DESERT

Desert
Online at http://desert.ut.ac.ir

Desert 20-1 (2015) 73-82

Treatment of expansive soils with quality saline pore water by cyclic drying and wetting

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Received: 14 December 2014; Received in revised form: 21 January 2015; Accepted: 18 February 2015

Abstract

Expansive soils can be found in many parts of the world particularly in arid and semi-arid regions. These soils pose a significant hazard to civil engineering structures due to its high swelling and shrinkage potential. This paper presents the results of an experimental program developed to investigate the effect of cyclic drying and wetting on the swelling potential of expansive soils with various pore water qualities. Soil samples were prepared by static compaction with distilled and saline pore water solutions consisting of sodium chloride (NaCl) with 50 and 250 g/L concentrations. Soil samples were subjected to drying and wetting cycles using a modified oedometer apparatus, under a surcharge pressure of 10 kPa. Axial deformations caused by drying and wetting during various cycles were measured until shrink-swell equilibrium condition was attained. The results indicated that conducting consecutive drying and wetting causes a considerable reduction in the swelling potential of soil samples prepared with different qualities of pore water. Shrink-swell equilibrium in soil samples prepared with distilled water and 50 g/L NaCl solution was achieved after 5 consecutive cycles while soil samples with 250 g/L NaCl solution as pore water, reached equilibrium condition after approximately 3 or 4 cycles. Furthermore, the overall swelling potential for soil samples prepared with 250 g/L NaCl solution was seen to be greater compared to distilled water and 50 g/L NaCl solution respectively.

Keywords: Expansive soil; Drying and wetting cycles; Pore water quality; Swelling potential; Shrink-swell equilibrium

1. Introduction

Expansive soils are considered a worldwide problem because they cause extreme damage to civil engineering structures such as embankment dams, water conveyance structures, irrigation and drainage channels, retaining walls, small buildings, tunnels, highways, roads and pavements (Nelson and Miller, 1992). These soils are prone to large volume changes (swelling and shrinkage) which are directly related to changes in water content. Expansive soils are found in many parts of the world particularly in arid and semi-arid regions (Gourley *et al*., 1993) and can be identified as soils which form deep cracks in drier seasons or years. The average cost of damage caused by expansive soils in the USA is approximately $9 billion dollars per year, which is more than twice the combined average annual damage caused by natural disasters such as earthquakes, floods, tornados, hurricanes and volcanoes in the USA (Jones and Jones, 1987). Furthermore, the American Society of Civil Engineers (ASCE) estimates that 1/4 of all homes and buildings in the USA have some damage caused by expansive soils.

Despite being classified as a problematic and destructive soil, expansive soils are widely utilized for civil engineering projects and landfilling of municipal, industrial and radioactive wastes (Komine and Ogata, 1994; Pusch, 2001; Siddiqua *et al*., 2011). Many researchers have proposed that cyclic drying and wetting conducted on expansive soils will likely cause reduction in swelling potential and

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hence, can be adopted as a simple and economic method to reduce the damage caused by swelling in arid and semi-arid regions. This method was first seen to be successfully carried out in a major irrigation project to reduce the damage caused to channel linings in Khuzestan Province, south of Iran (Ahmadi *et al*., 2012). However, for better understanding and dealing with the swelling phenomenon, the need for further research seems essential. For this purpose, an investigation is necessary upon other environmental factors which can likely influence the swelling behavior of these soils.

Many researchers such as Chu and Mou (1973), Dif and Bluemel (1991), Al-Homoud *et al*. (1995), Basma *et al*. (1996), Tripathy *et al*. (2002, 2009), Alonso *et al*. (2005) and Estabragh *et al*. (2012) stated that expansive soils subjected to consecutive drying and wetting cycles, show a significant reduction in swelling potential and the plastic deformations of the soil will reduce and finally diminish, by repeating the cyclic process of drying and wetting. Other researchers such as Popescu (1980), Osipov *et al*. (1987), Day (1994) and Tawfiq and Nabantoghlu (2009) concluded that the cyclic process of drying and wetting causes increase in the swelling potential of soils. Estabragh *et al*. (2013, 2014) studied the effect of different types of wetting fluids (distilled, saline and acidic water) on the behavior of an expansive soil during drying and wetting cycles. They stated that drying and wetting cycles cause reduction in swelling potential and concluded that the quality of wetting fluid is an important factor which directly influences swelling potential.

In natural conditions, the pore water of clayey soils can vary in terms of quality and chemistry, due to various natural and artificial causes such as salinity (Buckman and Brady 1969; Rogers *et al.*, 1994). Salinity is mainly associated with expansive soils in arid and semi-arid regions and is caused by various reasons such as mineral weathering, saline groundwater movement, gradual withdrawal of saline waters and irrigation. A review of the literature shows that there has been no specific study, regarding the influence of pore water quality on the swelling potential of expansive soils during drying and wetting cycles. Therefore, the main objective of this study was to investigate the effect of pore water quality on swelling potential of an expansive soil during drying and wetting. Three different fluids consisting of distilled water, 50 and 250 g/L sodium chloride (NaCl) solutions were used to prepare soil samples. Cyclic drying and wetting tests were conducted on samples in a modified oedometer apparatus. The swelling potential of soil samples with different pore water qualities was measured during various cycles of drying and wetting and the results were analyzed.

2. Material and methods

2.1. Expansive soil

The available soil was a typical clay soil collected from a site near the Qazvin Province of Iran. It was classified as clay with low plasticity (that is CL) according to the unified soil classification system (USCS). This soil had a moderate swelling potential according to the McKeen (1992) classification criteria for expansive soils. In order to achieve an appropriate soil with high expansive behavior, a number of mixtures of the clay soil and bentonite with different percentages (10, 20 and 30%) were prepared. A series of swelling tests were conducted on various clay-bentonite mixtures according to the ASTM-D4546 (2008) standard and finally, the mixture of 80% clay with 20% bentonite was chosen as the appropriate mixture for further experimental work. The selected clay-bentonite mixture was classified as clay with high plasticity (that is CH) and had a high swelling potential according to the McKeen (1992) classification system. The physical and mechanical properties of the clay-bentonite mixture, which hereafter will be simply referred to as soil, are shown in Table 1. In addition, the selected clay-bentonite mixture had a pH, electrical conductivity (EC) and sodium adsorption ratio (SAR) of 8.4, 13.9 dS/m and 38.65 respectively.

2.2. Pore water solutions

Three kinds of different fluids consisting of distilled water, sodium chloride with low concentration (50 g/L) and sodium chloride with high concentration (250 g/L) were used as pore water for this study. Therefore, this study investigated the effect of pore water salinity on the swelling potential of an expansive soil, during consecutive drying and wetting cycles. The physical and chemical properties of the proposed pore water solutions are presented in Table 2.

Table 1. Physical and mechanical properties of the soil (80% clay+20% bentonite)

Soil properties	Value/Description
Specific Gravity, G_s	2.75
Gravel (%)	0
Sand (%)	26
Fine grained (clay and silt) (%)	74
Liquid limit, ω_L (%)	81
Plastic limit, ω_P (%)	27.5
Plastic index, PI (%)	53.5
Shrinkage limit, ω_S (%)	14.5
Swelling potential (%)	22.6
USCS classification	CH
Optimum water content, OWC (%)	22
Maximum dry unit weight, MDD (kN/m^3)	16

Table 2. Physical and chemical properties of the salt solutions

Salt	pH	TDS* (g/L)	EC** (dS/m)	Density (gr/cm^3)	Molar mass (g/mol)	Mass percent (%)	Concentration (mol/L)	Solution density (gr/cm^3)
NaCl	4.8	50	78.125	2.17	58.44	4.9	0.86	1.026
	8.2	250	390.625			22.3	4.28	1.121

*Total dissolved solids **Electrical conductivity

2.3. Sample preparation

In order to better evaluate the effect of pore water salinity on the swelling potential of expansive soils during consecutive drying and wetting, it is necessary to prepare soil samples in a manner which would theoretically produce the highest amount of swelling potential. Cohesive soils with high plasticity show a dispersed structure behavior on the wet section of their standard compaction curve, while a flocculated structure can be considered on the dry section of the standard compaction curve (Lambe, 1958). In addition, Nelson and Miller (1992) stated that at a specific dry unit weight, cohesive soils with high plasticity show more swelling potential, in terms of lower moisture content compared to the optimum condition. Therefore, standard compaction tests were conducted on soil with distilled water and NaCl solutions at 50 and 250 g/L concentrations, according to the ASTM-D698 (2007) standard and standard compaction curves were determined. Soil samples with various pore water qualities were prepared by static compaction at a chosen water content and dry unit weight less than the optimum water content and maximum dry unit weight from standard compaction tests related to the soil-distilled water and soil-NaCl solutions (points “A”, “B” and “C” in Figure 2). In order to prepare homogenous and repeatable soil samples with different pore water qualities, a special mold similar to the one in the study of Estabragh *et al*. (2012, 2013, 2014) was designed from stainless steel which consisted of three sections, a top collar, a middle section identical to the oedometer mold (with a height of 20 and a diameter of 75 mm) and a bottom collar. The soil inside the mold which was mixed with pre-selected amounts of distilled water and NaCl solutions was compressed by a piston, using a special loading machine in three layers, to a maximum load of 1189 kPa for distilled water and 50g/L NaCl and 1529 kPa for 250g/L NaCl.

2.4. Apparatus

A modified oedometer apparatus was developed similar to that of Tripathy *et al*. (2002, 2009) and Estabragh *et al*. (2012, 2013, 2014), to conduct drying and wetting tests on the prepared soil samples with various pore water qualities. Similar to a conventional oedometer apparatus, the modified oedometer apparatus consists of a compartment to place soil samples between two porous stones, a loading plunger and a displacement dial gauge (with an accuracy of 0.01 mm) for recording axial deformation in soil samples. In addition to a conventional oedometer apparatus, a heating system was installed in order to apply heat and control temperature during drying cycles. A drainage valve was also designed and installed which allows the reservoir water to flow out quickly, at the end of the wetting cycles. A typical thermometer was installed within the compartment of the apparatus to calibrate temperature and ensure that the compartment temperature remains constant at 45°C during the conducting of drying cycles. The schematic presentation of the modified oedometer apparatus is as shown in Figure 1.

2.5. Test procedure

The soil sample which was prepared with the desired pore water quality was placed into the compartment of the modified oedometer apparatus between two porous stones. A surcharge pressure of 10 kPa was applied to the soil sample using the loading plunger. The heating system was switched on and an attempt was made to dry the soil sample under a constant temperature of 45°C. In addition, axial deformation caused by drying (shrinkage potential) was recorded by the displacement dial gauge during various periods of drying, until shrinkage equilibrium was achieved. After the completion of the drying stage, the heating system was switched off and apparatus temperature was allowed to cool down and reach equilibrium under laboratory conditions.

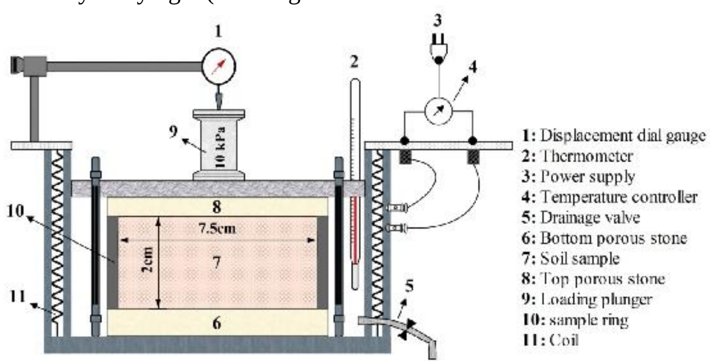

Fig. 1. Schematic layout of the modified oedometer apparatus

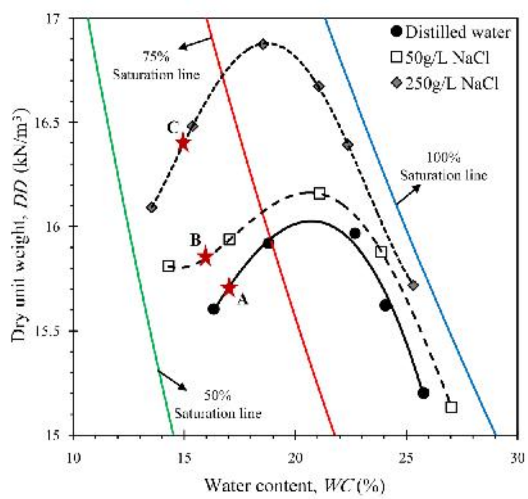

Fig. 2. Standard compaction curves for distilled water, 50 and 250g/L NaCl solutions

The soil sample was then flooded with distilled water and axial deformation caused by wetting (swelling potential) was recorded during various periods of wetting, until swelling equilibrium was achieved. Upon completion of the wetting cycle, the reservoir water was allowed to flow out using the special drainage valve and the second drying and wetting cycle was preformed. Consecutive drying and wetting cycles were similarly repeated on the soil sample to a point in which axial deformation recorded for drying and wetting, subject to a specific cycle were approximately equal (shrink-swell equilibrium). It should be noted that a typical cycle of drying or wetting took an average time of 7 days; therefore a typical cycle consisting of one drying and one wetting test lasted up to 14 days. Axial deformation during drying and wetting was calculated according to the following equation:

$$\text{£}_a = \frac{\Delta H}{H_0} \times 100 \qquad (1)$$

where ε_a is the axial deformation of the soil sample (%), ΔH is the height change in the soil sample subjected to drying or wetting and H_0 is the initial height of the soil sample at the start of a specific drying or wetting cycle which is being investigated (example the initial height in calculating axial deformation during the second wetting cycle is equal to the soil samples height at the end of the second drying cycle).

In order to calculate the overall swelling potential of the soil sample at the end of a specific drying and wetting cycle, Eq. 1 must be calculated in a cumulative manner, which changed as the following equations for drying and wetting respectively:

$$\varepsilon_{acd,i} = \frac{\overbrace{\Delta H_{D1} + \Delta H_{W1}}^{Cycle-1} + \overbrace{\Delta H_{D2} + \Delta H_{W2}}^{Cycle-2} + ... + \overbrace{\Delta H_{Di}}^{Cycle-i}}{H_0} \times 100 \quad (2)$$

$$\varepsilon_{acw,i} = \frac{\overbrace{\Delta H_{D1} + \Delta H_{W1}}^{Cycle-1} + \overbrace{\Delta H_{D2} + \Delta H_{W2}}^{Cycle-2} + ... + \overbrace{\Delta H_{Di} + \Delta H_{Wi}}^{Cycle-i}}{H_0} \times 100 \quad (3)$$

where $\varepsilon_{acd,i}$ and $\varepsilon_{acw,i}$ is the overall swelling potential at the end of a specific drying or wetting cycle respectively (for e.g. cycle No. *i*) (%), ΔH_{Di} *and* ΔH_{Wi} are the height change in the soil at the end of a specific drying and wetting cycle respectively, and H_0 is the initial height of the soil sample at the beginning of the drying and wetting experiments (20 mm).

3. Results

3.1. Standard compaction tests

Figure 2 shows the compaction curves along various saturation lines (100%, 75% and 50%) for various pore water qualities consisting of distilled water, 50 and 250 g/L NaCl solutions. As seen in the figure, all compaction curves are between the 50% and 100% saturation lines. It can be seen in this figure that the use of salt solutions as pore water, affected compaction characteristics consisting of optimum water content (*OWC*) and maximum dry unit weight (*MDD*). The maximum dry unit weight for samples with distilled water, 50 and 250g/L NaCl solutions were 16, 16.2 and 16.9kN/m^3 respectively and optimum water contents were 22, 21.1 and 19%, respectively. These curves indicate that the use of salt solutions causes optimum water content and maximum dry unit weight to decrease and increase respectively. Furthermore, increase in salt concentration causes more reduction in optimum water content and more increase in maximum dry unit weight.

Figure 3 shows the variations of optimum water content and maximum dry unit weight versus various salt concentrations or TDS. This figure shows that optimum water content and maximum dry unit weight both show a linear relationship with salt concentration. It must be noted that in order to better evaluate the relationship of optimum water content and maximum dry unit weight with salt concentration (*TDS*), an additional compaction test was also conducted on the soil with 100 g/L NaCl solution as pore water and the optimum water content and maximum dry unit weight were seen to be 20.5% and 16.4 kN/m^3, respectively. Equations 4 and 5 show the optimum water content and maximum dry unit weight relationship with salt concentration through simple linear regression models respectively.

$$OWC = -0.011 \times TDS + 21.80 + \varepsilon_r \quad (4)$$

$$MDD = 0.003 \times TDS + 16.01 + \varepsilon_r \quad (5)$$

where *OWC* is the optimum water content (%), *TDS* is the total dissolved solids which represents the salt concentration (g/L), *MDD* is the maximum dry unit weight (kN/m^3) and ε_r is the regression estimation error.

Figure 4 shows the variations of maximum dry unit weight and optimum water content for various compaction tests with distilled and saline water quality. As seen in this figure, the optimum water content and maximum dry unit weight for various salt concentrations show a linear relationship expressed as the following equation:

$$MDD = -0.3050 \times OWC + 22.67 + \varepsilon_r \quad (6)$$

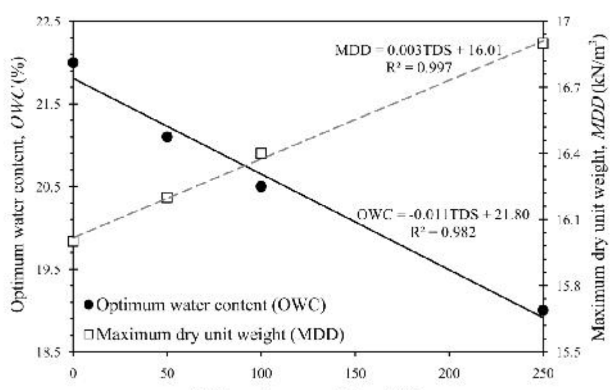

Fig. 3. Variations of optimum water content and maximum dry unit weight with various salt (NaCl) concentrations

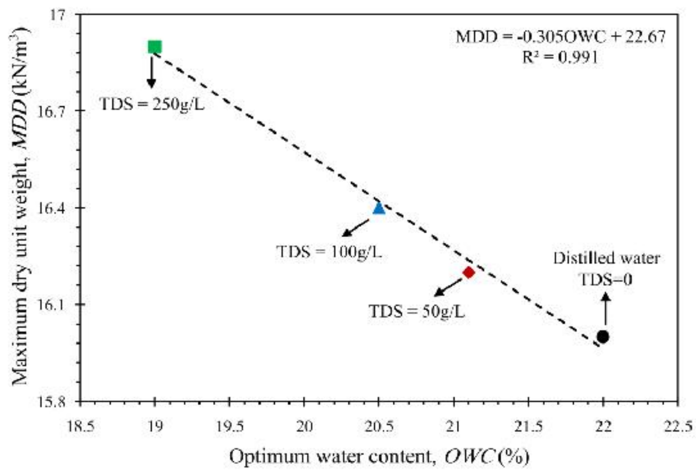

Fig. 4. Variations of maximum dry unit weight with optimum water content for various salt (NaCl) concentrations

3.2. Drying and wetting tests

Variation of axial deformation of soil samples prepared with distilled and saline pore water qualities during different drying and wetting cycles are presented in Figure 5a to 5c for distilled water, 50 and 250 g/L NaCl, respectively. According to Figures 3a and 3b, soil samples prepared with distilled water and 50 g/L NaCl solution, will reach shrink-swell equilibrium after 5 consecutive cycles; meanwhile the use of higher salt concentrations (250 g/L NaCl) resulted in reaching the same equilibrium condition after approximately 3 or 4 cycles. As clearly seen in these figures, plastic deformation which is defined as difference between axial deformation caused by swelling and shrinkage, reduced due to repeating the drying and wetting process and is approximately diminished or reached to a constant value at the equilibrium cycle. Therefore, at the shrink-swell condition, axial deformations caused by swelling or shrinkage are reversible to one another. For example considering Figure 5b, the axial deformation caused by shrinkage and swelling in the first drying and wetting cycle are 2.38 and 11.89%, respectively which shows that 9.51% of the deformations caused by shrinkage and swelling in the first cycle are irreversible or plastic deformations, while at equilibrium condition (5th cycle) axial deformations caused by shrinkage and swelling are 8 and 8.64%, respectively, which results only in 0.64% irreversible or plastic deformations.

Soil samples prepared with distilled water show a swelling potential of 14.5% at the first wetting cycle. However, after conducting consecutive drying and wetting this value reduced to 8.5%. In addition, soil samples prepared with 50 g/L NaCl solution show a 3.23% reduction in swelling potential (11.88% to 8.65%). Also, in regards to samples prepared with 250 g/L NaCl solution, the swelling potential showed a 5.12% reduction (13.45% to 8.33%) in swelling potential. Therefore, it can be concluded that conducting and repeating drying and wetting cycles will cause a considerable decrease in the soils axial deformation caused by swelling.

Figure 6 shows the effect of salt concentration on the overall swelling potential (Equations 3) of the soil during various cycles of wetting. As seen in this figure, the overall swelling potential of soil samples prepared with low salt concentration (50 g/L) are less than samples prepared with distilled water and 250 g/L NaCl solution in all wetting cycles, respectively. It can be easily attained that high salt concentration caused the overall swelling potential to increase, when compared to distilled water and 50 g/L NaCl solution.

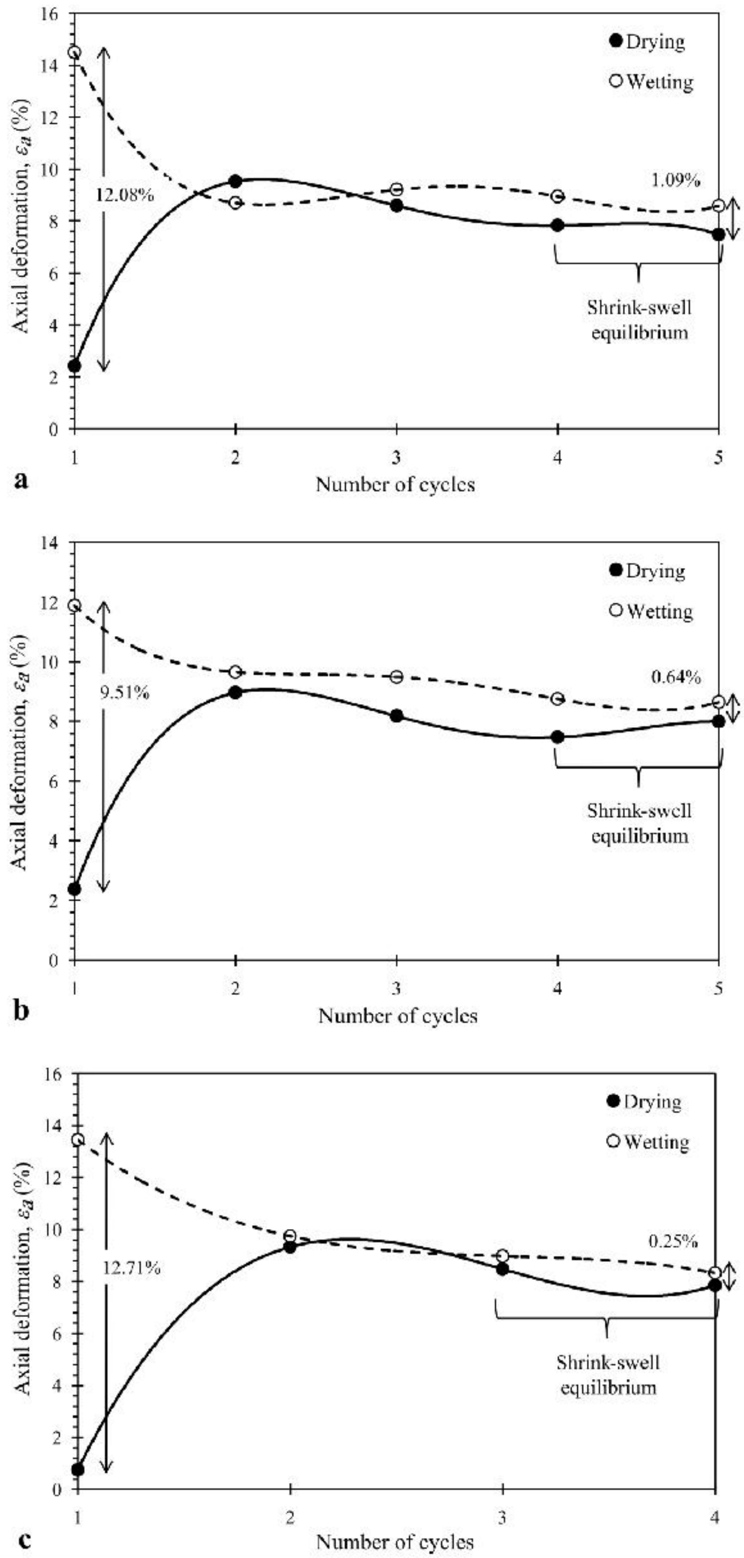

Fig. 5. Variations of axial deformation (shrinkage and swelling) of soil samples during different cycles of drying and wetting for (a) distilled water (b) 50g/L NaCl solution and (c) 250g/L NaCl solution

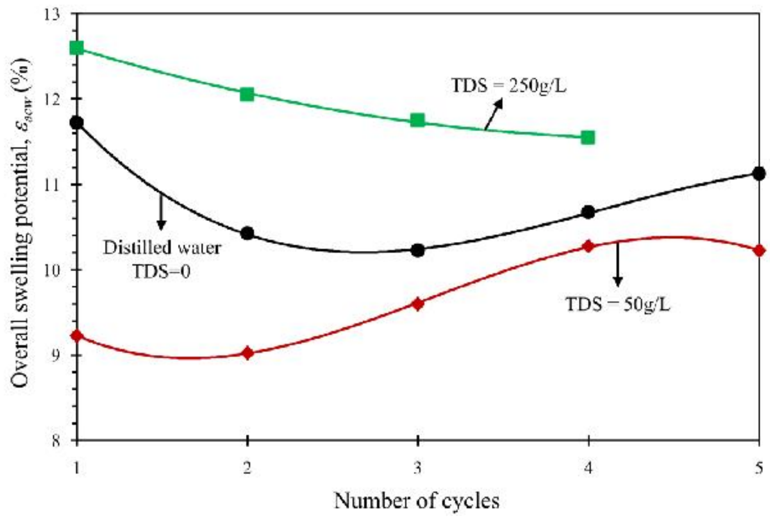

Fig. 6. Variations of overall swelling potential of soil samples during various cycles of wetting

4. Discussion

The results of the compaction tests (Fig. 2) show that the use of NaCl solutions as pore water, caused the optimum water content and maximum dry unit weight to decrease and increase, respectively. These results are in agreement with the studies of Abdullah *et al*. (1999), Singh and Prasad (2007), Alainachi and Alobaidy (2010) and Shariatmadari *et al*. (2011).

Clay particles carry an unbalanced negative charge which attracts positive ions (cations). These cations become strongly attached to a dry clay surface. When water was added to the soil, the cations migrated into the solution and the highest concentration of cations was seen near the clay surface, while the concentration of cations reduced by increasing the distance from the negatively charged clay particles. The negatively charged surface of the clay particles and the distributed cations in the adjacent phase are known as the diffuse double layer or simply DDL (Mitchell, 1993). Several studies have shown that clay behavior such as swelling potential and volume change can be explained and predicted through the DDL theory (Mesri and Olson, 1971; Sridharan and Rao, 1973). It is generally accepted that the use of salt solutions as pore water, causes the thickness of the DDL to decrease, thereby causing an increase in the attractive forces between soil particles. Therefore, using the same amount of energy for compaction will cause soil particles to better pack together and thus, the maximum dry unit weight will increase. In addition, the reduction of the DDL thickness brings the particles closer and decreases the water holding capacity that causes the optimum moisture content to decrease.

Figure 5 shows that the axial deformation caused by swelling (swelling potential) is reduced by repeating the drying and wetting process. Similar results were reported by other researchers such as Dif and Bluemel (1991), Al-Homoud *et al.* (1995), Tripathy *et al*. (2002, 2009), Alonso et al. (2005) and Estabragh et al. (2012, 2013, 2014). During consecutive cycles of drying and wetting, fine particles paste together and form coarse particles which results in a significant decrease in the soils specific surface area (SSA) due to larger particles in the soil structure, therefore conducting drying and wetting cycles on the soil will likely cause reduction of the swelling potential. The reduction in swelling potential is seen to be a function of increase in cycle number, however the relationship between swelling potential and cycle number is clearly nonlinear (illustration of wetting curves in Figure 5). Many researchers such as Basma *et al*. (1996), Tripathy *et al*. (2002, 2009) and Estabragh et al. (2013) have stated that gradual elimination of the hysteresis phenomenon caused by drying and wetting is due to the occurrence of the shrink-swell equilibrium condition; this condition is considered as a state in which the soil has achieved a stable structure.

When salts such as sodium chloride (NaCl) are dissolved in water, it ionizes into cations and anions which are positively and negatively charged molecules, respectively (Buckman and Brady, 1967). In the case of the NaCl solution in this study, the NaCl salt will breakdown to sodium cations (Na^+) and chloride anions (Cl^-). The Na^+ cation is base-forming, meaning that it often contributes to increasing and decreasing the hydroxide anion (OH^-) and hydrogen cation (H^+) concentrations, respectively (Miller and Donahue, 1995). In the case of low concentrations of NaCl solution (50 g/L), the amount of sodium cations and chloride anions dissolved in the soil pore water, acts as a salinity agent which is generally known to form a flocculated structure by pasting fine particles in the soil which results in reduction of the swelling potential compared to distilled water (Fig. 6), similar results were also reported by Abdullah *et al*. (1999) and Shariatmadari *et al*. (2011) who used a concentration of 1N (Normality) NaCl solution. However, in the case of high concentrations of the NaCl solution (250 g/L), the sodium and chloride ions dissolved in soil pore water act as a sodicity agent which mainly causes soil dispersion and increased swelling potential (Buckman and Brady, 1967; Chen and Banin, 1975; Frenkel *et al*., 1978; Hanson *et al*., 1999). When too many large sodium ions are present between clay particles, the attractive forces which paste and keep clay particles together are ruptured and dispersion of clay particles occur, therefore the swelling potential increases (Fig. 6) upon expansion of clay particles. Furthermore, conducting consecutive drying and wetting on soil with high pore water sodicity rather than salinity, causes dispersion of clay particles due to the dominance of repulsive forces, and upon completion of the dispersion process, clay particles form into a solidified cement-like soil (Chen and Banin, 1975; Frenkel *et al*., 1978).

5. Conclusion

The purpose of this study was to investigate the effect of pore water quality on the swelling potential of an expansive soil during drying and wetting cycles. Based on the experimental results, the following conclusions were drawn:

1. The use of NaCl solutions as pore water affected the compaction characteristics. The maximum dry unit weight increased while the optimum water content decreased. Variations of maximum dry unit weight and optimum water content with salt concentration (TDS) were seen to be a linear relationship.
2. Conducting drying and wetting cycles under a surcharge pressure of 10 kPa caused a considerable reduction in swelling potential for expansive soil samples prepared with different pore water qualities. Shrink-swell equilibrium in soil samples prepared with distilled water and low concentration of NaCl solution (50 g/L), was achieved after 5 consecutive cycles while soil samples with 250 g/L NaCl solution as pore water, reached the equilibrium condition after approximately 3 or 4 cycles.
3. The use of high concentration of NaCl solution (250 g/L) acted as a sodicity agent while the use of 50 g/L NaCl solution acted as a salinity agent. As a result, the overall swelling potential was seen to be greater for soil samples prepared with 250 g/L NaCl solution compared to distilled water and 50 g/L NaCl solution, respectively. Therefore, the use of low concentrations of NaCl solution can act as an additive stabilizer agent, that is not only economical compared to traditional methods of stabilization (for example the use of cement, lime and fly-ash) but also widely available in most arid and semi-arid regions.

Further experiments should be conducted using other salt solutions such as calcium chloride, magnesium chloride and potassium chloride with high and low concentrations to better understand the swelling behavior of these soils in arid and semi-arid weather conditions.

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