Effect of glycerol on the behavior of an expansive soil during wetting and drying cycles

The behavior of an expansive soil with different flooding fluid, i.e. distilled water and solution of glycerol with different percentages of glycerol (10, 20, 30 and 40%) was studied through a number of cyclic wetting and drying tests. Experimental tests were conducted on compacted samples of the expansive soil in a modified oedometer with different flooding fluids under a surcharge pressure of 10 kPa. The vertical and radial deformations of the samples were determined during different stages of wetting and drying. The results showed that during cycles of wetting and drying, the deformation of the soil decreased with increasing the number of cycles for all flooding fluids. The magnitude of deformation for samples flooded with solution of glycerol is less than distilled water and this reduction is a function of glycerol concentration. The equilibrium condition of samples with glycerol solution is reached in fewer cycles than distilled water and the number of cycles to reach equilibrium was a function of percent of glycerol. The results also indicated that the swelling-shrinking deformation was nearly the same when the equilibrium condition was attained. Comparison of the results showed that by increasing the percent of glycerol, these curves were contracted. Furthermore, the paths of wetting and drying converged to an S–shaped curve at equilibrium condition.

1. Introduction

Expansive soils have been reported extensively in many parts of the world, particularly in arid and semiarid areas. They have a great change in their volume due to swelling if water becomes available to them or shrinkage if water is removed from them. These volume changes can cause movements of the ground that may result in severe damage to roads and low rise buildings. Puppala and Cerato (2009) and Wray and Meyer (2004) reported that the annual damage due to expansive soils in the USA exceeds $13 billion and about one-third of the reported damage occurs in residential and commercial buildings. Pavements that are built on expansive soils are vulnerable to the damage from these soils. Chen (1988) estimated that nearly half of the overall costs due to damages from expansive soils is associated with pavements. He attributed this to the relatively light weight of pavements which is extended over a large area. Cameron (2006) and Zheng et al. (2009) discussed the damages to railways and highways constructed on expansive soils. Damage to pavements on expansive soils can occur in three major forms: longitudinal cracking, lateral cracking developed from significant localized deformations and localized pavement failure associated with disintegration of the surface.

The potential of swelling of an expansive soil is mainly dependent on its clay content, mineralogy, dry density, water content, surcharge pressure, non-expansive particles, etc (Al-Yaqoub et al., 2017). Young-Gui et al. (2016) and De'an et al. (2015) found that the structure of soil, particle interactions, stress history and salinization influence the properties of swelling soils. Behavior of expansive soils has been studied in laboratory by measuring potential of swelling, swelling pressure and suction (e.g., Ferber et al., 2009). It is generally known that expansive soils experience significant reduction in volume during drying.

However, many factors can influence the behavior of expansive soils and the mechanism of swelling is relatively more complex than shrinkage. Laird (2006) argued that six separate processes control swelling of smectites in aqueous systems. They are named as crystalline, diffuse double layer (DDL), formation and break up of quasicrystals, cation demixing, co-volume and brownian. He stated that crystalline, DDL and breakup of particles primarily control the swelling processes of expansive clay soils. Brownian swelling is an entropy driven process resulting from random thermal motion of suspended colloids (Laird, 2006). Several investigators such as Siddiqua et al. (2011) and Li et al. (2014) have studied the swelling behavior of expansive soils under chemical effects. They have shown that the quality of pore fluid affects the behavior of expansive soils.

In recent years a number of researchers have attempted to study the behavior of expansive soils in cycles of wetting and drying (e.g., Tripathy et al. (2002), Alonso et al. (2005) and Estabragh et al. (2018a)). They reported that the amount of swelling is decreased with increasing the number of cycles. However, Popescu (1980) and Pousada (1984) reported the opposite, i.e., the amount of swelling is increased with increasing the number of cycles. Rosenbalm and Zapata (2017) reported that the potential of swelling and shrinkage during cycles of wetting and drying is dependent on the ratio of the applied load to swelling pressure of soil.

Treatment of expansive soils is necessary to reduce or control the damage to the structures and infrastructure that are built on them. Houston et al. (2011) and Petry and Little (2002) among others, have suggested various chemical and mechanical techniques for stabilization of expansive soils. In chemical stabilization, some additive agents such as lime, cement and fly ash are added to the soil. The chemical reaction is formed in the soil

and the potential of swelling is reduced. For example, lime is commonly used as an additive agent for many structures such as highways, railways, canal lining and others (Petry and Little, 2002). Mechanical stabilization is another group of methods for treatment of expansive soils. In this method, non-swelling materials e.g. sand (Hudyma and Avar, 2006) or granulated tyre rubber and fiber (Patil et al., 2011, Estabragh et al., 2016a) are randomly mixed into an expansive soil to dilute its swelling potential. In addition to the above methods, there is experimental evidence that periodic flooding of swelling soils can reduce their potential of swelling. This is an easy and cost-effective method for treatment of expansive soils. In this method, the consideration of the types of soil minerals and the chemical quality of the flooding water is important in the treatment of soil. For example, the use of chemically treated fluids such as solution of glycerol can be considered in treatment of expansive soils if there is no pathway for leaching of contaminants to underground water or if the contaminants pose no risk to the public and the environment. To the authors' best knowledge, there have been no studies on the effect of hydrocarbon solutions on the behavior of expansive soils during wetting and drying.

In nature, the water in a river or a stream may be contaminated by industrial or urban sewage that may contain some hydrocarbons, changing its chemical quality. If this kind of water containing hydrocarbons floods an expansive soil, the potential of swelling may be different from the flooding by natural water. The aim of this work is to investigate the effect of treated pore fluids on the behavior of an expansive soil during wetting and drying under constant surcharge pressure. The results are compared with each other and with the results obtained for a soil that was flooded with natural water.

2. Experimental work

2.1. *Materials*

2.1.1. Soil

A suitable soil to be used in this research work would be a highly expansive clay. The reasons for selecting a highly expansive soil are: (i) the effectiveness of different flooding fluids in controlling the swelling behavior of expansive soil can be better highlighted if the soil is highly expansive, and (ii) the maximum interaction of soil and organic matters is when the soil minerals have a higher swelling index (as defined by Fang, 1997). This index is between 0 and 1. When it is between 0.6-0.9 the interaction between clay minerals and organic pore fluid is high. The value of index in this range is dependent on the active minerals of clay soil. Therefore, a number of kaolin–bentonite mixtures with different proportions were selected. Bentonite was obtained from Barite Company in Iran (Barite, 2018). The type of bentonite was Na-Montmorillonite. Kaolin was obtained from a local construction materials seller. A series of samples were prepared according to the method that will be presented in the subsequent section. The swelling potential for the prepared samples was measured according to the ASTM D4546-14 standard, and a suitable mixture with a high potential for swelling and shrinkage was chosen as per the classification criteria proposed by McKeen (1992). The chosen mixture was a mixture of 80% kaolin and 20% bentonite. Hereafter, this mixture will be simply referred to as soil. The physical and mechanical properties of the chosen soil were determined according to the ASTM standard and are presented in Table 1. The chemical properties of this soil are shown in Table 2. Based on the information provided in Table 1, the soil is classified as clay with high plasticity, i.e. CH, in accordance with the Unified Soil Classification System (USCS).

XRD (X-ray diffraction) tests were conducted on the samples of this soil and the results are presented in Figs.1a and 1b. Based on the XRD tests, the minerals of the chosen soil were quartz, calcite, feldspar (Na, Ca), feldspar (K) and clay mineral. The clay minerals of the soil were illite and montmorillonite.

2.1.2. Flooding fluid

Two types of liquids were used for flooding the samples: a) distilled water with pH=7.2 and electrical conductivity EC=0.14 dS/m; b) solution of glycerol and water with different concentrations.

Glycerol (Propane-1,2,3-triol) is an oxygenated organic compound. It was bought from an Industrial Chemical Complex Company (Yektachem, 2018). It was with assay> 98% and extra pure. Glycerol has been widely used in the chemical industry in the last decades. The main usage of glycerol has been reported in the detergents industry as well as in drugs and pharmaceuticals production (Pagliaro, 2017 and Wikipedia, 2018). It can be considered as a contaminating agent for soil and water. The dielectric constant, absolute viscosity and mass density of glycerol were 40.1, 0.9058 Pa s and 1258 (kg/m^3) according to the information provided by the supplier. In this work a solution of glycerol with concentrations of 10, 20, 30 and 40% in volume was used. The measured values of pH and EC for these solutions were nearly 7.5 and 0.14 dS/m respectively. To prepare the glycerol solutions, the required amount of glycerol was mixed with distilled water and the mixture was shaken thoroughly before it was used for flooding the samples. Table 3 shows the properties of different solutions of glycerol that were used in this work.

2.2. *Sample preparation*

Standard Proctor compaction test was carried out on the soil with distilled water as pore water according to the ASTM D698-07 standard, and the compaction curve was determined. In order to prepare compacted samples for testing, the required amount of air dry soil was weighed. Then the required quantity of water to reach the desired water content (i.e. 5% below the optimum water content according to the corresponding compaction curve) was added to the soil and mixed thoroughly by hand. After that the soil was placed in a plastic bag and sealed with a tape. The bag was kept in an air tight container for 24 hours to allow the water content to equalize throughout the soil mass. The static compaction method was used for preparing compacted samples. For static compaction a mould was designed and fabricated from stainless steel. This mould consisted of three sections (i.e., top collar, middle section and bottom collar). The dimensions of the middle section were exactly the same as those of the ring of conventional oedometer. A piston was also made for compression of the soil in the mould. A loading machine was used to provide compression at displacement rate of 1.5 mm/min. The soil was compacted in three layers. The load required for each layer to achieve the dry unit weight on the compaction curve corresponding to water content of 5% below optimum water content was determined by trial and error. Before compaction the internal walls of mould were lubricated with silicon oil. Then the required amount of soil for each layer was put in the mould. It was placed on the loading machine and loading was applied until the predefined load was reached. Then the top layer of compacted soil was scarified and next layer was added. At the end the top and bottom collars were removed and the excess of soil was trimmed from the middle section and then it was removed to the apparatus for testing.

2.3. *Apparatus and test procedure*

A conventional oedometer was modified to allow tests to be conducted under controlled temperature and surcharge pressure as shown in Fig.2. The modified oedometer consisted of a fixed ring with a modification to allow wetting and drying of the sample under controlled temperature and surcharge pressure (Fig.2). The fixed ring was placed in the cell or container of the apparatus and tightened to the outer ring by screws. A coil with a capacity of 1 kW was fitted around the outer surface of the container between two sheets of flexible insulators. A valve was provided at the lower side of the cell for draining the fluid and conducting the drying stage of the tests. A number of holes were made on the top load plate which acted as vents for easy removal of the evaporated fluid from the sample. A lever arm was used to apply the surcharge pressure on the sample. Before starting the main tests, the apparatus was calibrated for temperature by using a conventional thermometer. The modified oedometer works in a way similar to the field conditions because under a specific surcharge pressure the sample is subjected to wetting and drying. By using this apparatus only the vertical deformation of sample can be measured during wetting and drying, and measuring the lateral deformation and volume change of sample and its water content at the end of (or during) each cycle is not possible. On the other hand, the conventional oedometer is not equipped with heating system for drying the sample; the sample with mould and surcharge pressure should be moved to oven for drying. Although measuring of deformation, volume change and water content is possible with a conventional oedometer, but the way it works is not similar to field conditions.

The experimental program consisted of two groups of tests. The first group of tests was conducted in the modified oedometer apparatus to study the vertical deformation of the samples during wetting and drying. The second group was conducted to study the vertical

and lateral deformation of the samples during wetting and drying for which a conventional oedometer was used. For each test, the sample was placed in the apparatus (modified or conventional oedometer) between two saturated porous stones, one at the top and one at the bottom of the prepared sample. A seating load of 10 kPa was applied on the sample. The sample was allowed to settle or swell until reaching an equilibrium condition. The sample was then subjected to flooding by water or solution of glycerol in the wetting stage. The readings of the dial gauge were recorded until the equilibrium condition was achieved. The used fluid was then drained off from the cell of the apparatus and the temperature in the modified apparatus was set at 45°C for the drying stage of the tests during which the vertical deformation of the sample was recorded until equilibrium was attained. During the cycles of drying and wetting the volume change of the sample was three dimensional (i.e., deformations occurred in both vertical and lateral directions). The sample in conventional oedometer was placed in an oven at temperature of 45°C under the same surcharge pressure that was used during wetting (i.e., 10 kPa). The sample was then weighed and its dimensions were measured at different time intervals until they reached constant values. Each test was continued until the vertical deformations during wetting and drying reached nearly the same value. At least six or seven duplicated samples of different flooding fluids were tested during each wetting or drying cycle for plotting the variations of void ratio versus water content.

At the end of swelling stage in each test, three samples with volume of 10 cm^3 were taken from the oedometer reservoir. They were used to determine electric conductivity (EC) and pH of the fluid. The EC and pH were determined according to the ASTM D1125-14 and

D5464-16 respectively. Then the average of them was presented as the final results of the chemical tests.

3. Results

Fig. 3 shows typical compaction curves for the natural soil and soils contaminated with 30 and 40% solutions of glycerol. As shown in this figure, the maximum dry unit weight for samples contaminated with 30 and 40% solution of glycerol are 16.46 and 16.8 kN/m^3 and their corresponding optimum water contents are 19.9 and 18.0% respectively. The results show that the maximum dry unit weight increases and the optimum water content decreases with increasing the percent of glycerol solution.

The vertical deformation of the samples is expressed as the change in the height (ΔH) of the sample during either swelling or shrinkage. The percentage of vertical deformation is calculated from the deformation of sample (ΔH) over the initial height of sample (H_0). The sign of ΔH is considered positive for swelling and negative for shrinkage. By plotting the vertical deformation of a sample for several swell-shrink cycles the trend of variation of change in height of the sample during cycles of wetting and drying was observed. Surcharge pressure of 10 kPa was used for each sample that was flooded with a specific fluid and this surcharge pressure was kept constant during wetting and drying until equilibrium was achieved. As shown in Fig.4, the values of deformation during wetting at the first cycle for the samples flooded with distilled water and solutions of 10, 20, 30 and 40% glycerol are 8.8%, 12.3%, 9.15%, 10.1% and 8.6% respectively. These results show that the deformation for the sample flooded with solution of 10% glycerol is more than the other samples. During drying, in the first cycle the relative vertical deformation was ~~increased~~ changed (the sample height was decreased); the relative vertical deformation

was 11.5% for the sample that was flooded with distilled water and for the samples that were flooded with solutions with 10, 20, 30 and 40% glycerol they were 14.0%, 11.0%, 8.1% and 2.5 % respectively. The results (Fig.4) show that by increasing the number of cycles, the magnitude of irreversible deformation is reduced until the equilibrium condition where the deformation due to wetting and drying is nearly the same and reversible. The results in Fig.4 show that at equilibrium condition, the deformation of the sample flooded with distilled water is 14.05%. At equilibrium condition the deformation of the samples flooded with 10, 20, 30 and 40% glycerol are 12.5, 2.75, 0.6 and 0.0% respectively. The results show that the cyclic magnitude of deformation is decreased with increasing the concentration of glycerol. These results indicate that by increasing the concentration of glycerol the magnitude of irreversible deformation in subsequent cycles is decreased and equilibrium with reversible deformation is reached in fewer cycles of wetting and drying than the sample that was flooded with distilled water.

Typical results of void ratio versus water content for the samples flooded with solution of 20% glycerol under surcharge pressure of 10.0 kPa (that were obtained from duplicated samples) are shown in Fig. 5 along with various constant saturation lines. In this figure, the changes of void ratio (e) with water content (w) are shown from the initial (as compacted) condition to the third cycle of wetting and drying. In Fig. 5 points B, D and F show the positions of the samples at the end of swelling (wetting) stages in different cycles and points C, E and G indicate the positions of the samples at the end of shrinkage (drying) stages. As shown in this figure, point A represents the initial state of prepared sample with w=14% and e=0.785. In the first cycle, wetting starts from this point (A) by flooding the sample and is followed to point B that is located on the line of S_r=100%. In drying stage it

moves from point B to point C where the water content and void ratio of the soil are 15% and 0.759 respectively. The trend of cycles 2 and 3 starting from points C and E is similar to cycle 1. These results show that the soil reached nearly saturation in all stages of wetting and that all the wetting and drying curves were nearly S shaped. The tendency to converge to the same S shaped curve was evolved by repeating the cycles of wetting and drying.

Fig.6 shows the equilibrium conditions for the swelling-shrinkage paths for distilled water and different percentages of glycerol under surcharge pressure of 10.0 kPa. As shown in this figure, the paths of drying-wetting for different flooding fluids are nearly S shaped curves. This figure shows that the values of void ratio and water content at equilibrium condition are not the same for each flooded fluid. For example, the values of void ratio (e) at the end of drying for 20, 30 and 40% solution of glycerol are 0.725, 0.693 and 0.648 respectively. It is seen in this figure that the order of the curves in this space is dependent on the percent of glycerol; the curves for the sample flooded with distilled water and 40% glycerol are located at the top and bottom the space of void ratio against water content.

The average values of EC and pH, along with error bars, for the water samples taken from the reservoir at the end of each cycle are shown in Fig.7. As shown in this figure, the values of EC and pH of the reservoir fluids decreased from their values at the end of cycle 1 (EC=5.58 dS/m and pH=7.73). Fig. 8a shows the values of EC at the end of each cycle for different solutions of glycerol. As it is seen in this figure, at the end of cycle 1 the value of EC for solution of 10% glycerol is nearly 2.5 dS/m but for other solutions it is much less than this value. The rate of reduction of EC at the end of this cycle is decreased with increasing the concentration of glycerol. The reduction is also seen at the end of other cycles; for example at the end of the fourth cycle, the value of EC for 20, 30 and 40%

glycerol solutions is nearly 0. The variations of pH of the flooding fluid at the end of each cycle, relative to the previous cycle, are shown in Fig.8b for glycerol solutions with different concentrations. As shown in this figure, there is no specific trend in the variation of pH at the end of each cycle.

4. Discussion

In general, the surface of clay particles is negatively charged because of the complex arrangement of elements that make up the clay structure. Charge neutrality of clay is due to the positive ions present in the soil matrix or the exchangeable cations which are electrostatically attracted to the negative clay surface. The quantity of these exchangeable cations that is required to balance the surface charge is named the cation exchange capacity, CEC (Mitchell and Soga, 2005). By adding distilled water to the soil, the exchangeable cations hydrate. If instead of adding distilled water, a solution with different cations is added, then cation exchange reactions take place. But exchangeable cations also remain in the interlayer to keep electrical balance. The soluble cations in the soil are those than can solubilize if water is added. The charged surface and distributed charge in the adjacent phase are together termed the diffuse double layer (DDL). Interlayer swelling (due to exchangeable cations hydration) and osmotic swelling (taking place in the DDL) are two different processes that both contribute to the soil swelling. For a given soil particle, the thickness of DDL is dependent on factors such as valency and concentration of cations, temperature and dielectric constant. In the present work, the value of dielectric constant for water is 80 and for solutions of 10, 20, 30 and 40% glycerol they are 76.7, 73.2, 69.8 and 66.2 respectively (calculation was done according to the Ratnaweera and Meegoda, 2006).

Before testing the prepared samples were in unsaturated condition. When they were flooded with distilled water or solution of glycerol, the fluid flowed from the reservoir to the sample until the sample became saturated. After full saturation, the fluid may flow between the reservoir and the sample due to osmotic suction. When the flooding fluid is a solution of glycerol, the initial chemical composition of pore fluid in the sample is changed. The chemical composition of pore fluid has different effects on the structure of clay soil such as changing in the thickness of DDL (Musso et al.; 2003, Abdullah et al, 1999 and Sridharan and Rao, 1973). The attractive and repulsive forces between clay particles are inversely and directly related to dielectric constant. The reduction in the value of dielectric constant causes increase in the attractive forces and leads to the reduction in the thickness of DDL. When the flooding fluid is distilled water the pore fluid of samples has a dielectric constant of about 80. Therefore, the values of attractive and repulsive forces are not changed because of the same dielectric constant of flooding fluid and pore fluid. The results of tests on these samples (flooded with distilled water) show that by repeating the wetting and drying cycles the potential of swelling is reduced and after several cycles a reversible equilibrium condition is attained as shown in Fig.4. This can be attributed to the reconstruction of the clay structure during wetting and drying (Dif and Blumel, 1991 and Sridharan and Allam, 1982). The original structure of the expansive soil may be changed after the first or second cycle and repeating the cycles of wetting and drying causes the aggregation and re-arrangement of the structure of the soil. This is because by increasing the number of wetting and drying cycles, the potential of swelling and shrinkage is reduced (Zhang et al. 2006). When the pore fluid is solution of glycerol, the attractive forces are increased due to the reduction of dielectric constant of pore fluid and causes reduction in

the thickness of DDL. The shrinking of DDL causes formation of flocculated structure in the soil and results in pasting of particles together. This reduces the specific surface of the particles and the capacity of adsorbed water and results in the reduction of swelling potential. When the percent of glycerol in the solution is increased the dielectric constant is decreased and the magnitude of attractive forces is increased. This increases the degree of flocculation of the soil structure which in turn leads to more reduction in the potential of swelling. A higher percent of glycerol in the solution causes greater reduction in the potential of swelling (see Fig.4). Table 3 shows the variations of potential of swelling at equilibrium condition for different dielectric constants of various flooding fluids used. It is resulted from this table that the reduction in swelling potential is due to the dielectric constant of pore fluid.

The number of cycles (N) and percent of glycerol (P) were considered as two independent variables to develop a correlation for determining the vertical deformation during wetting and drying. Different types of regression model such as linear, quadratic, cubic, sigmoid and wave form were examined and compared based on their R^2 values. The following (damped sine) equation was chosen because of its comparatively high value of $R^2=0.90$ and good correlation between the measured and calculated data.

$$F(N,P) = \left[a.\exp(\frac{-N}{d}.Sin(\frac{2\pi N}{b}+c)\right]\left[e.\exp(\frac{-P}{g}).Sin(\frac{2\pi P}{h}+i)\right]$$

where F= percent of vertical deformation. a, b, c, d, e, i, g and h are the coefficients of the equation that were determined as:

a= 165.59, b= 1.0, c= -0.5, d= 3.76, e= 4.255, g= 0.1372, h=14.65, i= 0.0417

Fig.9 shows typical results of measured and regression model values of vertical deformation during wetting and drying for a sample that was flooded with 30% solution of

glycerol. As shown in this figure the trend of variation of regression model deformation is consistent with the experimental data. It is resulted from the above equation that the deformation during wetting and drying is reduced with increasing the percent of glycerol. Fig.6 shows the variations of void ratio with water content at equilibrium conditions for different flooding fluids. The results show that at a given water content, the void ratio of the sample decreases with increasing the percent of glycerol. The reduction in void ratio of samples at the equilibrium condition is a function of concentration of glycerol. This can be explained with the aid of compaction curves for natural soil and soil contaminated with glycerol and the behavior of solution of glycerol. The results of compaction tests (Fig.3) show that, for the soils contaminated with glycerol, the maximum dry unit weight is increased and optimum water content is decreased in comparison with the natural soil. These changes in compaction parameters are function of the percent of glycerol. These results indicate that by increasing the percent of glycerol the degree of flocculation is increased and more particles are pasted to each other so the soil particles move towards a granular condition. These results are consistent with results that were reported by Estabragh et al. (2018b). According to the results of the compaction tests, by increasing the percent of glycerol the void ratio is increased. Therefore, the flooding fluid can more easily penetrate to the mass of soil and saturate it. The rate of penetration of fluid into soil mass is dependent on the degree of flocculation of the soil structure which is in turn, dependent on the percentage of glycerol used. By increasing the percent of glycerol in the solution, larger voids are formed and time for saturation is decreased. The results in Fig.6 show that the value of void ratio at equilibrium condition is decreased with increasing the percent of glycerol in the flooding fluid. For example, for a sample that was flooded with 40%

glycerol solution the void ratio was less than the samples that were flooded with a lower

percent of glycerol. As mentioned above, the repeating cycles of wetting and drying and

also the dielectric constant of pore fluid are effective in changing the structure of soil and

reduction of the potential of swelling. The viscosity of pore fluid plays an important role

in reduction of the void ratio and compression of the sample (Ratnaweera and Meegoda,

2006). Table 3 shows that the value of viscosity is increased with increasing the percent of

glycerol. The viscosity of the pore fluid can facilitate lubrication at particle contacts and

reduce the voids between the particles and make a closer packing. During flooding, the

fluid penetrates between the particles. The viscosity of this fluid is dependent on the percent

of glycerol; the higher the percent of glycerol, the higher is the viscosity. Since the samples

are under constant surcharge pressure, the reduction of voids is dependent on the percent

of glycerol or viscosity of the fluid. Therefore, the viscosity of pore fluid and its effect on

diffuse double layer (that is a function of percent of glycerol) are important in reducing the

number of cycles and deformation during wetting and drying. It is resulted from

compaction curves (Fig.3) that the degree of flocculation for natural soil is less than the

soil contaminated with solution of glycerol. In other words, the larger voids between

particles of the natural soil are less than the contaminated soil. Clay soils may have some

salts in their pore spaces and when a sample of clay is flooded with distilled water, they

are dissolved in pore water. By increasing the concentration of pore water due to the

dissolved salts the electrical forces between particles are changed and this affects the

swelling behavior of the soil. Therefore, osmotic water flow also occurs in the soil sample

due to chemical gradient between pore water and reservoir. Osmotic flow into the sample

causes salt diffusion from the pores of the soil. Diffusion of salt causes increase in the

interparticle repulsive forces and swelling potential. It is observed from Fig.6 that at a given water content, the value of void ratio is more than the samples that are flooded with solution of glycerol, which is due to the increasing repulsion forces between particles.

As shown in Fig.6 the final water content of soil flooded with 40% glycerol is 15% that is close to water content of 10 % for samples that were flooded with other percents of glycerol solution. The boiling points for water and glycerol are 100 and 290°C respectively. The oedometer tests were conducted at 45°C (representing the field temperature). At this temperature the evaporation of the existing glycerol may not occur. When the percent of glycerol is increased in the solution, during drying more glycerol remains in the soil and causes increase in the water content. Therefore, the water content of the sample flooded with 40% glycerol is more than the other solutions of glycerol. The measurement of water content was similar to the method that was used by other researcher such as Ratnaweera and Meegoda (2006) and Meegoda and Ratnaweera (1994) for contaminated soil.

It is shown that when the drying and wetting curves coincide, each can be simplified to a unique S–shaped curve. This (S-shaped) curve consists of three sections: two curvilinear portions at the top and bottom, and a linear portion in the middle. The variations of void ratio and water content at the top and bottom of the S–shaped curve are insignificant. The middle section of the curve, however, is linear and nearly parallel with the full saturation line with high variations of void ratio and water content. These results are in agreement with the results that were reported by Hanafy (1991) and Tripathy et al. (2002).

Expansive soils can cause damage to structures, particularly light buildings and pavements, because of the volume change during wetting and drying due to the changes in water content. Treatment of these soils is necessary before constructing any buildings on

them or using these soils as borrow area for construction of structures, roads or pavements. The results obtained from this work reveal that flooding of these soils with solution of glycerol and water and conducting the wetting and drying cycles is an effective method for their treatment. This method has many advantages such as low cost and ease of in situ application, in comparison with other methods. Before applying this method for treatment of soil, the effect of solution of glycerol and water on environment should be studied.

Conclusion

Cyclic drying and wetting tests were performed on samples of an expansive soil prepared with different pore water qualities. The following conclusions can be drawn from the results of this work:

1- Irreversible deformation was observed for samples that were flooded with distilled water and with solutions of glycerol and water as flooding fluids. After a number of cycles these deformations diminished and equilibrium condition was attained. Solutions of glycerol and water caused greater reduction in the potential of swelling in comparison with distilled water. The higher the percent of glycerol, the greater the reduction in swelling potential.

2- The reduction in the potential of swelling is dependent on the dielectric constant of used flooding fluid. For the glycerol solution, the reduction in swelling potential is a function of concentration of glycerol.

3- The wetting and drying paths in the space of void ratio and water content are *S*–shaped curves. For samples with different quality of flooding fluid, these curves

nearly coincide with each other at equilibrium condition (reversible deformation). The variation in the void ratio of samples flooded with solution of glycerol is smaller than distilled water.

References

Abdullah, W. S., Alshibli, K. A., Al-Zoubi, M. S., 1999. Influence of pore water chemistry on the swelling behavior of compacted clays. *Applied Clay Science*, **15**(5–6), 447–462.

Alonso, E.E., Romero, E. Hoffmann, C., Carcia-Escudero, E. 2005. Expansive bentonite-sand mixtures in cyclic controlled-suction drying and wetting. *Engineering Geology*, **8**, 213-226.

Al-Yaqoub, T.H., Parol, J., Znidarcic, D., 2017. Experimental investigation of volume change behavior of swelling soil. *Applied Clay Science*, **137**, 22-19.

ASTM, 2007, *Annual book of ASTM standards, soil and rock*, West Conshohocken, PA: American Society for testing Materials.

ASTM, 2014, *Annual book of ASTM standards, soil and rock*, West Conshohocken, PA: American Society for testing Materials.

ASTM, 2016, *Annual book of ASTM standards, soil and rock*, West Conshohocken, PA: American Society for testing Materials.

Barite, 2018, www.barite.iran

Cameron, D.A., 2006. The role of vegetation in stabilizing highly plastic clay subgrades. *In: Proceeding. Of Railway Foundations, RailFound 06,* (Ghataora G.S. and Burrow M.P.N. eds), Birmingham, UK, pp. 165-186.

Chen, F.H., 1988. *Foundations on expansive soils*. Elsevier, Amsterdam, the Netherlands.

De'an, S., Long, Z., Jie, L., Benchen, Z., 2015. Evaluation and prediction of the swelling pressures of GMZ bentonites saturated with saline solution. *Applied Clay Science*, **105-106**, 207-216.

Dif, A.E., Bluemel, W.F., 1991. Expansive soils under cyclic drying and wetting. ASTM *Geotechnical Testing Journal*, **14**(1), 96-102.

Estabragh, A. R., Moghadas, M., and Javadi, A. A., 2013. Effect of different types of wetting fluids on the behaviour of expansive soil during wetting and drying. *Soils and Foundations*, **53**(5), 617–627.

Estabragh, A. R., Parsaei, B., and Javadi, A. A., 2015. Laboratory investigation of the effect of cyclic wetting and drying on the behaviour of an expansive soil. *Soils and Foundations*, **55**(2), 304–314.

Estabragh A.R., Beytolahpour I., Moradi M. and Javadi, A.A., 2016a. Mechanical behavior of a clay soil contaminated with glycerol and ethanol. *European Journal of Environmental and Civil Engineering,* **20** (5), 503-519.

Estabragh, A.R., Khatibi M. and A.A. Javadi, A.A., 2016b. Effect of cement on treatment of a clay soil contaminated with glycerol. *Journal of Material in Civil Engineering, ASCE*, **28** (4), pp.04015157-1-10

Estabragh, A.R., Soltani, A. and Javadi, A.A., 2018a. Effect of pore water chemistry on the behaviour of a kaolin–bentonite mixture during drying and wetting cycles. *European Journal of Environmental and Civil Engineering*, Published online

Estabragh, A.R., Afsari, E., Javadi, A.A. and Babalar, M., 2018b. Effect of two organic chemical fluids on the mechanical properties of an expansive clay soil. *Journal of Testing and Evaluation, ASTM*, **48**(5) pp. 20170623.

Fang H.Y., 1997. *Introduction to Environmental Geotechnology*, CRC Press, Boca Raton, FL.

Ferber, V., Auriol, J.C., Cui, Y.J., Magnan, J.P., 2009. On the swelling potential of compacted high plasticity clays. *Engineering Geology*. **104**, 200-210.

Hanafy, E.A.D.E., 1991. Swelling/shrinkage characteristic curve of desiccated expansive clays. *Geotechnical Testing Journal*, ASTM, **14**(2), 206-211.

Houston, S.L., Dye, H.B., Zapata, C.E., Walsh, K.D. and Houston, W.N. 2011. Study of expansive soils and residential foundations on expansive soils in Arizona. *Journal of performance of constructed facilities,* **25** (1), 31- 44.

Hudyma, N.B. and Avar, B., 2006. Changes in swell behavior of expansive soils from dilution with sand. *Environmental Engineering Geoscience*, **12** (2), 137 – 145

Laird D.A., 2006. Influence of layer charge on swelling of smectites, *Applied Clay Science*, **34**, 74-87.

Li, Z., Tang, C., Hu, R., and Zhou, Y., 2014. Experimental research on expansion characteristics of Mengzi expansive soil with water, salt and acid immersion. *Environmental Earth Science*, **72**(2), 363–371.

McKeen, R.G., 1992. A model for predicting expansive soil behavior. *In: Proceedings of the 7th International Conference on Expansive Soils*. Dallas, pp. 1-6.

Meegoda N.J. and Ratnaweera P., 1994. Compressibility of contaminated fine-grained soils, *Geotechnical Testing Journal*, **17**(1), pp. 101-112.

Mitchell, J. K., and Soga, K., 2005. *Fundamentals of soil behavior* (3rd Ed). Hoboken: John Wiley & Sons.

Murray, H.H., 2007. *Applied clay mineralogy: occurrence. Processing and Application of Kaolins, Bentonites, Palygorskite-Sepiolite, and Common Clays*. Elsevier.

Musso, G., Morales, E. R., Gens, A., and Castellanos, E., 2003. The role of structure in the chemically induced deformations of FEBEX bentonite. *Applied Clay Science*, **23**(1–4), 229–237.

Pagliaro, M., 2017. *Glycerol*, 1st edition, The renewable platform chemical, Elsevier,

Patil, U., Valdes, J.R. and Evans, M.T., 2011. Swell mitigation with granulated tire rubber. *Journal of Materials in Civil Engineering*, **25** (5), 721-727.

Petry, T.M. and Little, D.N., 2002. Review of stabilization of clays and expansive soils in pavement and lightly loaded structures – History, practice and future. *Journal of Materialsin Civil Engineering*, **14** (6), 447-460.

Popescu, M.E. 1980. Engineering problems associated with expansive clays from Romanian. *Engineering Geology*, **14**, 43-53.

Pousada, E., 1984. *Deformabilidad de arcillas expansivas bajo succio´n controlada*. Doctoral Thesis, Universidad Politecnica de Madrid, Spain.

Puppala, A.J., Cerato, A., 2009. Heave distress problems in chemically-treated sulfate-laden materials. *Geo-Strata*, **10**(2), 28-32.

Pusch, R., Yong, R.N., 2006. *Microstructure of Smectite Clays and Engineering Performance*. Taylor & Francis.

Ratnaweera, P., and Meegoda, J. N., 2006. Shear strength and stress–strain behavior of contaminated soil. *Geotechnical Testing Journal*, **29**(2), 133–140.

Rosenbalm, D., Zapata, C.E., 2017. Effect of wetting and drying cycles on the behavior of compacted expansive soil. *Journal of Material in Civil Engineering*, 04016191-9.

Siddiqua, S., Blatz, J., and Siemens, G., 2011. Evaluation of the impact of pore fluid chemistry on the hydromechanical behaviour of clay–based sealing materials. *Canadian Geotechnical Journal*, **48**(2), 199–213.

Sridharan, A., Rao, G.V., 1973. Mechanisms controlling volume change of saturated clays and the role of the effective stress concept. *Géotechnique*, **23**(3), 359-382.

Sridharan, A., and Allam, M. M., 1982. Volume change behavior of desiccated soils. *Journal of Geotechnical Engineering*, Division ASCE. **108**(8), 1057–1071.

Tripathy, S., Subba Rao, K.S., Fredlund, D.G. 2002. Water content-void ratio swell-shrink paths of compacted expansive soils. *Canadian Geotechnical Journal*, **39**, 938-959.

Wikipedia, 2018. https://en.wikipedia.org/wiki/Glycerol

Wray, W.K., Meyer, K.T., 2004. Expansive clay-soil-A widespread and costly Geohazard. *GeoStrata*, ASCE, **5**(4), 24-28.

Yektachem, 2018. www.yektachem.com

Young-Gui, C., Chun-Min, Z., Wei-Min, Y., Yu-Jun, C., Bao, C., 2016. Effect of solution concentration and vertical stress on the swelling beahviour of compacted GMZ01 bentonite. *Applied Clay Science*, **124–125**, 11–20.

Zhang R., Yang, H. and Zheng, J. 2006. The effect of vertical pressure on the deformation and strength of expansive soil during cyclic wetting and drying. *In: Proceedings of the 4ᵗʰ International Conference on Unsaturated soil.* Arizona, USA, P., 894-905.

Zheng, J.L., Zhang, R. and Yang, H.P., 2009. Highway subgrade construction in expansive soil areas. *Journal of Materials in Civil Engineering,* **21** (4), 154-162.

Table 1. Physical and mechanical properties of the used soil.

Properties	Value
Specific gravity, G_s	2.75
Grain–size distribution	
Gravel (%)	0.0
Sand (%)	26.0
Silt and Clay (%)	74.0
Consistency limits	
Liquid limit, LL (%)	81.0
Plastic limit, PL (%)	27.5
Plasticity index, PI (%)	53.5
USCS classification	CH
Compaction characteristics	
Optimum water content, w_{opt} (%)	22.0
Maximum dry unit weight, γ_{dmax} (kN/m^3)	16.0

Table 2. Chemical composition of the used soil.

Chemical components	Amount
pH	8.4
EC^a (dS/m)	13.9
Na^+ (meq/L)	142.0
Ca^{2+} (meq/L)	21.0
Mg^{2+} (meq/L)	6.0
Cl^- (meq/L)	49.0
HCO_3^- (meq/L)	7.5
SO_4^{2-} (meq/L)	112.0

[a]Electrical conductivity.

Table 3. Measured physical and chemical properties of pore fluids tested at 25°C

Fluid	Mass density (kg/m^3)	Absolute viscosity (mPa s)	Dielectric constant	Relative vertical deformation at equilibrium condition (%)
Water	996.89	8.927	80.0	14.05
10% glycerol + water	997.76	9.159	76.7	12.50
20% glycerol + water	1002.60	9.475	73.2	3.75
30% glycerol + water	1005.50	9.766	69.8	0.60
40% glycerol + water	1008.5	10.070	66.2	0.00
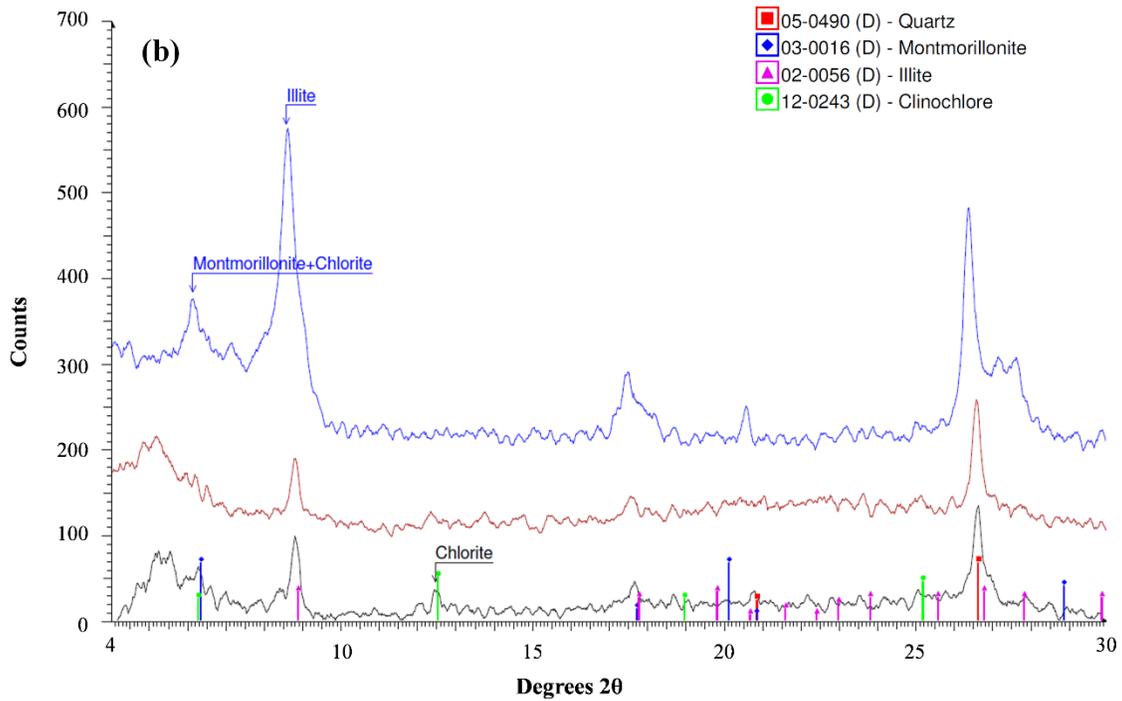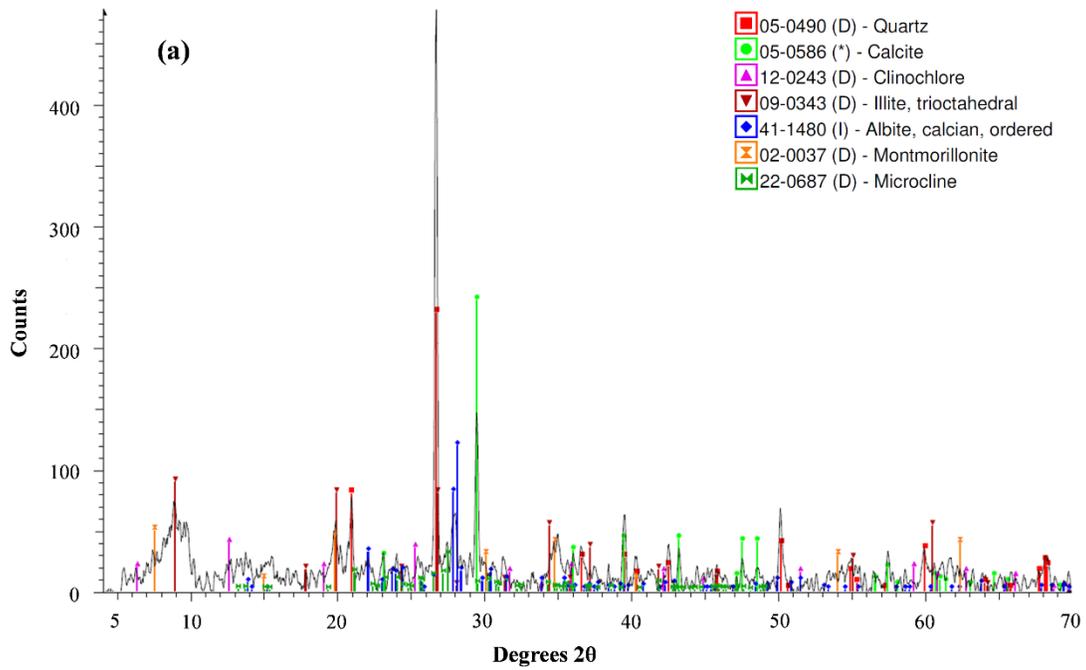
Fig.1. X-ray diffraction plots (a) minerals (b) clay minerals of soil

1: load plate
2: top porous stone
3: bottom porous stone
4: specimen ring
5: outer ring
6: vent
7: loading plunger
8: wire
9: temperature controller
10: power supply
11: asbestos insulation
12: coil
13: drainage valve
14: strain dial gauge
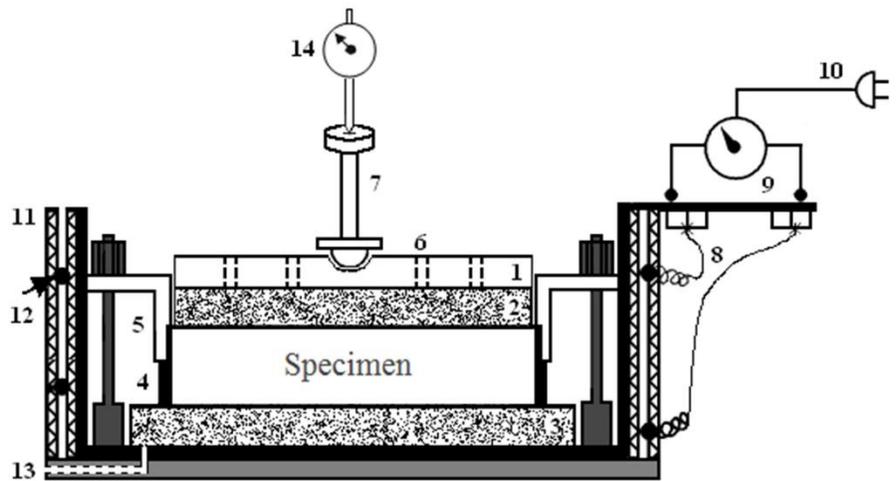
Fig.2. Layout of apparatus
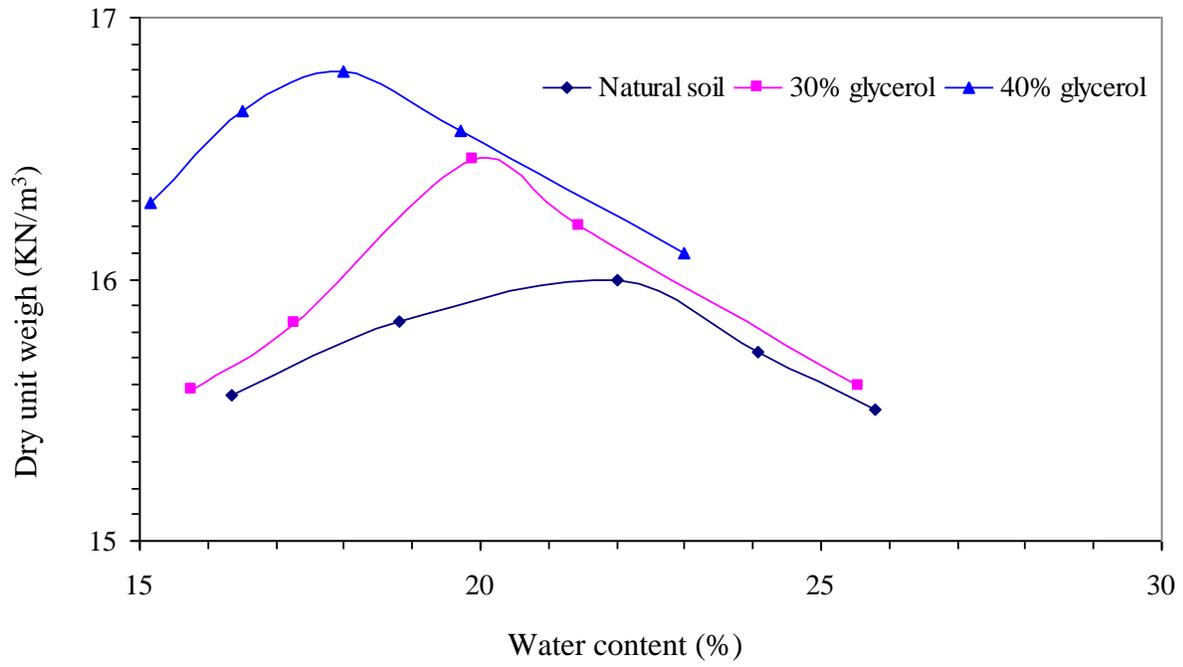
Fig.3 Compaction curves for natural soil and soil contaminated with 30 and 40% solution of glycerol
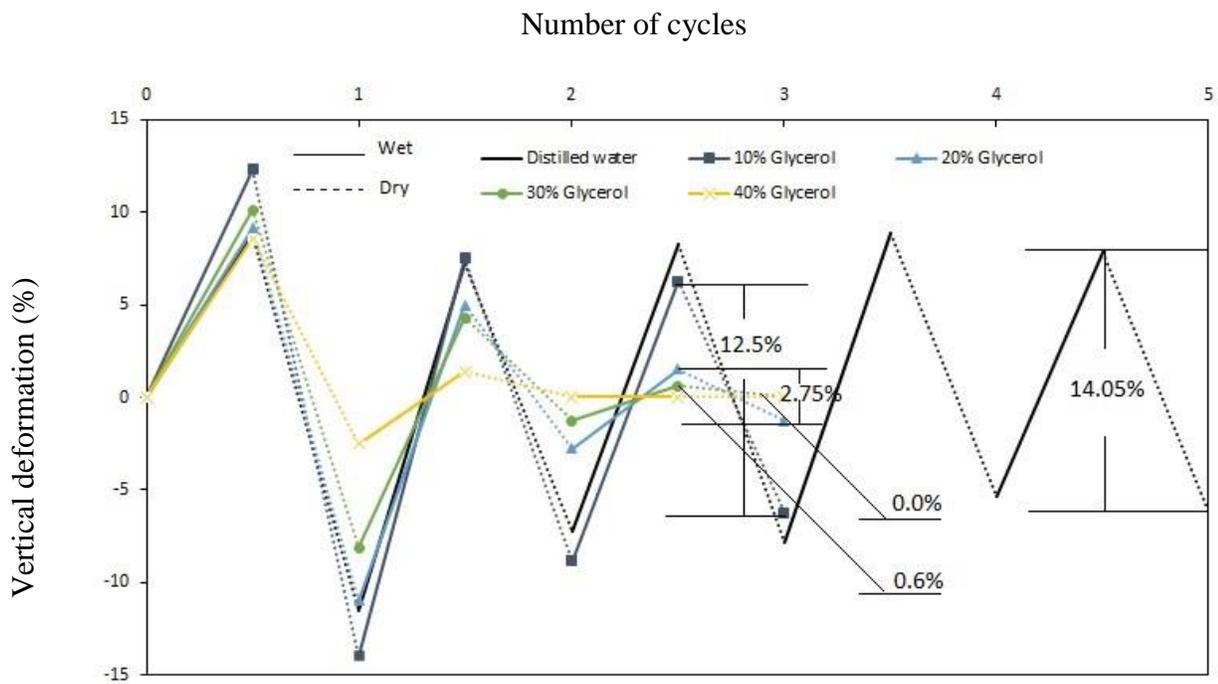
Fig.4. Relative **v**ertical deformation (%) during wetting and drying cycles for different quality of flooding fluid
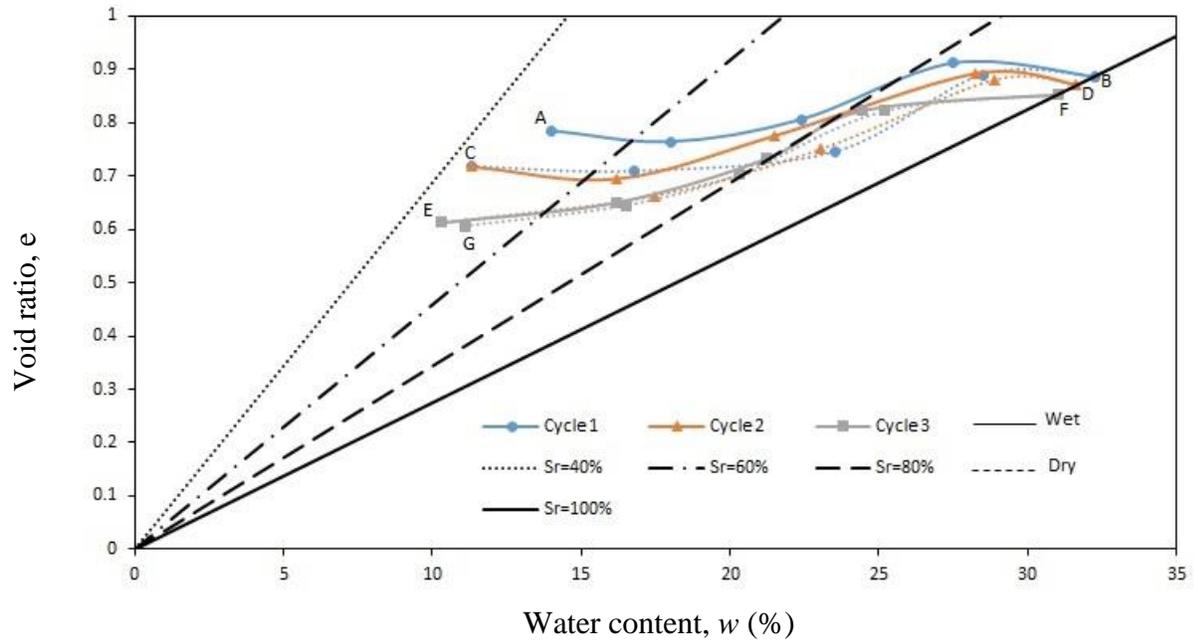
Fig.5. Variations of **w**ater content with void ratio paths for solution of 20% glycerol during different cycles.
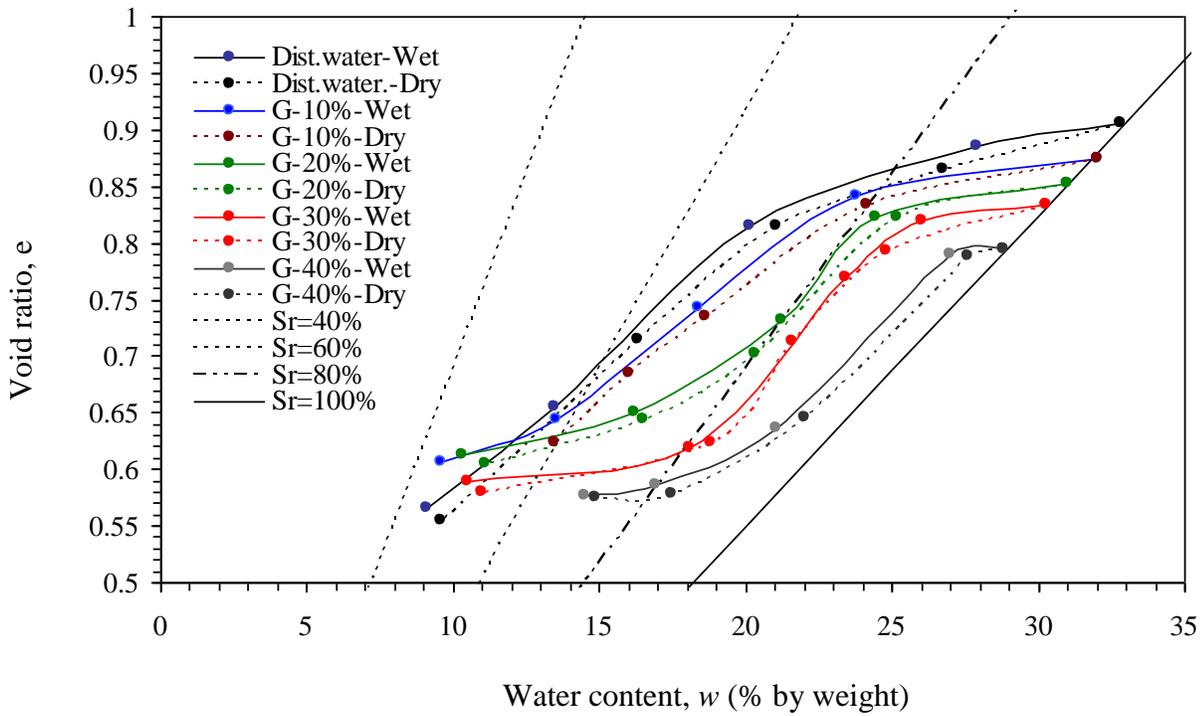
Dist..= Distilled, G=Glycerol

**Fig.6**. Equilibrium condition of swell-shrink paths for different flooding water quality
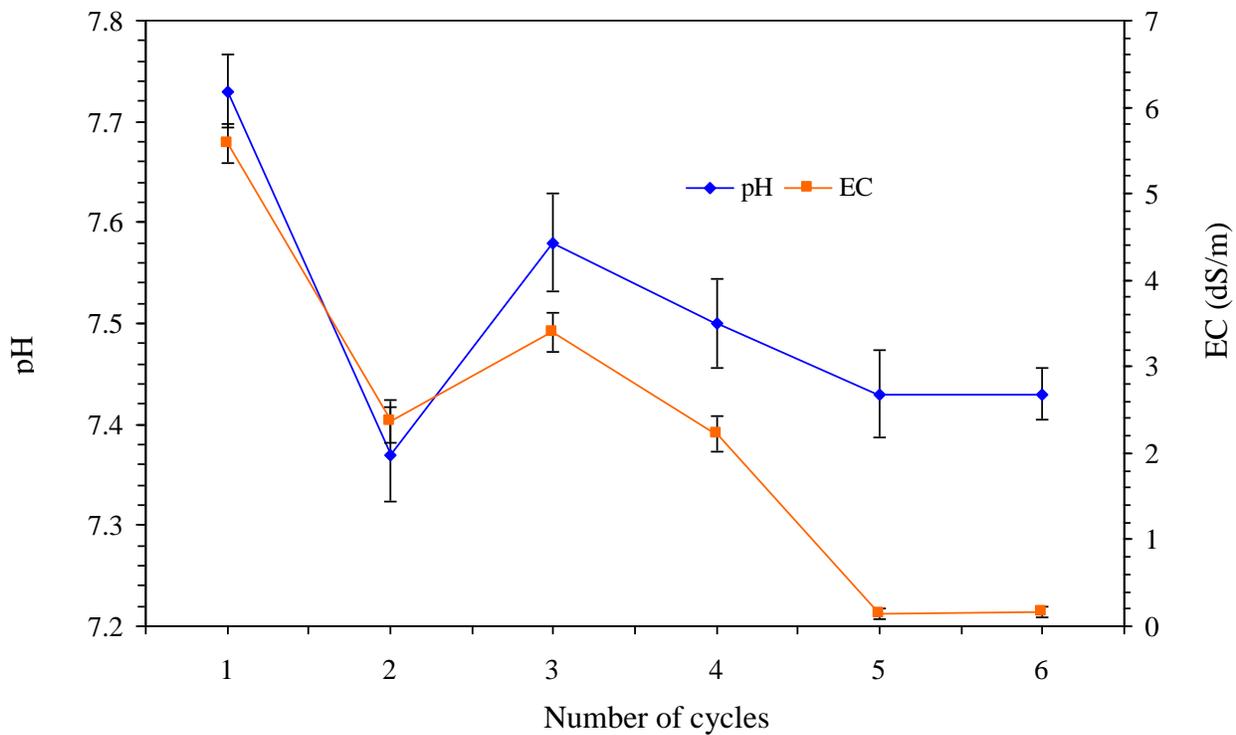
**Fig.7**. Variations of (a) EC and (b) pH at the end of each cycle for distilled water with error bars
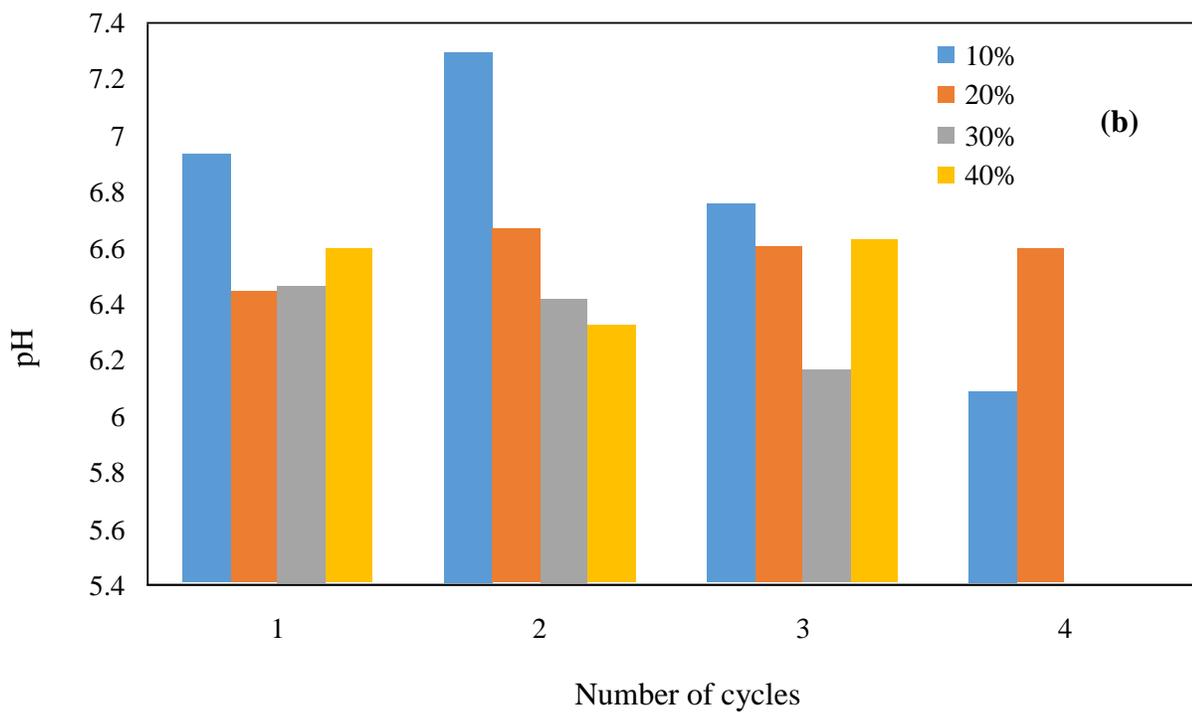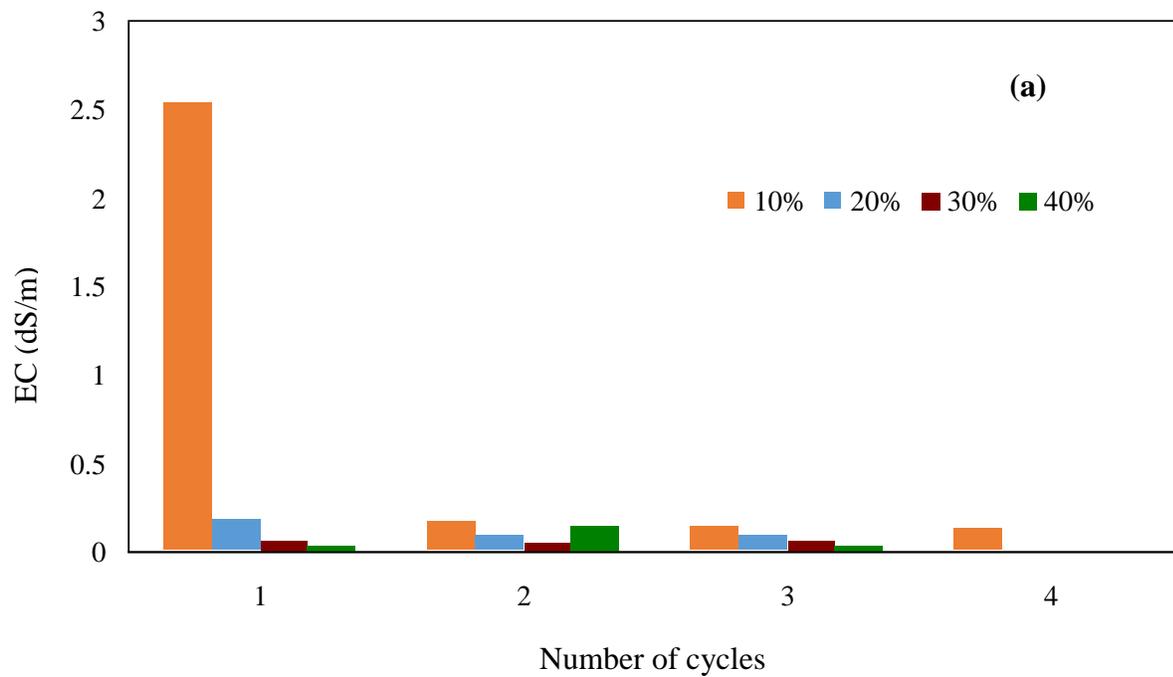
Fig.8. EC (a) and pH (b) at the end of each cycle for solution of glycerol with different concentrations
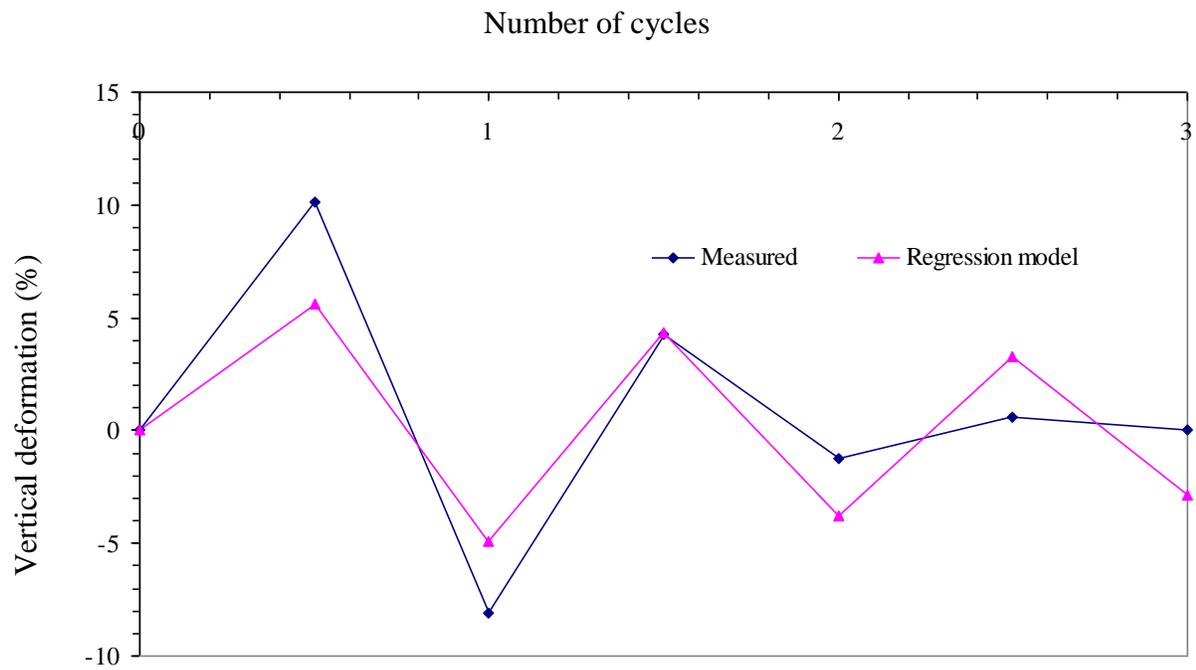
Fig.9. Measured and predicated deformation of samples during drying and wetting for a sample that was flooded with 30% solution of glycerol.