tangent modulus increment was observed with the period of ageing and this increment was greater in the early stages of ageing. In another study, it was observed that the yield stress developed in the aged sample was higher than that of the unaged sample for the initial moisture content ranging from 0.55 to 1.25 times their respective liquid limits (Shahriar *et al.* 2018). However, as the effective vertical stress exceeded the 40 kPa–100 kPa range, compressibility was not impacted by ageing. The ageing effect on swelling behavior of soils were investigated on the samples at constant water content and dry unit weight (w=15% ve γ_d=16.7 kN/m^3) by Gehling *et al.* (1995). The 9% swelling was observed after 3 hours and 70 kPa swelling pressure was observed after 1000 minutes in the sample by pressure sensors. This phenomenon was interpreted in terms of water exchange occurring between the intra-aggregate and inter-aggregate porosities of the soil microstructure. The increment in swelling pressure was explained by water movement in the micro-structure of soil grains. The swelling and shrinkage behavior were investigated during 7, 15, 30 and 90 days of a soil which has 100% liquid limit value in Subba Rao and Tripathy (2003)'s study. According to the results of this study, as a result of ageing effect resistance of soil against compressibility increased and swelling potential decreased. According to the results of these studies, it seems that swelling properties decrease somewhat with ageing.

*Corresponding author, Professor
E-mail: yeliz.yukselen@deu.edu.tr

ISSN: 2005-307X (Print), 2092-6219 (Online)

However, this feature is not particularly critical in the case of engineered barriers, because it is expected that the swelling properties that remain after ageing are still sufficient to fill the interbrick joints.

The time-dependent changes in the microstructure of compacted MX80 bentonite samples kept at a constant bulk density up to 90 days after compaction in Delage *et al.* (2006) study. The changes in micro structure of bentonite was related to the redistribution of the pore water, because suction is not fully equilibrated along the various levels of microstructure just after compaction is completed. In this study, the time effects observed in the large inter-aggregate pores which was related to water redistribution that occurs at a constant water content, after compaction, as initially suggested by Gehling *et al.* (1995). It was noted that, the compaction is quite a rapid process which does not allow internal water redistribution inside compacted samples of swelling clays. The two time-dependent changes observed at the levels of inter-aggregate and intra-aggregate porosities correspond to changes that would be caused by suction decrease (Gehling *et al.* 1995, Cui *et al.* 2002). The reduction with time of the inter-aggregate porosity related to the exfoliation of the clay particles that form the walls of the inter-aggregate pores, resulting in a gel that progressively fills the inter-aggregate pores. As ageing progress, inter-aggregate porosity reduces hence permeability reduces (Delage *et al.* 2006), which is good for waste isolation.

The salt ions affect short-term and long-term performance of clayey soils. Mazzieri *et al.* (2017) investigated that the amended bentonites' longterm performance remains limited. A drastic increase in permeability (three orders of magnitude) were obtained as a result of wet and dry ageing. Muhammad and Marri (2018) observed that the liquid limit of clayey soil with 6% of lime at the beginning slightly increased but after the curing duration it reached to constant value. However, the plastic limit increased from 35.5% to 50.9% with 6% lime at the end of the curing time (90 days).

Engineering properties of clays with different pore water chemistry are mainly controlled by two distinct mechanisms depending if the predominant clay mineral is either montmorillonite or kaolinite (Sridharan and Rao 1975, Di Maio 1996, Katsumi *et al.* 2008, Li *et al.* 2018). The contribution of diffuse double layer to the physical properties dominates for montmorillonitic or swelling soils. The liquid limit of montmorillonitic soils decreases with the increase in ion concentration and valence due to the compression of diffuse double layer (Sridharan 1991, Yukselen Aksoy *et al.* 2008). The increase in ion concentration and valence for kaolinitic (non-swelling) soils enhances the coagulation; therefore explaining an increase of the shearing resistance and liquid limit. Mario and Fenelli (1994) investigated the role of minerals and pore fluid composition on the residual strength of kaolin, bentonite and their mixtures exposed to distilled water and sodium chloride solutions with given concentrations. It was reported that the shear strength of kaolin is not affected by the solutions used; whereas, the residual strength of bentonite varies greatly due to inward salt diffusion towards the clay.

In this study, ageing and pore fluid chemistry effect were determined in the presence of NaCl and $CaCl_2$ solutions on the kaolinitic and bentonitic clay soil samples. The change in compressibility, permeability and shear strength properties of kaolin and bentonite samples as a result of ageing were observed.

2. Materials and methods

2.1 Material characterization

Kaolin sample supplied from Eczacıbaşı Esan Mining Company and mined from Canakkale Sarıbeyli (Turkey) region. Bentonite sample supplied from Süd-Chemie Company. The samples dried in a oven at 105 °C for 24 hours and then crushed with the help of a jaw crusher and then samples were sieved with mesh No. 40 (0.425 mm). In order to determine pore fluid effect, two different type salt solutions were used. Salts solutions were NaCl and $CaCl_2.2H_2O$ from Merck Chemical Company. X-ray diffraction analyses were conducted to determine mineralogical content of the samples. These analyses were done at Tubitak-Materials Research Center Shimadzu XRD-6000 instrument with Cu X-ray tube (wavelength = 1.5405 Angstroms). Liquid limit, plastic limit and specific gravity values of soil samples determined in accordance with ASTM D 4318 (2011) and ASTM D 854 (2014) standards. The results are given in Table 1. The sieve analyses and hydrometer analyses were conducted to determine the particle size distribution of the samples according to ASTM D 422 (2007) standard. The particle size distribution of the kaolin and bentonite samples are shown in Fig. 1.

Table 1 Physicochemical properties of kaolin and bentonite samples

	Kaolin	Bentonite
Specific gravity	2.696	2.672
Liquid limit (%)	25.5	94.1
Plastic limit (%)	Non-plastic	50.8
Clay fraction (<0.002 mm) (%)	18	42
Mineralogic content	Quartz Kaolinite	Montmorillonite Dolomite Calcite Quartz

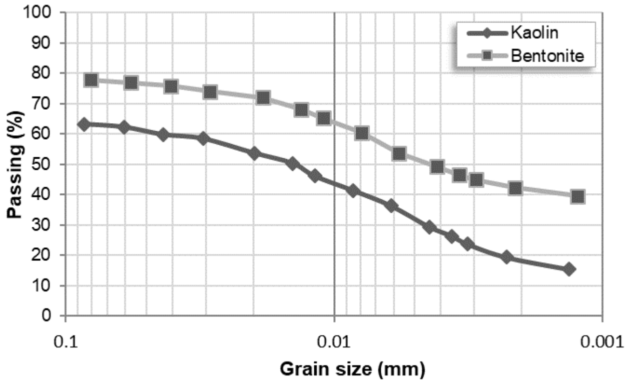

Fig. 1 Grain size distribution of the kaolin and bentonite samples

Table 2 Experimental set-up

Sample / Solution	Time (Day)			
	0*, **	60*, **	190*	250**
Bentonite/Kaolin-DI water / 0.5M NaCl	+	+	+	+
Bentonite/Kaolin-0.5M NaCl / 0.5M NaCl	+	+	+	+
Bentonite/Kaolin-DI water / 0.5M $CaCl_2$	+	+	+	+
Bentonite/Kaolin-0.5M $CaCl_2$ / 0.5M $CaCl_2$	+	+	+	+

*Direct shear tests, ** Consolidation tests

2.2 Methods

In order to determine pore fluid effect two different type salt solutions (NaCl and $CaCl_2$) were used as pore water. The salts were solubilized in distilled water at 0.5 M concentration and mixed homogenously with kaolin and bentonite samples. The samples were prepared in two different ways. The first group of kaolin and bentonite samples mixed with DI water, while the second set of samples were mixed with 0.5 M NaCl and 0.5 M $CaCl_2$ solutions.

In order to determine the ageing effect, kaolin and bentonite samples which were mixed with distilled water, 0.5 M NaCl and 0.5 M $CaCl_2$ were placed into metal rings with 5 cm height and 5.5 and 6.5 cm diameters. The initial water contents for all tested clays were fixed at their liquid limit values which were measured in the presence of Na^+ and Ca^{2+} cations. It should be noted that the liquid limit values of the samples were changed depending on pore fluid chemistry. In order to prepare identical soil samples, bentonite and kaolin samples were prepared at 14.7 kN/m^3 and 18.6 kN/m^3 density values, respectively. The moist clay specimens were remolded in the steel rings taking care to prevent any air entrapment in the specimens. The top and bottom surfaces of the samples were covered with filter papers and then the samples were placed into the plastic cylindrical tubes. The soil samples were cured during 60, 190, and 250 days in the presence of 0.5 M NaCl and 0.5 M $CaCl_2$ solutions in the closed containers in submerged condition. The room temperature was 23±2°C during ageing process.

The one-dimensional consolidation and direct shear tests were performed according to the ASTM D 2435 (2011) and ASTM D 3080 (2011) standards, respectively. The diameter values of the odeometer ring and cell of the direct shear test device were 5.0 and 6.3 cm, respectively. The direct shear tests were conducted under consolidated-drained (CD) conditions. The permeability parameters were determined from one-dimensional consolidation test at 98 kPa load by the following equation indirectly:

$$k = c_v \ m_v \ \gamma_w \qquad (1)$$

where k is the coefficient of permeability, c_v is the coefficient of consolidation, m_v is the coefficient of volume change and γ_w is the density of water.

The one-dimensional consolidation experiments were conducted at two different ageing times which 60 days and 250 days. The direct shear tests were conducted on the 60 and 190 days aged samples. Table 2 summarizes the applied experimental set-up for the tests. In the consolidation and permeability tests, the remolded specimens were placed into the ring making sure that no air pockets were left in the specimen. The soil specimens were loaded axially under 24.5, 49, 98.1, 196.1, 392.3, and 784.5 kPa. Each load was applied until deformations were negligible. The permeability values of the specimens were evaulated from one-dimensional consolidation tests.

The shear strength parameters were determined according to ASTM D 3080 (2011) by using shear box test. The samples were consolidated under normal stress of 49 kPa, 98 kPa, and 196 kPa. After primary consolidation completed, samples were sheared. Since the consolidated drained test procedure was followed, horizontal displacement rate was very important. Therefore after each consolidation test, t_{50} (time to reach 50% consolidation) values were determined by using the log-time method. After a few trials, it was seen that lateral displacement to reach the peak soil strength was between 4 mm to 5 mm. Hence displacement rate was chosen as 0.05 mm/minute. The compressibility and shear strength tests were repeated for each specimen and variation between two trials was about 5-7%.

3. Atterberg limits test results

Kaolin and bentonite samples were mixed with DI water, 0.5 M NaCl and 0.5 M $CaCl_2$ solutions and their liquid and plastic limit values were determined. The obatined results are shown in Table 3.

The obtained results highlighted the impact of pore fluid chemistry in the presence of the NaCl and $CaCl_2$ solutions. Although there is consensus among researchers that consistency limits of soils composed of mostly montmorillonite minerals decrease with higher salt concentrations, there is no agreement on how high concentration of salt solutions affect the consistency limits of kaolinitic soils. Sridharan (1991) reported that inorganic ion concentration causes an increase in the consistency limits of kaolinitic soils and indicated that capped water between edge-to-face soil aggregates due to flocculation causes an increase in the consistency limits. Kaolinites have an ability of making edge-to-face particle arrangements and form flocculated fabrics. It is reported that air pockets that occurred between the flocculated particles capped the available water during the tests, and caused an increase in the liquid limit and sediment volumes of kaolinites (Yukselen *et al.* 2008). However, according to the results of this study there was a slight decrease in the liquid limit values of kaolin. The liquid limit values of bentonite decreased according to the diffuse double layer theory. Monovalent ions at low concentration would give the most extended diffuse ion layer (Yong and Warkentin 1975). For that reason, in the presence of Na^+ ions, the liquid limit of bentonite increases. However, increasing the salt concentration in the pore water would reduce it. The kaolin

Table 3 The liquid and plastic limit values of the bentonite and kaolin samples

	Liquid Limit (LL) (%)		Plastic Limit (PL) (%)	
Solution	**Kaolin**	**Bentonite**	**Kaolin**	**Bentonite**
DI water	25.5	94.1	Non-plastic	50.8
0.5 M NaCl	23.9	89.1	-	41.3
0.5 M $CaCl_2$	23.0	80.8	-	26.1

sample has non-plastic property, however the plastic limit values of bentonite samples decreased in the presence of Na^+ and Ca^{2+} cations. According to results of this study, high concentration of 0.5 M NaCl decreased the plastic limit value of bentonite. The Ca^{2+} ions in the structure of the bentonite replace with other cations and reduce the diffuse layer thickness of bentonite, the plastic limit value of bentonite decreases, consequently.

4. Ageing effect on compressibility behavior of kaolin and bentonite samples

The one dimensional consolidation tests were conducted on the kaolin and bentonite samples in the presence of NaCl and $CaCl_2$ pore fluids which were aged at three different curing times (0, 60, and 250 days). The compression index values of bentonite and kaolin samples were investigated in order to determine the ageing and pore fluid effect on the compression index parameter. Initially, the samples were mixed with pore fluids and tested without any curing (0 day). The other samples were cured in 0.5 M NaCl and 0.5 M $CaCl_2$ solutions for 60 and 250 days. The compression index (C_c) values of non-cured (0 day) and cured (60 and 250 days) bentonite and kaolin samples were determined with one-dimensional consolidation tests. Although all samples were prepared under identical conditions, their structure may be different. For that reason, in order to compare results accurately, the compression index (C_c) values were normalized by dividing the void ratio at liquid limit (e_L). Table 4 presents the normalized compression index (C_c/e_L) values for kaolin and bentonite samples.

The kaolin sample showed different behavior with Na^+ and Ca^{2+} ions. When unaged samples results were compared, the normalized compression index values of kaolin are higher in the presence of NaCl than $CaCl_2$. The normalized compression index values of kaolin 0.161 and 0.128 in the presence Na^+ and Ca^{2+} ions, respectively. It means that, the amount of settlement in the presence NaCl solution will be higher than in the presence of $CaCl_2$ solution. The electrical diffuse double layer does not have a prominent role in the compressibility behavior of kaolinites (Sridharan 1991). For that reason, geometric arrangement of clay particles regulates the compressibility behavior of kaolinitic soils in different pore fluids. The increase in ion concentration and cation valence cause to coagulation of kaolinite particles (Sridharan and Rao, 1975; Sridharan 1991). Hence, more flocculated structure may compose in the presence of Ca^{2+} ions. Thus, kaolin sample showed

Table 4 Normalized compression index values (C_c/e_L) of kaolin and bentonite samples cured in 0.5 M NaCl and 0.5 M $CaCl_2$ solutions

			C_c / e_L			
Sample preparation solution			**DI water**	**0.5 M NaCl**	**DI water**	**0.5 M $CaCl_2$**
Curing solution			**0.5 M NaCl**	**0.5 M NaCl**	**0.5 M $CaCl_2$**	**0.5 M $CaCl_2$**
Time (Day)	0	**Kaolin**	0.142	0.161	0.142	0.128
	60		0.124	0.129	0.148	0.153
	250		0.116	0.126	0.165	0.141
	0	**Bentonite**	0.283	0.286	0.283	0.243
	60		0.217	0.258	0.290	0.259
	250		0.254	0.296	0.367	0.281

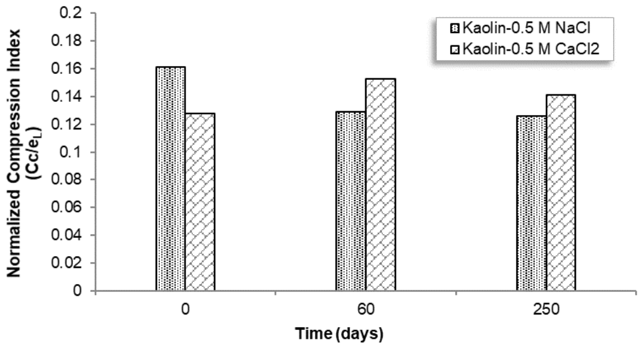

Fig. 2 Pore fluid and ageing effect on compression index of kaolin

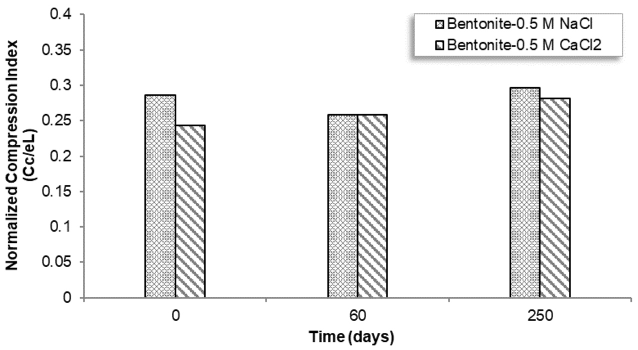

Fig. 3 Pore fluid and ageing effect on compression index of bentonite

resistance to the compressibility in the presence of divalent cations than monovalent cations. Similar results were reported by Horpibulsuk *et al.* (2011) and they stated that at the same void ratio, kaolin sustain higher vertical consolidation pressure when the ion valence increased. The difference between the normalized compression indexes and the effect of pore fluid chemistry clearly can be seen from Fig. 2. The ageing effect can be observed when 0 day, 60 days and 250 days samples normalized compression index values were compared. The normalized compression index values of kaolin decrease as ageing progress for both kaolin-DI water and kaolin-NaCl mixtures which were cured in 0.5 M NaCl solution. However, the results are in reverse direction in the presence of 0.5 M $CaCl_2$ solution.

Table 5 k/e_L values of kaolin and bentonite samples in the presence of 0.5 M NaCl and $CaCl_2$ solutions

Sample		Kaolin-DI water	Kaolin-DI water	Bentonite-DI water	Bentonite-DI water
Curing solution		0.5 M NaCl	0.5 M $CaCl_2$	0.5 M NaCl	0.5 M $CaCl_2$
		k/e_L (*10^{-8} cm/s)			
Time (Day)	0	32.33	32.33	0.44	0.44
	60	21.81	36.51	0.78	1.00
	250	15.58	71.26	0.66	1.04

The kaolin sample becomes more compressible in the presence Ca^{2+} ions with ageing. It should be noted that the decrease or increase in compression index completed in 60 days after that there is no significant change later 60 days until 250 days.

Table 4 shows the normalized compression index values (C_c/e_L) of bentonite samples which were cured in 0.5 M NaCl and 0.5 M $CaCl_2$ solutions. Depending on the pore fluid chemistry, the bentonite sample has different behavior in the presence of Na^+ and Ca^{2+} ions. When unaged samples results were compared, the normalized compression index values of bentonite are higher in the presence of NaCl than $CaCl_2$. The normalized compression index values of bentonite 0.286 and 0.243 in the presence Na^+ and Ca^{2+} ions, respectively. The amount of settlement in the presence NaCl solution will be higher than in the presence of $CaCl_2$ solution. In the presence of monovalent ions (Na^+), bentonite has extended diffuse double layer than divalent and trivalent ions. As a result of the diffuse double layer thickness increase, compressibility of the bentonite increased in the presence of the Na^+ ions. Horpibulsuk *et al.* (2011) stated that, at the same void ratio, the resistance to vertical consolidation pressure of bentonite decreased as the ion concentration and valence increased. However, the results of this study showed that as valence increased the resistance to vertical consolidation pressure for bentonite increased.

Generally, the normalized compression index values of bentonite samples increased at the end of 60 days and 250 days curing time periods. This effect is very significant in the presence of 0.5 M $CaCl_2$ solution. The pore fluid and ageing effect clearly can be seen from Figure 3 which shows the normalized compression index values of bentonite sample in the presence of 0.5 M NaCl and 0.5 M $CaCl_2$ solutions. The results have shown that, NaCl solution has no significant effect on the normalized compression index values of bentonite. However, the resistance of bentonite against to settlement decreases with ageing.

The kaolin and bentonite samples were mixed with distilled water and then cured in 0.5 M NaCl and 0.5 M $CaCl_2$ solutions for 60 days and 250 days, then their permeability values were determined indirectly from one-dimensional odeometer tests at 98 kPa loading level. For better comparison, the permeability values were normalized by dividing permeability values to e_L values. The normalized permeability values of the kaolin sample are shown in Table 5.

The previous studies have shown that as ionic concentration and cation valence increase, the permeability of kaolin decreases. Reversely, the permeability of bentonite increases with increase in ionic concentration and cation valence (Horpibulsuk 2011). Sridharan (1991) reported that inorganic ion concentration causes capped water between edge-to-face soil aggregates due to flocculation. Due to this flocculation effect, permeability of kaolin decreases. However, in terms of ageing effect on the permeability the results of this study have shown that, the normalized permeability value of kaolin decreased by ageing in the presence of Na^+ ions. At the end of the 250 days ageing, the permeability of kaolin decreased almost twofold. However, the permeability values of kaolin increased in the presence of Ca^{2+} ions during ageing. Kaolinites have an ability of making edge-to-face particle arrangements as cationic valence and ionic concentration increased, for that reason in the presence of Ca^{2+} ions more flocculated structure develops in the kaolinitic soils structure (Sridharan 1991, Horpibulsuk *et al.* 2011). During ageing, the chemical bonds between particle layers and at particle contacts becomes more stronger (Allam and Sridharan 1979), for that reason in general the normalized permability values of the kaolin decreased with Ca^{2+} ions. According to the results of this study, Ca^{2+} ions cause more flocculated structure than Na^+ ions. As a result of this phonemenon, permeability of kaolin decreases in the presence of Na^+ ions, reversely it increases in the presence of Ca^{2+} ions.

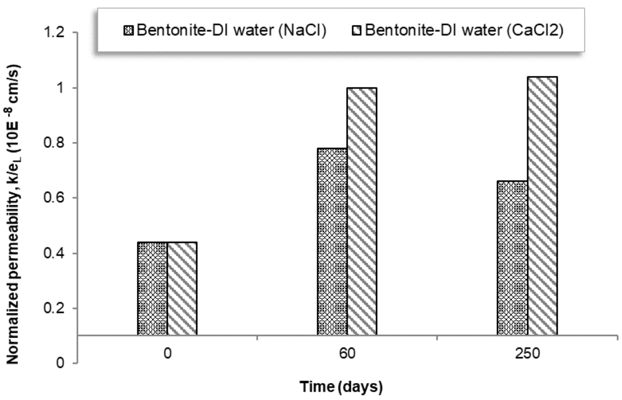

Fig. 4 The permeability values of bentonite in the presence of NaCl and $CaCl_2$ solutions

The results of the normalized permeability values of bentonite-distilled water mixtures in the presence of 0.5 M NaCl and 0.5 M $CaCl_2$ solutions are shown in Table 5. The permeability values of bentonite decreased both in NaCl and $CaCl_2$ solutions during ageing. The effect is more significant in the presence of Ca^{2+} ions. Similar results were reported by Delage et al (2006); MX80 bentonite samples were exposed to leachate water at a certain water content and density did not show a significant change in the void rate in the first days, but after 90 days of ageing period, the void rate showed a significant decrease with the aging effect (from e = 0.649 to e = 0.461).The ageing effect on the bentonite sample clearly can be seen in Fig. 4.

Increase in permeability during ageing is very important especially for geosynhetic clay liners (GCLs). The results of this study have shown that in the presence of salt solutions the permeability values of GCLs may increase by ageing. For that reason, this effect should be considered in designing landfill liners.

5. Ageing effect on shear strength behavior of kaolin and bentonite samples

The shear strength behavior of kaolin and bentonite samples were determined on the aged samples in the presence of NaCl and $CaCl_2$ solutions. The samples were consolidated and then sheared under three different normal pressures (49, 98, 196 kPa). The maximum residual shear stress values under 98 kPa are shown in Table 6. The kaolin and bentonite samples were mixed with distilled water and cured in 0.5 M concentration of NaCl and $CaCl_2$ solutions.

The pore fluid chemistry effect can be seen when the results of unaged samples were compared. In the presence of Na^+ ions kaolin has higher max. shear stress value than Ca^{2+} ions. The edge-to-face particle arrangements of the fabric of kaolin results higher capped water volume between edge-to-face soil aggregates. This flocculated structure and capped water between soil grains decreased the maximum shear stress value of the kaolin sample. When the maximum shear stress values of 0 (uanged), 60 and 190 days samples were compared, it is seen that NaCl solution has no significant effect on the shear strength of kaolin sample (Cakar *et al.* 2014). However, the shear strength of kaolin significantly increased in the $CaCl_2$ solution during ageing. Similar to these findings, Allam and Sridharan (1979) observed that the tangent modulus of kaolin increased after 30 days in the presence of distilled water.

The effect of NaCl and $CaCl_2$ solutions clearly can be seen from unaged samples maximum shear stress values. In the presence of Ca^{2+} ions the max. shear stress value is higher. The thickness of the diffuse double layer decreases in the presence of divalent ions. This effect increases the friction between clay particles. As a result of this, the shear strength of bentonite increases. When the results of 0, 60, and 190 days cured bentonite samples were compared, it is seen that the max. shear stress values increased by ageing effect. The increase in shear stress values on ageing is due to the increase in intrinsic effective stress occuring because of the development of bonds at particle contacts as well as fabric changes (Allam and Sridharan 1979).

Table 6 The maximum shear stress values of kaolin and bentonite samples in the presence of NaCl and $CaCl_2$ solutions

Sample		Kaolin-DI water	Kaolin-DI water	Bentonite-DI water	Bentonite-DI water
Curing solution		0.5 M NaCl	0.5 M $CaCl_2$	0.5 M NaCl	0.5 M $CaCl_2$
Maximum shear stress* (kPa)					
Time (Day)	0	73	34	12	58
	60	70	69	74	90
	190	69	104	69	135

*Under 98 kPa normal stress

6. Conclusions

The ageing effects on the compressibility, permeability and shear strentgh behavior of kaolin and bentonite samples were investigated in the presence of NaCl and $CaCl_2$ solutions.

In terms of pore fluid chemistry, the kaolin sample has different behavior with Na^+ and Ca^{2+} ions. When 0 day (without ageing) samples results were compared, the normalized compression index values of kaolin and bentonite are higher in the presence of solution NaCl than $CaCl_2$ solution. The normalized compression index values of kaolin decrease as ageing progress for both kaolin-DI water and kaolin-NaCl mixtures which were cured in 0.5 M NaCl solution. However, reversely the kaolin sample becomes more compressible in the presence Ca^{2+} ions with ageing. Generally, the normalized compression index values of bentonite samples increased at the end of 60 days and 250 days curing time periods. The resistance of bentonite against to settlement decreases with ageing. At the end of the 250 days ageing period, the permeability of kaolin decreased almost twofold. However, the permeability values of kaolin increased in the presence of Ca^{2+} ions during ageing period. The permeability values of bentonite increased both in NaCl and $CaCl_2$ solutions during ageing. The effect is more significant in the presence of Ca^{2+} ions. It is expected that, as ageing progress, bonds between particles increase; therefore permeability of the soils decrease. However, the results of this study have shown that this is not true for kaolin and bentonite samples that as ageing progress the permeability values of bentonite increased in the presence of 0.5 M NaCl and 0.5 M $CaCl_2$ solutions.

The pore fluid chemistry effect can be seen when the results of unaged samples were compared. In the presence of Na^+ ions kaolin has higher max. shear stress value than Ca^{2+} ions. The edge-to-face particle arrangements of the fabric of kaolin results higher capped water volume between edge-to-face soil aggregates. This flocculated structure and capped water between soil grains decreased the maximum shear stress value of the kaolin sample. When the maximum shear stress values of 0, 60 and 190 days samples were compared, it is seen that NaCl solution has no significant effect on the shear strength of kaolin sample. However, the shear strength of kaolin significantly increased in the $CaCl_2$ solution during ageing. When the results of 0, 60, and 190 days cured bentonite samples were compared, it is seen that the max. shear stress values increased by ageing effect.

Increase in permeability during ageing is very important especially for geosynhetic clay liners (GCLs) and barriers. If permeability change, leakage from landfill liners may cause contamination at the underneath layers. The results of this study have shown that in the presence of salt solutions the permeability values of GCLs may increase by ageing. The long term performance of the bentonitic GCLs should be investigated in the presence of mixture of different cations. Engineering properties of clays with different pore water chemistry are mainly controlled by predominant clay mineral is either montmorillonite or kaolinite. Depending on mineralogy and pore water chemistry long term performance of liners should be considered in designing landfill liners.

Acknowledgments

The authors appreciate the support of Celal Bayar University Scientific Research Project Support (CBU-BAP 2011-049).

References

Allam, M.M. and Sridharan, A. (1979), "The influence of ageing on the shear strength behavior of two fine-grained soils", *Can. Geotech. J.*, **16**(2), 850-859. https://doi.org/10.1139/t79-037.

ASTM D 4318 (2011), Standard test method for liquid limit, plastic limit, and plasticity index of soils, ASTM International, West Conshohocken, Pennsylvania, U.S.A.

ASTM D 854 (2014), Standard test method for specific gravity of soils. ASTM International, West Conshohocken, Pennsylvania, U.S.A.

ASTM D 422 (2007), Standard test method for particle-size analysis of soils. ASTM International, West Conshohocken, Pennsylvania, U.S.A.

ASTM D 2435 (2011), Standard test method for one-dimensional consolidation properties of soils. ASTM International, West Conshohocken, Pennsylvania, U.S.A.

ASTM D 3080 (2011), Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions, ASTM International, West Conshohocken, Pennsylvania, U.S.A.

Bo, M.W., Arulrajah, A., Sukmak, P. and Horpibulsuk, S. (2015). "Mineralogy and geotechnical properties of Singapore marine clay at Changi", *Soils Found*., **55**(3), 600-613. https://doi.org/10.1016/j.sandf.2015.04.011.

Cakar, E., Pulat, H.F. and Yukselen-Aksoy, Y. (2014), "Pore fluid chemistry and aging effect on swelling, shear strength and pore size distribution behavior of soils", *Geoenviron. Eng.,* **241**, 242-250. https://doi.org/10.1061/9780784413432.025.

Cui, Y.J., Yahia-Aissa, M. and Delage, P. (2002), "A model for the volume change behavior of heavily compacted swelling clays", *Eng. Geol*., **64**(2-3), 233-250. https://doi.org/10.1016/S0013-7952(01)00113-2.

Delage, P., Marcial, D., Cui, Y.J. and Ruiz, X. (2006), "Aging effects in a compacted bentonite: A microstructure approach", *Geotechnique*, **56**(5), 291-304. https://doi.org/10.1680/geot.2006.56.5.291.

Di Maio, C. (1996), "Exposure of bentonite to salt solution: osmotic and mechanical effects", *Geotechnique*, **46**(4), 695-707. https://doi.org/10.1680/geot.1996.46.4.695.

Gehling, W.Y.Y., Alonso, E.E. and Gens, A. (1995), "Stress-path testing of expansive compacted soils", *Proceedings of the 1st International Conference on Unsaturated Soils*, Paris, France, September.

Horpibulsuk, S., Yangsukkaseam, N., Chinkulkijniwat, A. and Du, Y.J. (2011), "Compressibility and permeability of Bangkok clay compared with kaolinite and bentonite", *Appl. Clay Sci*., **52**, 150-159. https://doi.org/10.1016/j.clay.2011.02.014.

Katsumi, T., Ishimori, H., Onikata, M. and Fukagawa, R. (2008), "Long term barrier performance of modified bentonite materials against sodium and calcium permeant solutions", *Geotext. Geomembrances*, **26**(1), 14-30. https://doi.org/10.1016/j.geotexmem.2007.04.003.

Li, X., Yuan, G., Fu, H., Wang, J. and Cai, Y. (2018), "Effect of electrochemical treatment on consolidation of soft clay", *Geomech. Eng*., **15**(4), 957-964. https://doi.org/10.12989/gae.2018.15.4.957.

Mazzieri, F., Emidio, G.D. and Pasqualini, E. (2017), "Effect of wet and dry ageing in seawater on the swelling properties and hydraulic conductivity of two amended bentonites", *Appl. Clay Sci*., **142**, 40-51. https://doi.org/10.1016/j.clay.2016.10.031.

Muhammad, M. and Marri, A. (2018), "Immediate and long-term effects of lime and wheat straw on consistency characteristics of clayey soil", *Geomech. Eng*., **16**(3), 217-231. https://doi.org/10.12989/gae.2018.16.3.217.

Shackelford, C.D., Sevick, G.W. and Eykholt, G.R. (2010), "Hydraulic conductivity of geosynthetic clay liners to tailings impoundment solutions", *Geotext. Geomembranes*, **28**(2), 149-162. https://doi.org/10.1016/j.geotexmem.2009.10.005.

Shahriar, A.R., Abedin, M.Z. and Jadid, R. (2018), "Thixotropic aging and its effect on 1-D compression behavior of soft reconstituted clays", *Appl. Clay Sci*., **153**, 217-227. https://doi.org/10.1016/j.clay.2017.12.029.

Shahriar, A.R. and Jadid, R. (2018), "An experimental investigation on the effect of thixotropic aging on primary and secondary compression of reconstituted dredged clays", *Appl. Clay Sci*., **162**, 524-533. https://doi.org/10.1016/j.clay.2018.05.023.

Sridharan, A. and Rao, G.V. (1979), "Shear strength behavior of saturated clays and the role of the effective stress concept", *Geotechnique*, **29**(2), 177-193. https://doi.org/10.1680/geot.1979.29.2.177.

Sridharan, A. (1991), "Engineering behavior of fine grained soils - a fundamental approach", *Indian Geotech. J*., **21**(1), 1-136.

Sridharan, A. and Rao, G.V. (1975), "Mechanisms controlling the liquid limit of clays", *Proceedings of the Istanbul Conference on Soil Mechanics and Foundation Engineering*, Istanbul, Turkey, April.

Sridharan, A., Rao, S.M. and Murthy, N.S. (1986), "Compressibility behavior of homoionized bentonites" *Geotechnique*, **3**(4), 551-564. https://doi.org/10.1680/geot.1986.36.4.551.

Sridharan, A., Rao, S.M. and Murthy, N.S. (1988), "Liquid limit of kaolinitic soils", *Geotechnique*, **38**(2), 191-198. https://doi.org/10.1680/geot.1988.38.2.191.

Subba Rao, K.S. and Tripathy, S. (2003), "Effect of ageing on swelling and swell-shrink behavior of a compacted expansive soil", *Geotech. Test. J*., **26**(1), 36-46. https://doi.org/10.1520/GTJ11100J.

Yong, R.N. and Warkentin, B.P. (1975), *Soil Properties and Behavior*, Elsevier Scientific Publishing Co., New York, U.S.A.

Yukselen-Aksoy, Y., Kaya, A. and Ören, A.H. (2008), "Seawater effect on consistency limits and compressibility characteristics of clays", *Eng. Geol*., **102**(1-2), 54-61. https://doi.org/10.1016/j.enggeo.2008.07.005.

Zeng, L.L., Hong, Z.S. and Cui, Y.J. (2016), "Time-dependent compression behaviour of dredged clays at high water contents in China", *Appl. Clay Sci*., **123**, 320-328. https://doi.org/10.1016/j.clay.2016.01.039.

CC