

**Treatment of a clay soil deposited in saline water by cement**

**A. R. Estabragh**

**Associate Professor. Faculty of Soil and Water Engineering, University  
of Tehran, PO BOX 4411 Karaj 31587-77871, Iran**

**Tel: +98 26 32241119**

**Fax: +98 26 32226181**

**Email: raeesi@ut.ac.ir**

**M. Kouchakzadeh**

**Postgraduate Student, Department of Civil Engineering, University  
Science and Culture.**

**Tehran, Iran**

**Email: mh\_kchz@yahoo.com**

**A.A. Javadi**

**Professor. Computational Geomechanics Group, Department of  
Engineering, University of Exeter, Devon, EX4 4QF, UK**

**Tel: +44 1392 723640**

**Fax: +44 1392 217965**

**Email: a.a.javadi@exeter.ac.uk**

## **Abstract**

The behavior and treatment of a clay soil deposited in natural and saline (sodium chloride) water is studied through experimental tests. A clay soil was deposited in natural water and water with different concentrations of sodium chloride (40, 80 and 150 g/L) in a reservoir at lab. The samples were taken from dry deposited soil and they were treated with 5, 8 and 10% cement. Atterberg limits, compaction and unconfined compression tests were carried out on the deposited soil and treated soil samples. The results show that the physical and mechanical behaviors of soil deposited in natural water and salinity water are not the same and they are function of salt concentration. The results also indicate that cement can improve the strength of the deposited soil in saline water but this improvement is not a direct function of salt concentration. In addition, for a constant salt concentration the strength of treated soil is function of percent of cement and curing time. Based on SEM (Scanning Electron Microscopy) analysis, it was found that salt concentrations of 80 and 150 g/L may have prevented the interaction between soil and cement in the deposited soil.

Key words: Treatment soil, deposited soil, saline water, cement, strength, SEM

## **Introduction**

Soils originate from rock and minerals of the earth's crust. There is ongoing but rather inconspicuous and very slow process whereby rocks are decomposed into soil (Cernica, 1995). The process of rock disintegration and break down of rock mass into small sizes is

referred to as weathering. Weathering can occur as a result of physical or chemical processes. If the products of weathering remain at their original location they constitute residual soils. Residual soil may be carried away from original location to another place by water, wind, glacier and etc. This kind of transported and deposited soil is referred as transported soils. When transported soils are deposited in water, sedimentary soil is formed. The soil transported by water may be in the form of suspended particles in the flowing water, or large particles that are rolled or pushed over the bottom of river or stream. With reduction in the velocity of water, the coarse particles are the first to be deposited. The finer particles remain in suspended condition until the velocity decreases further and they are deposited at a much further point downstream. This condition can be related to typical river that flows into a large body of water such as lake, sea or ocean.

Sedimentation is the tendency of soil particles to settle out of suspension and is a function of particle size, shape and density and fluid density and viscosity (Van Olphen, 1964, Benna et al., 1999; Bessho and Degueldre, 2009; Gorakhki and Barither, 2015). In general, the type of clay mineral, ionic strength, solid to water ratio and pore fluid control the settling process of soils in aqueous environment (Imai, 1980; Kaya et al., 2006). Sridharan and Prakash (2001) indicated that due to mutual interaction among the settling particles segregated and non-segregated sediments may be formed. They stated that the initiation of flocculation during the settling process is important in the formation of less segregated and more homogeneous sediment. There are different forces that affect the settling process of particles in aqueous environment and the three main forces are self-weight, electrical forces of attraction and repulsion (Sridharan and Prakash, 1999).

The reaction of salt (sodium chloride) with soil has been studied by many researchers such as Van Lier et al. (1960); Moore (1973) and Singh and Das (1999). They have indicated that the solubility of silica is greatly increased in the presence of sodium chloride and hence it can be used as an agent for stabilization of highway construction. Yukselen-Aksoy et al. (2008) showed that the presence of salt solution in water can change the engineering behavior of soils. Palomino and Santamarina (2005) presented a fabric map for kaolinite as a function of salinity and pH solution to explain factors influencing sedimentation. The fabric of kaolinite is changed with the pH of the solution; acidic environment causes flocculated fabric while alkaline environment leads to dispersed fabric (Kaya et al., 2006).

There is limited information on the behavior and treatment of this kind of soil with cement or other agents. Xing et al. (2009) found that  $\text{Cl}^-$  in soil has a negative effect on the short and long-term strength of soil-cement. Modmoltin and Voottipruex (2009) concluded from the results of experimental tests on different clay soils that the influence of salt on the behavior of these soils when treated with cement varies as a result of the soil structure and chemical reactions. They also reported that the existence of  $\text{Na}^+$  in natural clay soil is beneficial in dissolving the soil silica and alumina which induces high strength than  $\text{Ca}^{+2}$ . Medmoltin et al. (2004) showed that the existence salt in clay soil can decrease the detrimental effect of organic matter on the strength of lime and cement-treated soils. Dingwen et al. (2013) studied the effects of cement in treatment of a clay soil with different salt contents. They prepared samples with no salt and also with different salt contents by adding and mixing 2.5, 5.0, 7.5, and 10.0% salt and treated the samples by mixing them with different amounts of cement (10, 15 and 20%). The results

of unconfined compression tests showed that the strength is increased with increasing the percent of cement. On the other hand, at the same curing time and percent of cement the strength is decreased by increasing the salt concentration. Similar results were reported by Sinat (2006); Xing et al. (2009); Miura et al. (1998) and Onitsuka et al. (2004) showed that the existence of salt in soil can cause increase in strength of soil-cement while Dingwen et al. (2013) showed the effect of salt on reduction in strength of soil-cement. They indicated that increasing the percent of cement and curing time is also effective in increasing the strength of salty soil mixed with cement. A review of the literature indicates that there has been very limited research on the treatment of salty soils, particularly the soils formed by deposition in saline water. On the other hand, the existing investigations have primarily focused on salty clay soils that were artificially made (by adding a certain amount of salt to the soil) and then treated with cement. In other words, they considered the short-term condition (short term referring to the condition of soil that a portion of voids has been filled with salt solution). There has been no investigation on the behavior and treatment of clay soils that were deposited in a saline aqueous environment (produced naturally). There are soils deposited in high sodium chloride concentration around coastal areas with high water content, low strength and high compressibility (Dingwen et al. 2013). These sediments may be used as geomaterials for construction of roads, embankments, etc. Therefore, understanding the behavior and treatment of these soils would be necessary for such construction projects.

This study consists of two stages. In the first stage, the mechanical behavior of a sediment that has been deposited in water is examined (long term condition) and then the treatment of the sediment by adding 5, 8 and 10% cement is investigated. In the second stage, the

mechanical behavior of sediments that were deposited in solutions of salt (sodium chloride) with concentrations of 40, 80 and 150 g/L is studied their treatment by adding different percentages of cement (5, 8 and 10%) is investigated. The results of the two stages are compared to study the effect of different percentages of salt solution on the behavior of sediment and the effect of cement on treatment of the deposits at different curing times.

### **Materials and experimental methods**

The main materials that were used in this program are soil, Portland cement and salt (sodium chloride). The properties of these materials are described in this section.

#### **Soil**

The soil that was used in this work was a clay soil comprising of 12.6% sand, 54.2% silt and 33.2% clay. The physical and mechanical properties of soil were determined according to ASTM standard and are depicted in Table 1. According to the Unified Soil Classification System (USCS), the soil can be classified as clay with high plasticity (CH). Table 2 shows the chemical composition of this soil.

#### **Cement**

The Cement used in this experimental work was Portland cement type 1 with Blaine fineness of 4100 cm<sup>2</sup>/g and specific gravity of 3.15. Table 3 shows the physical and mechanical properties of the cement.

#### **Water**

Drinking water was used in this work. It had a pH of 7.76, chloride content of 17 meq/L and calcium+magnesium content of 9.1 meq/L.

## **Sodium chloride**

Sodium chloride is an ionic compound with chemical formula NaCl showing a 1:1 ratio of sodium and chloride ions. Sodium chloride is the salt most responsible for the salinity of seawater. On average, seawater has a salinity of about 35 g/L. Local lakes in some countries are in hypersaline condition. For example, the salinity of Urmia Lake in the northwest of Iran has risen to more than 300 g/L (Eimanifar and Mohebi, 2007). Large quantities of sodium chloride are used in many industrial processes as well as de-icing of roadways in sub-freezing weather where salt enters the soil and changes the properties of the soil. Review of the literature shows that up to now, the effect of high salinity on the behavior of sediments has not been studied. On the other hand, the deposited soil in high salinity water may be used as construction material such as borrow area or foundation for buildings. In such projects, it is necessary to understand the behavior of these soils and also improve the mechanical properties of them. Therefore, solutions of sodium chloride with concentrations of 40, 80 and 150 g/L were selected. The measured values of pH for these solutions are nearly the same as drinking water.

## **Sediment and sample preparation**

The soil samples used in this study are natural soil, soil sediment deposited in water and soil sediment deposited in 40, 80 and 150 g/L sodium chloride dissolved in water. The sedimentation process was carried out through a circular reservoir with 1.6 m diameter and 0.4 m height. Selection of the ratio of solid to water is important in controlling the settling process of soils in aqueous environment (Imai, 1980 and Kaya et al., 2006). The ratio of solid was chosen as 5% weight of the mixture (fluid+solid) that is similar to the recommended value for hydrometer testing (ASTM D 422-63). The required quantity of

dry soil was added to the reservoir in increments and mixed thoroughly to reach a dilute soil-water mixture. For the other test series, 40, 80 and 150 g/L sodium chloride was added to water and mixed thoroughly to reach water-salt solution to the desired value of solution content. The soil was then added to each of these solutions as in the previous stage and mixed to obtain a dilute mixture of soil and solution water. This dilute mixture was then allowed to settle for two weeks. After that the excess liquid above the soil was drained off, the soil was then air dried and the desired samples were prepared from this sediment for the experimental tests. Standard compaction tests according to ASTM D 698-07e were conducted on the sediments deposited in normal water and in different salt solutions. 5, 8 or 10% cement was added to the soil samples that were taken from each deposited soil and standard compaction tests were carried out on these mixtures as well. The maximum dry unit weight and optimum water content were determined for each of them. The samples for unconfined compression test were prepared from different dry sediments at the optimum water content and maximum dry unit weight from the compaction test. For preparing the soil samples the grounded sediment was mixed with an amount of water corresponding to the optimum water content. For the soil-cement samples, after weighing the required amounts of materials, they were mixed in a container and then water was added up to the optimum water content. The prepared samples for testing should be uniform and repeatable. Different methods are available for compaction and preparing samples including dynamic and static compaction methods. Sivakumar (1993) examined these two methods of compaction and found that preparing samples by dynamic compaction is less repeatable than static compaction. He used static compaction in his research work. Wheeler and Sivakumar (1995) and Estabragh and



Javadi (2008) also used this method of compaction for preparing samples. Based on previous research, the static method was used in this work for preparing the samples. Compaction was done in a special mould by applying a static pressure to the soil in three layers using a loading machine. Each layer was compacted at a fixed displacement of 1.5 mm/min until the maximum dry unit weight corresponding to compaction curve was achieved. The diameter and length of the samples were 50 and 100 mm respectively. After preparing soil-cement samples they were stored in a special curing cabinet, according to ASTM standard, at constant temperature and relative humidity for curing times of 7, 14 and 28 days.

### **Test Program**

Suspension tests were conducted on samples of soil. In these tests 50 g of natural dry soil was mixed with 125 cm<sup>3</sup> liquid of desired composition (water or water with sodium chloride with concentrations of 40, 80 or 150 g/L) and transferred in an electrical mixture for a duration about 30 minutes. The mixed solution was poured in a cylinder and then more fluid was added to bring the total volume of the mix to 1000 cm<sup>3</sup>. The top of the cylinder was then covered and it was shaken by hand for a few minutes in order to ensure that the soil particles were completely mixed in the solution. The soil was then allowed to settle until it reached the condition that no changes in the sediment thickness were observed. During the settlement, the height of the sediment was measured with accuracy of 1.0 mm. Atterberg limits, compaction and unconfined compression tests were also conducted on the samples of natural soil, soil sediment in water and soil sediment in different concentrations of salt according to the ASTM standard. For unconfined compression tests the samples were loaded in a compression loading frame at an axial

displacement rate of 1 mm/min. The applied load was recorded continually, and tests were terminated when the failure of samples was attained.

Scanning electron microscopy (SEM) tests were performed on the samples in order to observe the microstructure of the samples in different conditions (sediments with different quality of pore fluid and treated with different percentages of cement at various curing times). The samples of sediment were obtained from air dry sediments and the treated soil samples were prepared at the optimum water content and maximum dry unit weight. The SEM tests on samples were performed according to the method that was used by Tremblay et al. (2002) and Estabragh et al. (2017).

## **Results and Discussion**

Clay particles surfaces, dry or wet, carry residual negative charges. When water is added to dry clay, a number of anions and cations are released in pore water because of dissolved salt sediments between particles. The cations existing in pore water are attracted to the clay surface to neutralize the existing imbalanced charges along the clay surface. The net effect is the formation of a dispersed layer around the particles and the concentration of cations is decreased with increasing distance from the surface until the concentration becomes equal to that in the normal water in void space (Craig, 1995). The term diffused double layer (DDL) is referred to the negative charge of a particle surface and the dispersed layer of cations and anions around it. The change in the thickness of this layer produces different soil structures. The shrinking and reduction of the DDL thickness causes a flocculated structure and increase of thickness of the DDL results in a dispersed structure in the soil. Dielectric constant is one of the important parameters that influence on the thickness of DDL.

The results of variations of height of sediment with time for the soil deposited in water and in salt solutions with different concentrations are shown in Fig.1. As shown in this figure, after about 48 hours, the sediment thickness for the soil deposited in water reached a constant value of 5 cm. The thicknesses of the sediments deposited in salt solutions with concentrations 40, 80 and 150 g/L after 2 hours reached to 2.3, 1.6 and 1.4 cm respectively. This shows that the settlement of particles is slower in water than the salt solutions. It is resulted from Fig.1 that the structure of the deposited sediment is flocculated but the degree of flocculation is increased with concentration of sodium chloride. Figs. 2a, b, c and d show the results of the SEM tests for soil sediments in water and in salt solutions with concentrations 40, 80 and 150 g/L respectively. As shown in Fig.2, for the soil sediment in water, the spaces between particles are relatively large in comparison with sediments in salt solutions. Increasing the salt concentration causes the particles to be formed as parallel sheets pasted together with small spaces between them (Figs.2b, c and d). Therefore, by increasing the salt concentration the deposited sediments attain a denser fabric (with less void ratio) than those deposited in water. Kaya et al. (2006) stated that the variations in the thickness and structure of sediments are a function of pH and number of existing ions in solution. With increasing the concentration of the solution of sodium chloride, the exchange of ions between soil and pore fluid is increased and this leads to increase in the degree of flocculation and pasting of particles to each other.

Fig.3 shows the results of LL (liquid limit) and PI (Plastic index) for the soil deposited in water and salt solutions with different concentrations. For the soil deposited in water the values of LL and PI are 56 and 26% while for the soil deposited in salt solution with

concentration of 150 g/L they change to 31 and 12% respectively. This shows a reduction of about 50% in the values of LL and PI at this concentration in comparison with natural water. Kaya and Fang (1997) indicated that the dielectric constant of solution of sodium chloride is less than water (the dielectric constant of water is 80) and there is a reduction in the amount of dielectric constant with increasing the concentration of sodium chloride. Therefore, the degree of flocculation of the soil deposited in 150 g/L sodium chloride solution is more than the soil deposited in natural water. When the structure of soil becomes flocculated, the particles paste to each other and form coarse particles; so their specific surface is less than the particles of soil deposited in natural water. Therefore, the capacity to adsorb water is reduced which causes reduction in the Atterberg limits. Similar results were reported by Bowders et al. (1985), Foreman and Daniel (1986), Sridharan et al. (2000), Kaya and Fang (2005) and Modmoltin and Voottipruex (2009) who suggested that the reduction in consistency limits of soil is due to the decrease of dielectric constant. Reduction in the value of dielectric constant of pore fluid compresses and shrinks the thickness of the DDL and in turn, the resulting increase in electrostatic repulsion causes coagulation of soil particles.

The results of Atterberg limits for the soil at different concentrations of salt, treated by 10% cement are also shown in Fig.3. Adding cement causes reduction in the Atterberg limits. For example, for salt concentration of 80 g/L, the values of LL and PI are 43 and 20%. By adding 10% cement they are changed to 34 and 10% respectively. There is a reduction in the values of LL and PI in comparison with the values for the soil with no cement. At a constant concentration of salt, by increasing the percent of cement the reduction in the values of LL and PI becomes higher.

One of the effects of cement on soil is cation exchange. Cation exchange starts when the cement is mixed with soil. Therefore, adding cement causes substitution of ions in soil particles which results in pasting of the particles to each other and reduces the water absorption capacity of soil due to the reduction in the specific surface of particles (Estabragh et al., 2016). This results in reduction of Atterberg limits.

Typical results of compaction tests for the soil at different salt concentrations and also with 8 % cement are shown in Fig.4. The results show that by increasing the concentration of salt, the maximum dry unit weight of the soil deposited in salt solutions is increased (Fig. 4a) and the optimum water content is decreased (Fig.4b). The maximum dry unit weight and optimum water content of the soil deposited in water are  $16.28 \text{ kN/m}^3$  and 24.2% respectively. These values for the soil deposited in salt solution with concentration of 80 g/L are changed to  $17.1 \text{ kN/m}^3$  and 19.0%. As explained earlier, this is due to the reduction of the DDL thickness due to the salt concentration that leads to flocculated structure and formation of new grain size distribution of soil by pasting the fine particles together. These results are consistent with the findings that were presented by Moore (1973). Fig.4 also shows that adding 8% cement to the soil deposited in salt solution results in an increase in maximum dry unit weight until the concentration of about 40 g/L followed by decrease in maximum dry unit weight at higher used salt concentrations. However, the optimum water content of treated soil is decreased with increasing the salt concentration (Fig.4b). The same trend is observed for 10% cement, however, for 5% cement there is increase and then decrease in maximum dry unit weight and optimum water content for all concentrations of salt. It is also shown in Fig.4a that the values of maximum dry unit weight are lower for the soil treated with cement than the

untreated soil (deposited in water and salt solution). It can be said when cement is added to the soil deposited in 40 g/L salt solution, it fills the spaces between particles and the reactions that occur between them produce coarse particles. This results in increase in maximum dry unit weight in compaction test. For the soil deposited in salt solutions with concentrations of 80 and 150 g/L, the cement cannot fill the pores between the particles completely because of the limited pore spaces between particles in comparison with the soil deposited in water with salt concentration of 40 g/L. As it was explained the structure of deposited soils is changed with the concentration of salt. In other words, the arrangement of particles relative to each other is dependent on the degree of salt concentration as shown in Fig.1. At low concentrations the flocculated structure is in the cardhouse form with large pores between them but at high concentrations, the particles tend to be parallel with small voids (Lintern, 2003) as shown in Figs. 2c and d. Fig.1 also shows that the sediment deposited in water with salt solution of 150 g/L is denser than the sediments deposited in 80 and 40 g/L salt solutions or water. Therefore, it can be concluded that the voids between the particles of soil deposited in salt solution with concentration of 40 g/L are more than the soil deposited in salt solutions with concentrations of 80 or 150 g/L (see Fig.2a).

Fig. 5 shows typical results of SEM for different sediments (sediments in water and in salt solutions with concentrations of 40, 80 and 150 g/L) treated with 8% cement at curing time of 7 days. As shown in Figs. 5c and d, the particles of soil are pasted to form lump masses with spaces between them, therefore, the cement cannot chemically interact with some of the soil particles. The additional cement may cover the surface of particles or remain as lumps in the matrix of soil. Therefore, for soil deposited in salt solutions

with concentrations of 80 and 150 g/L the ability of cement for reaction with soil particles is less than the soil deposited at salt solution with concentration of 40 g/L. Since the compaction test is carried out under constant energy at constant volume, therefore the maximum dry unit weight of treated soil deposited at 80 and 150 g/L concentrations is reduced in comparison with the treated soil deposited in water with salt concentration of 40 g/L. It can be said that, for the soil deposited in 40 g/L salt solution, all the added cement causes chemical reaction with soil and creates a strongly bonded soil in comparison with soil deposited in water with salt solutions of 80 and 150 g/L. The created bonds prevent from displacement of particles during compaction. The results showed the optimum water content is reduced for all conditions of salt concentration. This may be due to the formation of coarse particles at concentration of 40 g/L and adsorption of water by additional cement that was not able to cause chemical reactions with soil particles due to the limited amount of voids at concentrations 80 and 150 g/L.

The stress-strain curves for the soil samples deposited in water and solutions with different concentrations of salt are shown in Fig.6. As shown in this figure, the final strength of the soil deposited in water is 190.2 kPa but for the soils deposited in saline water with concentrations of 40, 80 and 150 g/L it changes to 353.7, 242 and 142 kPa respectively. It is seen (Fig.6) that the strength at concentration of 150 g/L is even less than the soil deposited in water. It can be said that the attractive Van der Waals and electrostatic forces contribute to the formation of flocculated structure. When the electrostatic forces are dominated by the Van der Waals forces in saline water, the positive charges at the edge of clay particles are attracted to the negative charges of the face, leading to a nearly perpendicular array of particles constituting a flocculated structure.

structure. If the dominated forces are Van der Waals forces, this leads the plates pasting nearly parallel to each other (as shown in Figs.2c and d). When the particles are nearly parallel the friction between particles is less than when they are perpendicular to each other. It is resulted that by increasing the concentration of salt, the dominated forces are Van der Waals forces and it tends to change the formation of deposited particles to parallel condition which leads to the reduction in strength in comparison with low concentration.

Fig.7 shows the stress-strain curves for the soils that were deposited in water with different concentrations of salt and also the samples treated with 5% cement at curing time of 7 days. As shown in this figure, the final strength of the soil deposited at concentration of 40 g/L is 353 kPa at 3.6 % strain. By treating the soil with 5% cement the final strength changes to 2005 kPa to strain of 1.6%. The results show that adding cement increases the strength and brittleness of the sample and the amount of increase in strength is dependent on the concentration of salt. The effect of curing time for the soil with 8% cement that was deposited in saline water with concentration of 80 g/L is shown in Fig.8 As shown in this figure, the final strength of the treated soil after 7 days curing time is 1481.7 kPa and it changes to 1940 and 2341 kPa at curing times of 14 and 28 days respectively. It is seen that curing time is important in increasing the strength of the treated soil. Fig.9 shows the effect of different percentages of cement in treating soil deposited in saline water with concentration of 150 g/L at curing time of 28 days. It is seen from this figure that with 5% cement, the final strength is 681 kPa and it changes to 958 and 1764 kPa with 8 and 10% cement. It is resulted that, at a constant curing time, increasing the percent of cement causes increase in strength of the soil. When cement is



mixed with soil, the resulting reactions can be divided into three stages, namely cation exchange, cement hydration and pozzolanic reaction. The hydration stage leads to increase in the pH value of the pore water and production of strong bases. The produced bases dissolve both aluminium and silicon from the clay minerals and amorphous material on the clay particle surfaces. During pozzolanic stage, the cementation of the soil mass is formed. In this stage, the calcium hydroxide in the soil water reacts with silicates and aluminates (pozzolans) that were liberated in previous stage form cementing materials. Calcium ions react with dissolved  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$  to produce hydrated gel of calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH). These gels bind the soil particles in a manner similar to that produced by the hydration of cement and form a hard structure so that particles of soil can no longer slide over each other (Estabragh et al., 2016). This stage increases the strength and reduces the water holding capacity. The results show that the treatment of soil deposited in saline water is also possible by cement.

Figs.10a, b and c show the variations of compressive strength with curing time for 5, 8 and 10% cement for samples that were deposited in water with different percentages of salt. As shown in these figures, increasing the curing time causes increase in strength. The results indicate that the compressive strength of the soil deposited in water with salt concentration of 40 g/L and treated with different percentages of cement is more than that of the corresponding soil-cement mixtures deposited in water and 80, 150 g/L salt concentrations. By increasing the concentration of salt beyond a certain limit (40 g/L) there is a reduction in the strength of the soil with different cement contents. At a specific curing time and salt concentration, increasing in the percent of cement causes increasing

in strength. Therefore, the curing time, percent of cement and concentration of salt are important factors in strength of treated deposited soils.

Fig.11 shows the results of compressive strength at different curing times for different amounts of salt concentration at constant percent of cement. As shown in Fig.11a, for the soil treated with 5% cement content, the strength is increased by increasing the concentration of salt up to about 40 g/L beyond which, further increase in salt concentration leads to reduction in strength. For the soil deposited in the salt solution with concentration of 40 g/L, the particles are not parallel to each other because of the dominated electrostatic forces but for the soils deposited in solutions with 80 and 150 g/L salt, the particles are nearly parallel to each other due to the dominating Van der Waals forces. It can be said that the volume of voids for the soil deposited in water solution with salt concentration of 40 g/L is more than the soil deposited in the solutions with concentrations of 80 and 150 g/L. The volume of void space is decreased with increasing the concentration of salt. Therefore, when a specific percent of cement is added to soil samples with different deposition conditions, it fills the space between the particles. As shown in Fig.5, adding cement causes reduction in pore size of soil in comparison with the soil deposited in water (Fig.5a). Since the space for the soil deposited in 40 g/L solution is more than the soils deposited in 80 and 150 g/L solutions, most of the added cement fills the voids but for other concentrations a portion of the added cement can fill the space between particles and the rest of it may cover the surface of particles. This leads to greater increase in strength for the soil deposited in 40 g/L solution than those in 80 and 150 g/L solutions. Figs. 5c and d show the effect of cement on the microstructure of soil deposited in salt solutions with concentrations 80 and 150 g/L. It is seen from these

figures that the particles of soil are in the form of parallel sheets. The cement pastes these particles together which leads to the formation of lumped masses with relatively large voids between them.

This study shows that it is possible to treat clay soils deposited in saline water. An important factor that should be considered is the concentration of salt in the water in which the soil is deposited which can change the results of treatment. A high concentration of salt may not produce a reasonable treatment, while at low degree of concentration there is a positive effect of the process of cementation and treatment of soil.

### **Conclusion**

The behavior and treatment of a clay soil deposited in natural water and water with salt concentrations of 40, 80 and 150 g/L by cement as an agent was studied through a program of experimental tests. The following conclusions can be drawn from this study based on the experimental results:

- Atterberg limits (LL and PI) of soil deposited in saline water are decreased with increasing the concentration of salt. The maximum dry unit weight increases and optimum water content decreases with increasing the salt concentration.
- The strength of soil deposited in saline water is a function of salt concentration. The strength is higher at 40 g/L and by increasing the concentration to 80 and 150 g/L there is reduction in strength.
- Cement as an agent can improve the behavior of clay soils deposited in saline water but the amount of improvement is dependent on the salt concentration. The Atterberg limits of a soil treated with a constant amount of cement are decreased with increasing the salt concentration. The strength of the treated soil is higher in

comparison with the soil deposited in natural water but for the soil deposited in saline water there is reduction in strength with increasing the salt concentration.

## References

- Benna, M. Kbir-Ariguib, N. Magnin, A. & Bergaya, F. (1999). Effect of pH on rheological properties of purified sodium bentonite suspensions. *Journal of Colloid Interface Science*, 218(2), 442-455.
- Bessho, K. & Degueudre, C. (2009). Concentration and sedimentation of colloidal bentonite particles in water. *Applied Clay Science* 43(2), 253-259.
- Bowders, J. Daniel, D.E. Broderick, G.P. & Liljestrang, H.M. (1985). Methods for testing the compressibility of clay liners with landfill leachate. ASTM STP 886, Hazardous and Industrial Solid waste Testing. In *4<sup>th</sup> Symposium American Society for Testing Materials*, P. 233-250.
- Cernica, J.N. (1995). *Geotechnical Engineering: Soil Mechanics*. John Wiley & Sons, Inc., USA.
- Craig, R.F. (1995). *Soil Mechanics*. Chapman and Hall, UK.
- Dingwen, Z. Libin, F. Songyu, L. & Yongfeng, D. (2013). Experimental investigation of unconfined compression strength and stiffness of cement treated salt-rich clay. *Marine Georesources Geotechnology* 31, 360-374.
- Eimanfar, A. & Mohebbi, F. (2007). Saline systems, *BioMed*, 3(5), 1-8.
- Estabragh A.R., Ranjbari, S. & Javadi, A.A. (2017). Properties of a Clay Soil and Soil-Cement Reinforced with Polypropylene Fibers. *ACI, Materials Journal* 114 (2), 195-205.
- Estabragh, A.R. Khatibi, M. & Javadi, A.A. (2016). Effect of cement on the mechanical behaviour of a soil contaminated with Mono Ethylene Glycol (MEG). *ACI Material Journal* 113 (6), 709-717.

- Estabragh, A.R. & Javadi A.A. (2008). Critical state for overconsolidated silty soil. *Canadian Geotechnical Journal* 45, 408-420.
- Foreman, D.E. & Daniel, D.E. (1986). Permeation of compacted clay with organic chemicals. *Journal of Geotechnical Engineering* 112(7), 669-681.
- Gorakhki, M.H. & Bareither, C.A. (2015). Salinity effects on sedimentation behaviour of kaolin, bentonite and soda ash mine tailing. *Applied Clay Science* 114, 593-602.
- Imai, G. (1980). Setting behaviour of clay suspension . *Soils and Foundations* 20, 61-77.
- Kaya, A. & Fang, H.-Y. (1997). Identification of contaminated soils by dielectric constant and electrical conductivity. *Journal of Environmental Engineering* 123(2), 169-177.
- Kaya, A. & Fang, H.-Y. (2005). Experimental evidence of reduction in attractive and repulsive forces between clay particles permeated with organic fluids. *Canadian Geotechnical Journal* 42, 632-640.
- Kaya, A. Ören, A.H. & Yukselen-Aksoy, Y. (2006). Setting of kaolinite in different aqueous environment. *Marine Georesources Geotechnology* 24 (3), 203-218.
- Lintern, D.G. (2003). *Influences of flocculation on bed properties for fine grained cohesive sediment*. PhD thesis University of Oxford, Oxford, UK.
- Miura, N. Taesiri, Y. Koga, Y. & Nishida, K. (1998). Practical of Improvement of Ariake clay by mixing admixtures. *Proceeding International Symposium On Shallow Sea and Low land*, Saga, pp.159-168.
- Modmoltin, C.M. Lu, M.J. & Onistsuka, K. (2004). Influence of humic acid and salt concentration on lime stabilised and ariake cays and microstructure research. *Chinese Journal of Geotechnical Engineering* 26(2), 281-286.

- Modmoltin, C. & Vootripruex , P. (2009). Influence of salts on strength of cemented clays. *Proceeding of the Institute of Civil Engineering, Ground Improvement, GI*, 15-26.
- Moore, J.C. (1973). *Effect of sodium chloride treatment on the engineering properties of compacted earth materials*. PhD Dissertation University of Illinois, Champaign-Urbana, IL
- Onitsuka, K. Modmoltin, M. Kouno, M. & Negami, T. (2004). Effect of organic matter on lime and cement stabilised ariake clay. *Journal of Geotechnical Engineering, ASCE* 729, III-62, 1-13.
- Palomino, A.M. & Santamarina , J.C. (2005). Fabric map for kaolinite : effect of pH and ionic concentration on behaviour. *Clay and Clay Minerals*. 56 (6), 599-611.
- Sinat, K. (2006). *Influence of storage condition on geotechnical properties of Ariake clay and on its chemical stabilization*. PhD Dissertation Saga University, Saga, Japan
- Singh, G. & Das, B.M. (1999). Soil stabilization with sodium chloride. *Transportation Research Record: Journal of Transportation and Research Board* 1673,46-55.
- Sivakumar, V. (1993). *A critical state framework for unsaturated soil*. Ph.D. thesis, University of Sheffield, Sheffield, UK.
- Sridharan, A. & Prakash, K. (1999). Influence of clay mineralogy and pore medium chemistry on clay sediment formation. *Canadian Geotechnical Journal* 36, 961-966.
- Sridharan, A. El-Shafei, A. & Miura, N. (2000). A study on the dominating mechanisms and parameters influence the physical properties of Ariake clay. *International Association Lowland Technology Journal* 2, 55-70.

- Sridharan, A. & Prakash, K. (2001). Setting behaviour and clay mineralogy. *Soils and Foundations* 4(2), 105-109.
- Tremblay H., Duchesne J., Locat J., & Leroueil S. (2002). Influence of the natural of organic compounds on fine soil stabilization with cement, *Canadian Geotechnical Journal*, 39 (3), 535-546.
- Van Lier, J.A. Bruyn, P.L. & Overbek, J.T.G. (1960). The solubility of quartz. *Journal physics and Chemistry* 64
- Van Olphen, H. (1964). Internal mutual flocculation in clay suspension. *Journal of Colloid and Interface Science* 19, 313-319.
- Wheeler, S.J., and Sivakumar, V. (1995). An elasto plastic critical state framework for unsaturated soil. *Géotechnique* 45(1), 35-53.
- Xing, H.F. Yang, X.M. Xu, C. & Ye, G.B. (2009). Strength characteristics and mechanisms of salt-rich soil-cement. *Engineering Geology* 103(1-2), 33-38.
- Yukselen-Aksoy, Y. Kaya, A. & Ören, A.H. 2008. Seawater effect on consistency limits and compressibility characteristics of clays. *Engineering Geology* 102, 54-61.



**Table 1.** Physical and mechanical properties of soil

<b>Property</b>	<b>Standard designation</b>	<b>Value</b>
Specific gravity, $G_s$	ASTM D 854-10	2.70
<i>Particle distribution</i>		
Gravel (%)		0.0
Sand (%)		12.6
Silt (%)		54.2
Clay (%)		33.2
<i>Consistency limits</i>		
Liquid limit, LL (%)	ASTM D 4318-10	52.0
Plastic limit, PL (%)	ASTM D 4318-10	26.0
Plastic index, PI (%)	ASTM D 4318-10	26.0
Shrinkage limit, SL (%)	ASTM D 427-04	13.0
USCS classification	ASTM D 2487-11	CH
<i>Compaction characteristics</i>		
Optimum water content, $w$ (%)	ASTM D 698-07e	16.3
Maximum dry unit weight, $\gamma_{dmax}$ (kN/m <sup>3</sup> )		19.0

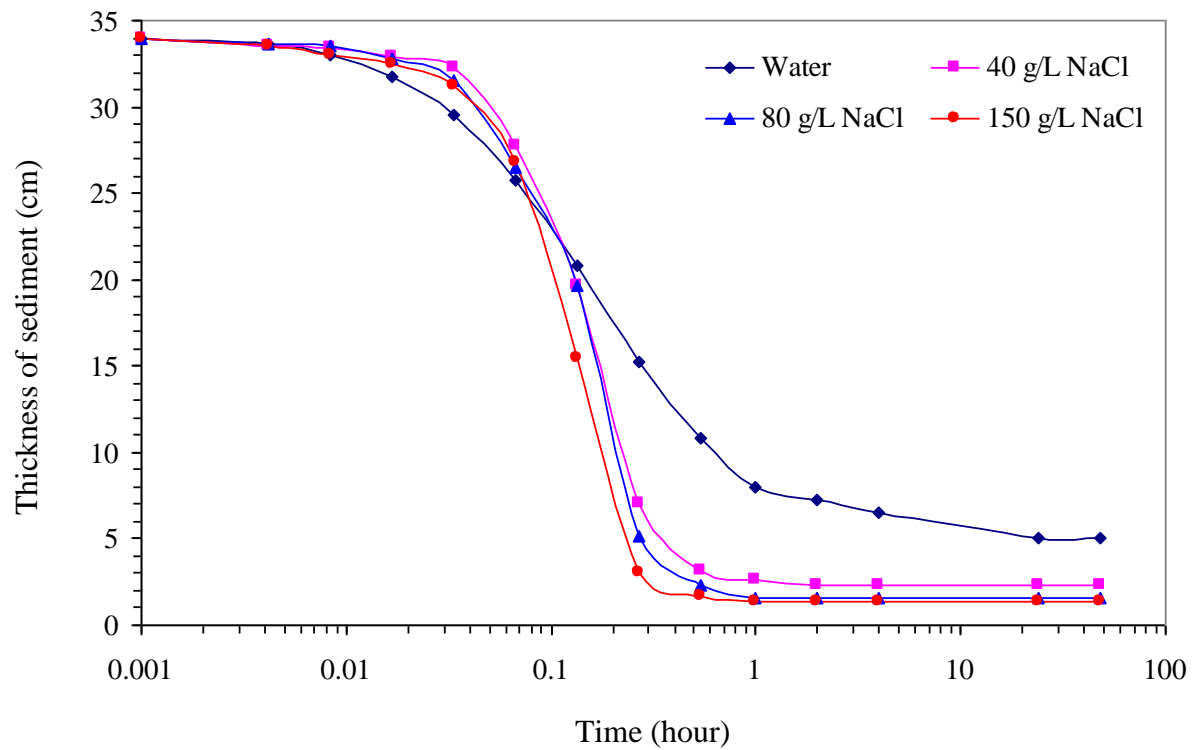
**Table. 2** Chemical components of soil

<b>Chemical component</b>	<b>Amount</b>	<b>Chemical component</b>	<b>Amount</b>
pH	8.4	Mg <sup>2+</sup> (meq/L)	6.0
EC* (dS/m)	13.90	Cl <sup>-</sup> (meq/L)	49.0
Na <sup>+</sup> (meq/L)	142.0	HCO <sub>3</sub> <sup>-</sup> (meq/L)	7.5
Ca <sup>2+</sup> (meq/L)	21.0	SO <sub>4</sub> <sup>2-</sup> (meq/L)	112.0

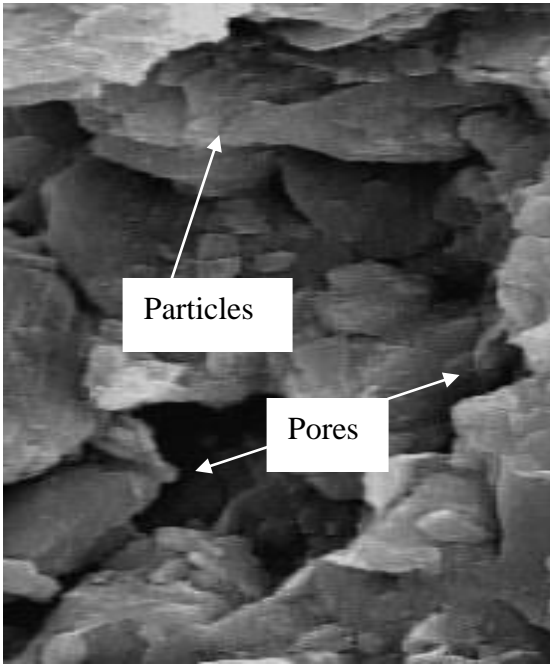
- Electrical Conductivity

**Table. 3** Properties of cement

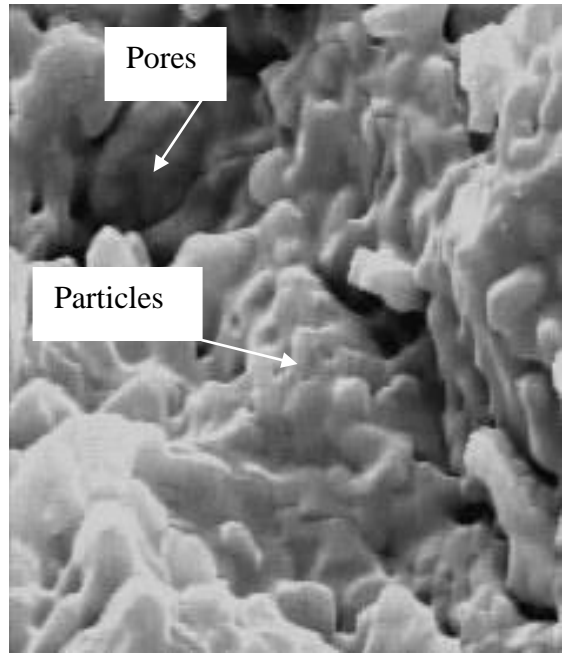
<b>Properties</b>	<b>Standard designation</b>	<b>Value</b>
Normal consistency (%)	ASTM C 187-10	27.3
Primary setting time (min)	ASTM C 191-08	90
Final setting time (min)	ASTM C 191-08	220
Compressive strength (MPa) 7days	ASTM C 109-08	26.3
Tensile strength (MPa) 7 days	ASTM C 190-85	2.8
Flexure strength (MPa) 7 days		5.2



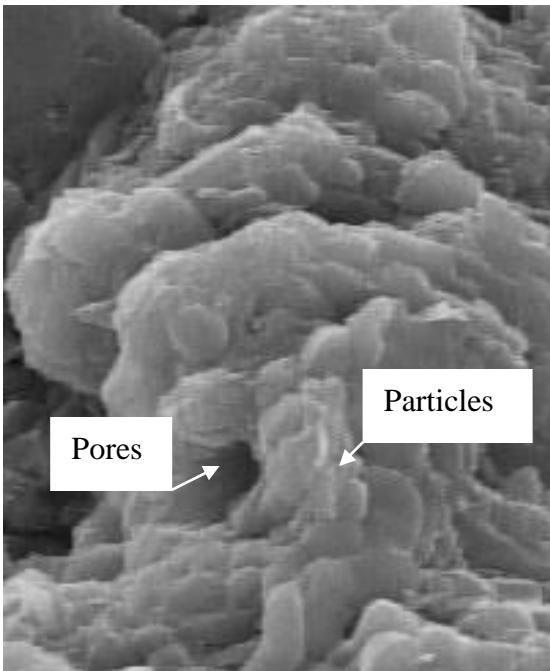
**Fig.1.** Variations of sediment with setting time for soil suspension in water and water with different salt concentrations



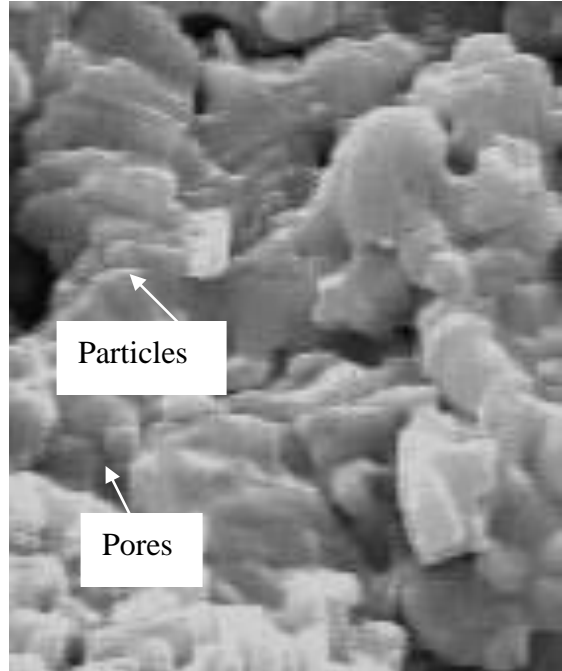
(a)



(b)

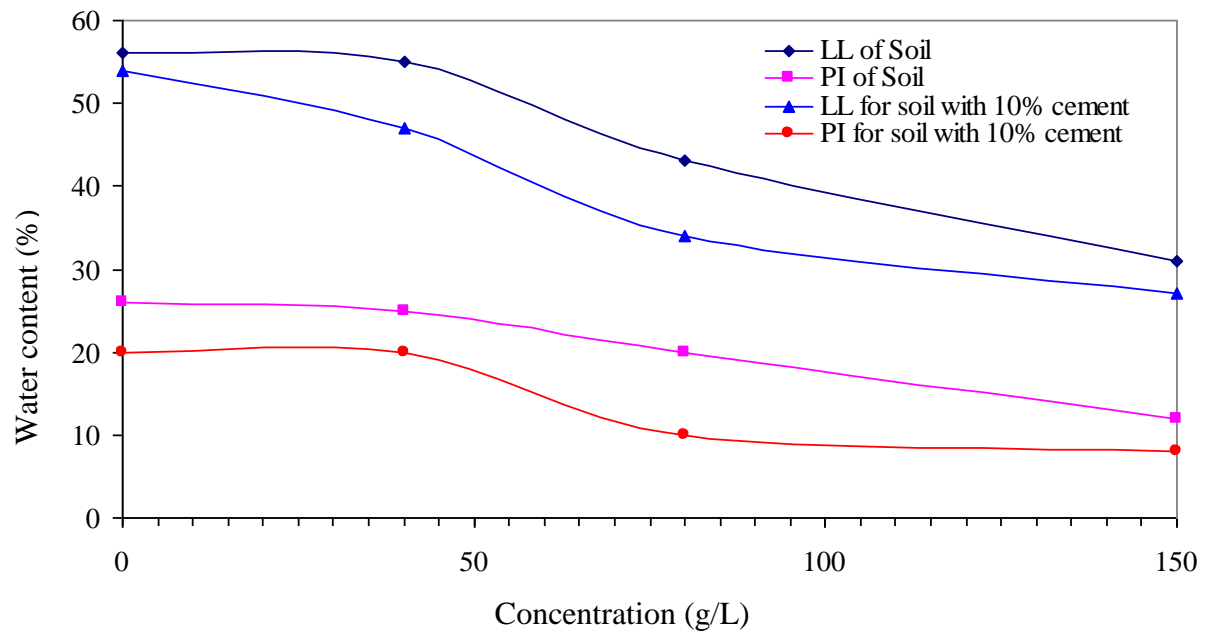


(c)

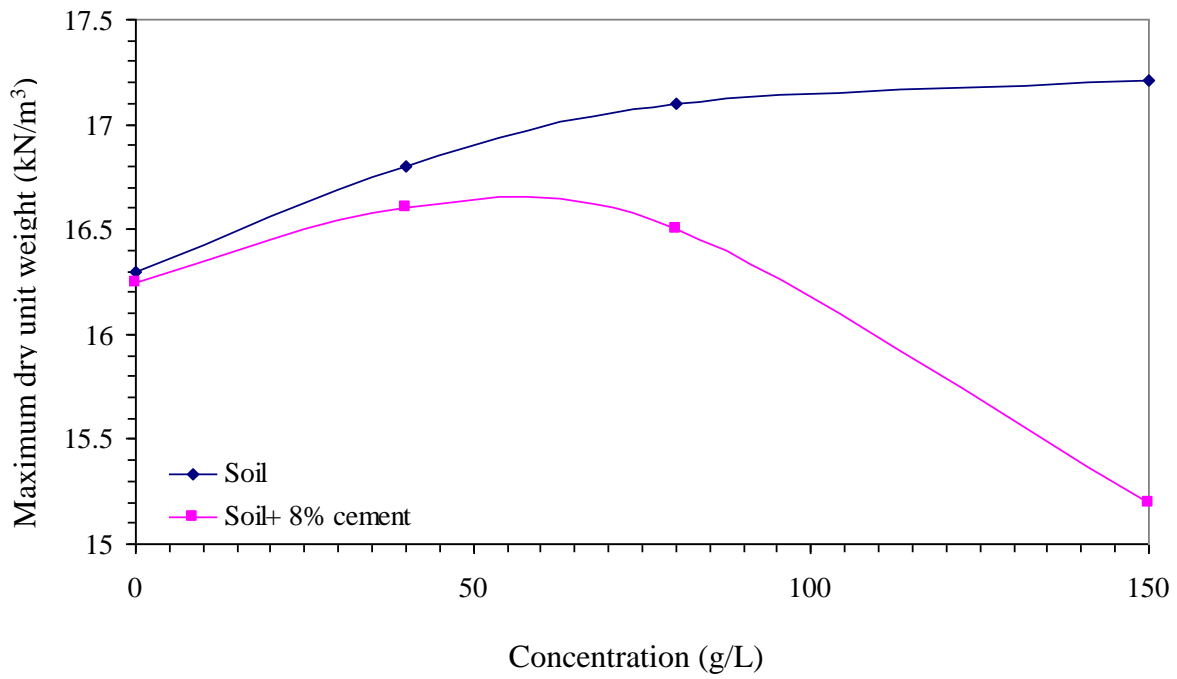


(d)

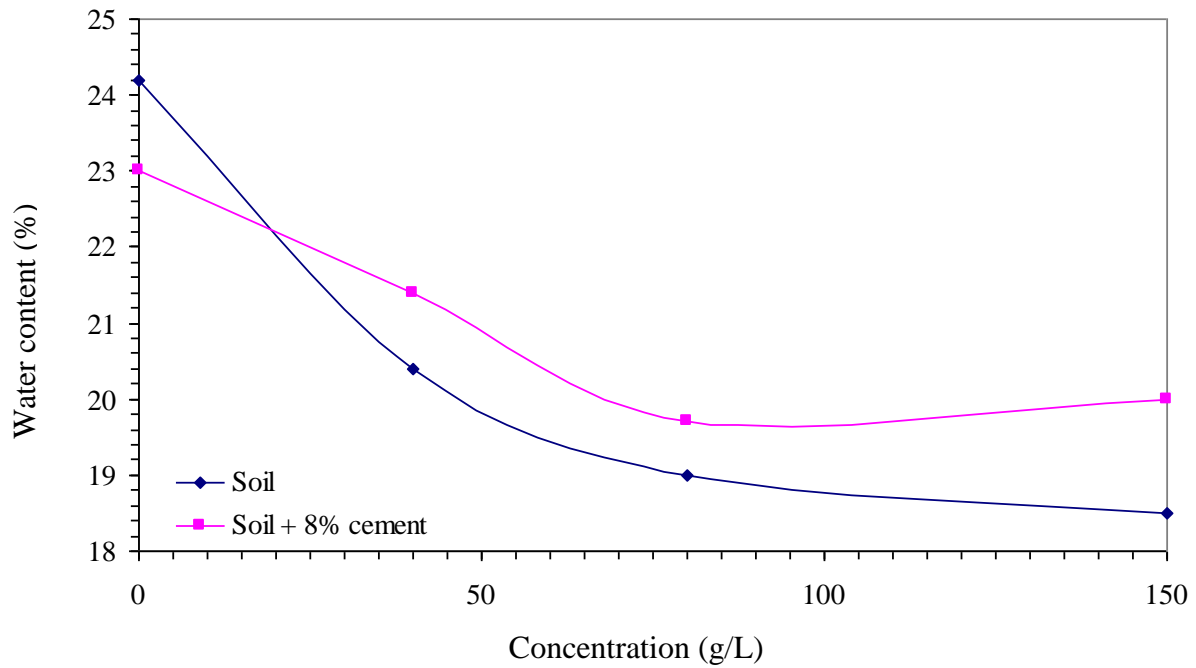
**Fig.2** . SEM images of various soil sediments in (a) water and in; (b) 40 g/L ; (c ) 80 g/L and (d) 150 g/L NaCl solutions



**Fig.3.** Variations of Atterberg limits for soil and treated soil at different salt concentrations

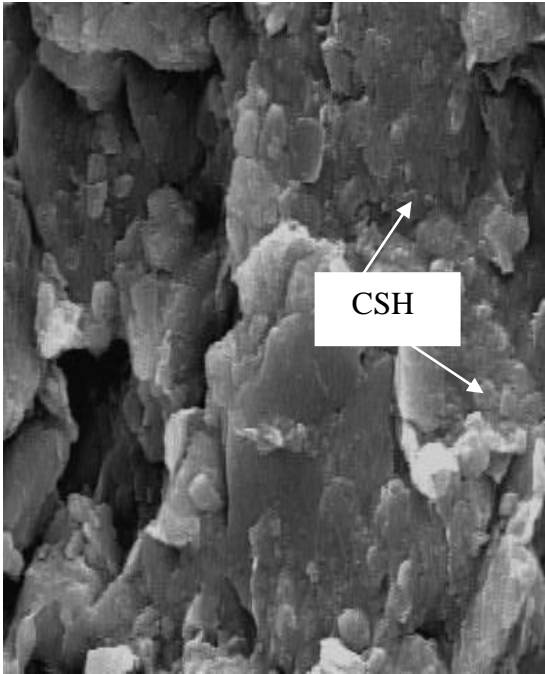


(a)

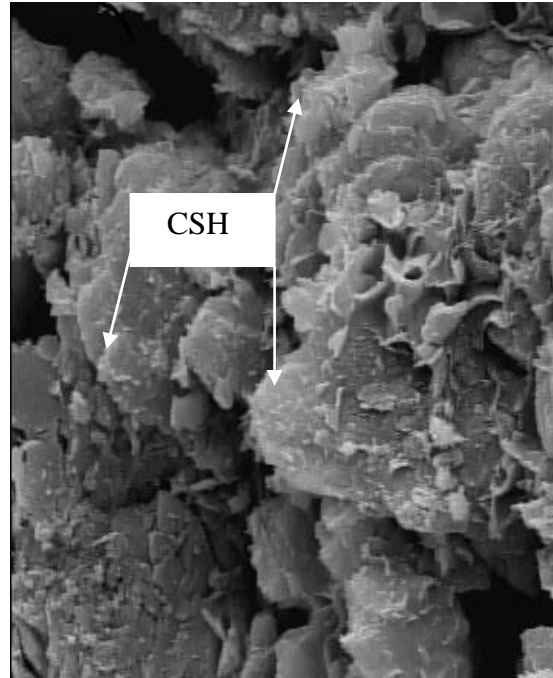


(b)

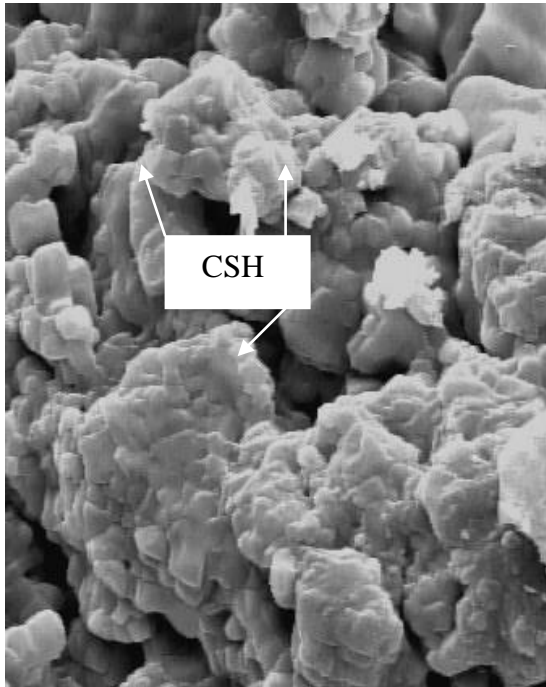
**Fig.4.** Compaction parameters a) maximum dry unit weight, b) optimum water content for soil and treated soil at different salt concentration



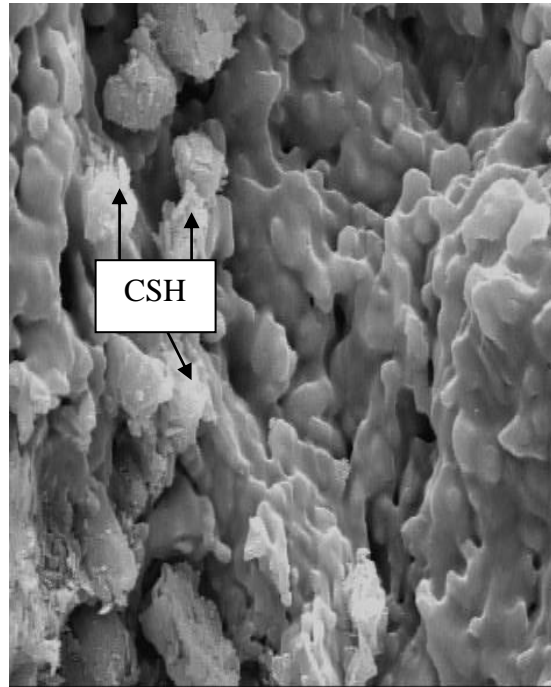
(a)



(b)

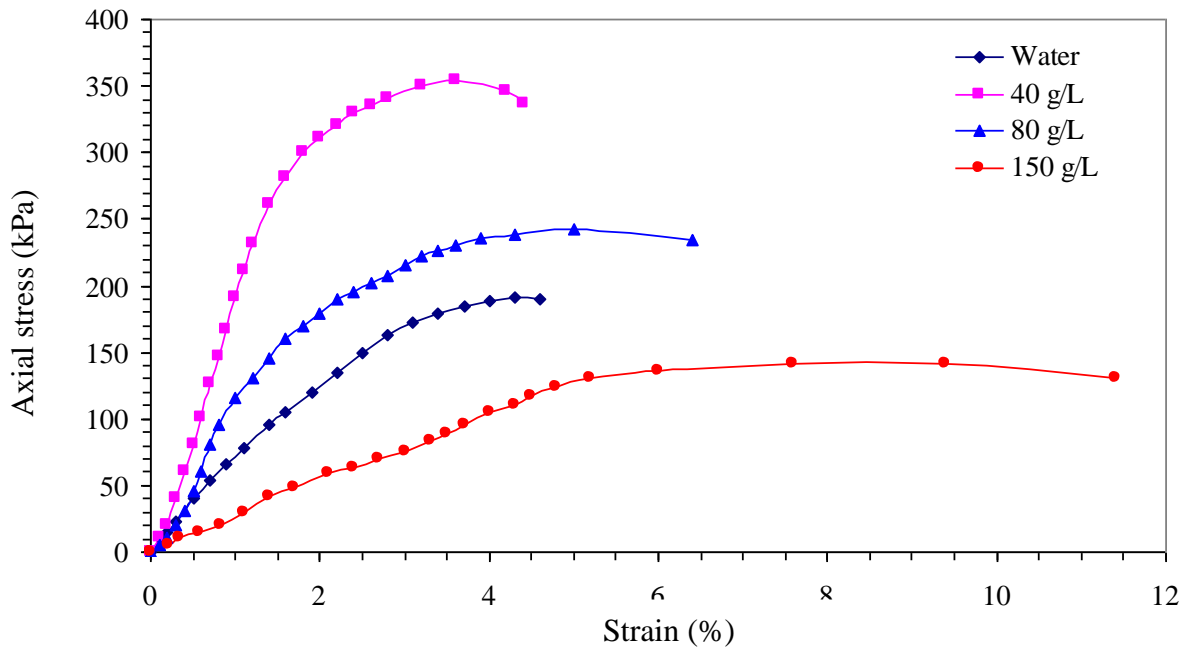


(c)

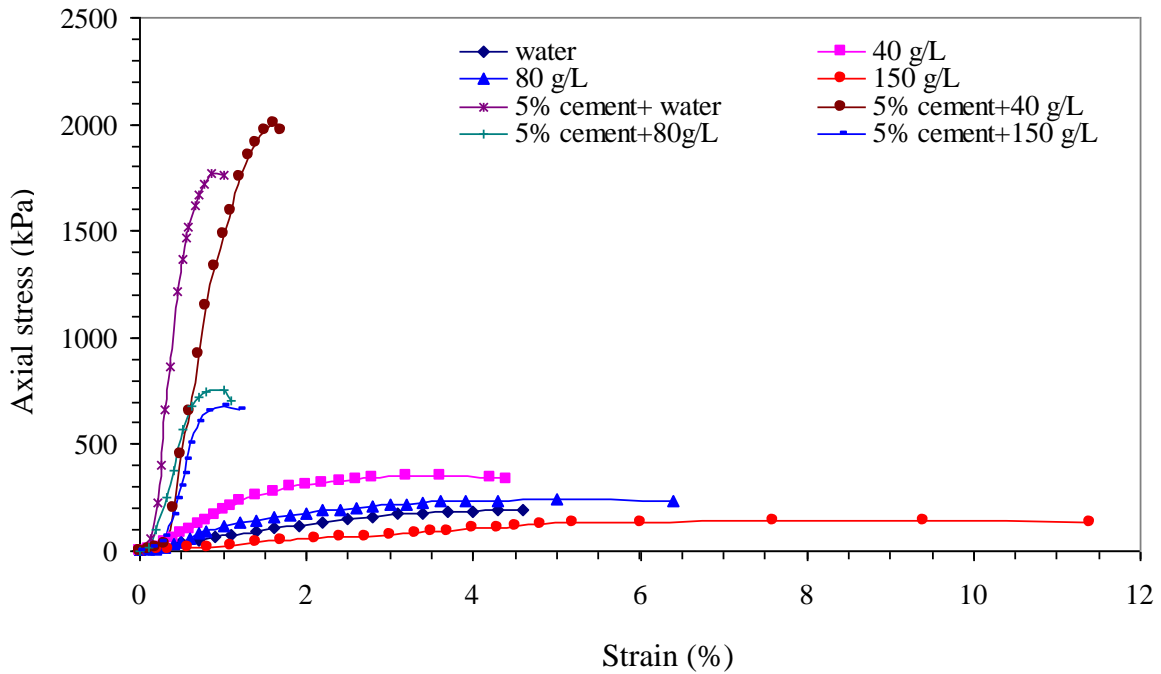


(d)

**Fig.5.** SEM images of various soil sediments treated with 8% cement at curing time of 7 days for: (a) soil deposited in water ; (b) soil deposited in 40 g/L ; (c) 80 g/L and (d) 150 g/L NaCl solutions.

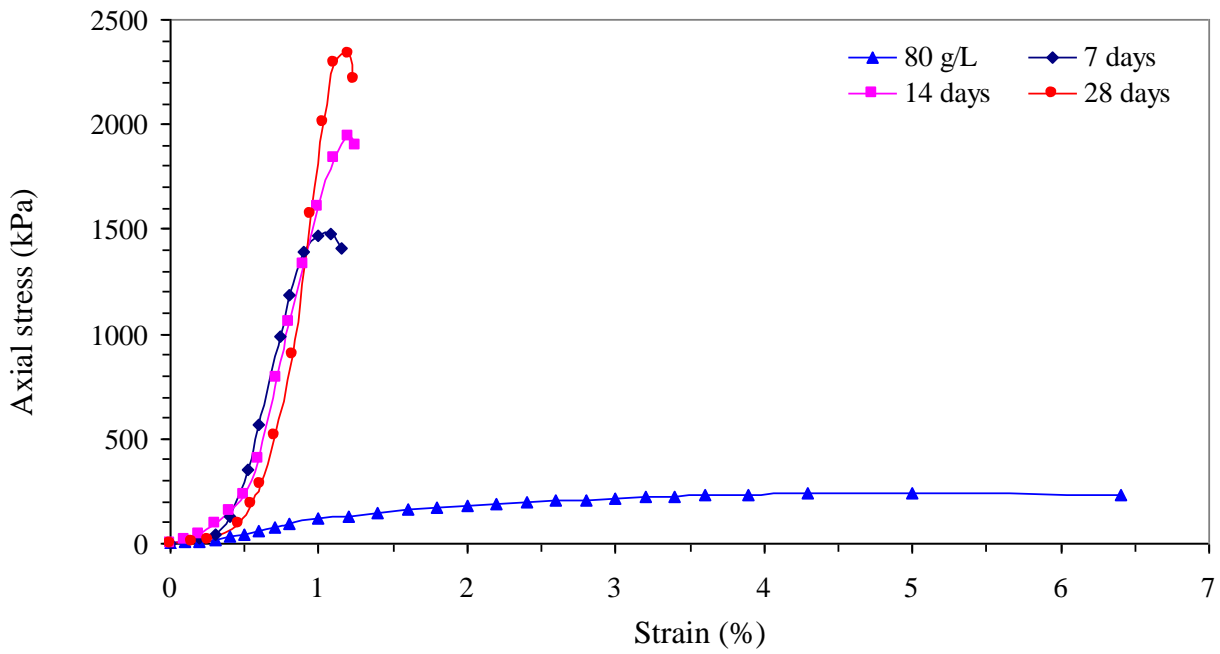


**Fig.6.** Stress-strain curves for soil deposited at different salt concentrations

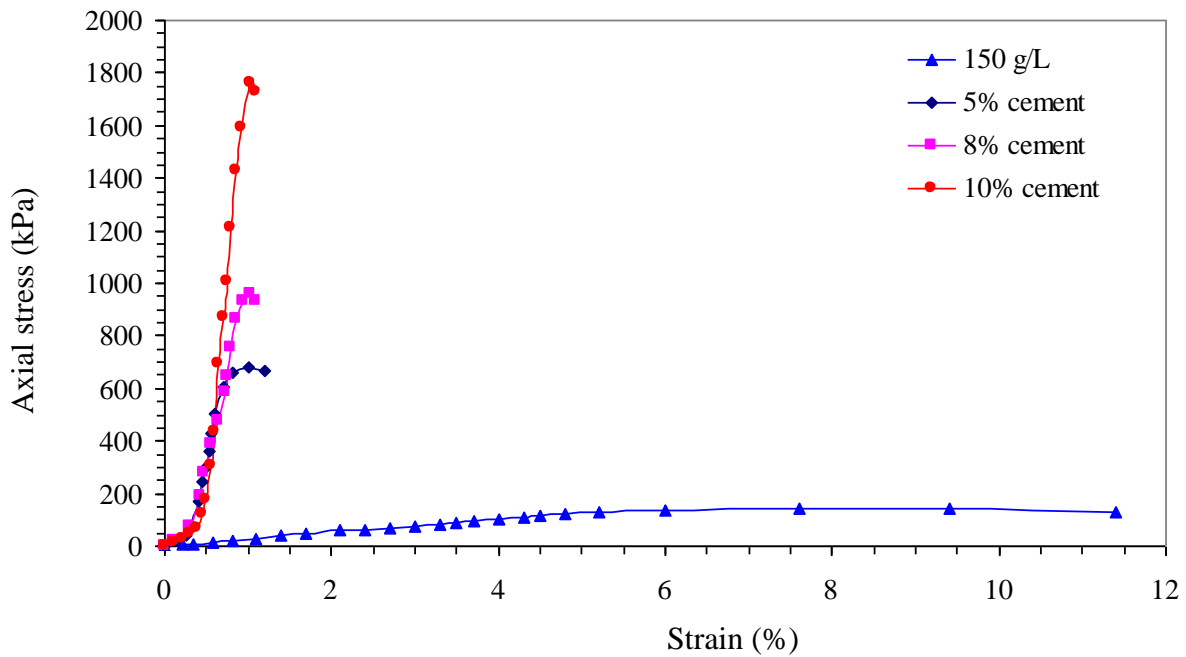


**Fig.7.** Stress-strain curves for soil deposited at different salt concentrations and treated soil with 5% cement at curing time of 7 days

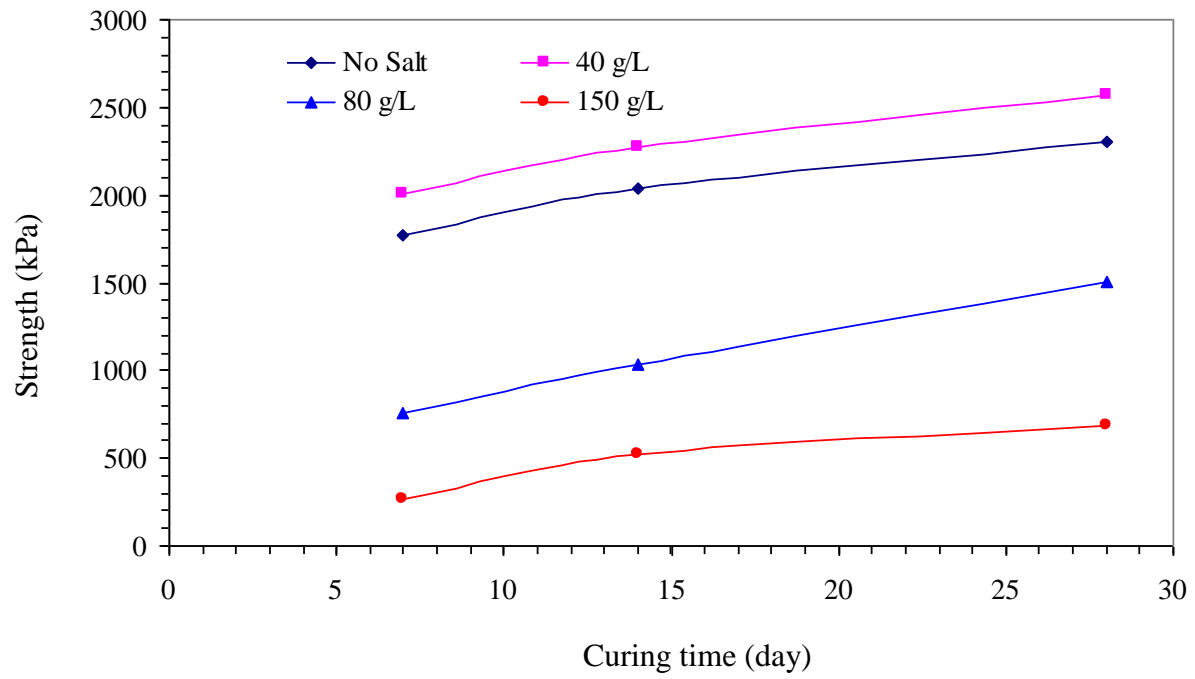




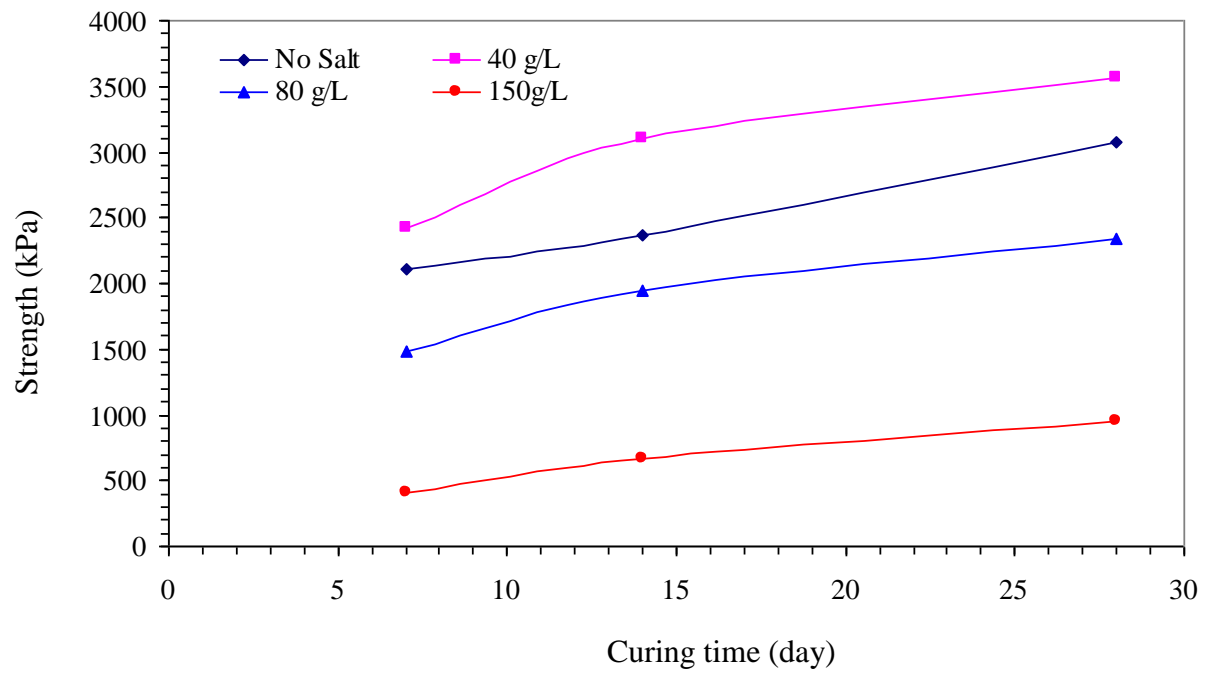
**Fig.8.** Stress-strain curves for soil deposited at 80 g/L salt solution and treated with 8% cement at different curing times



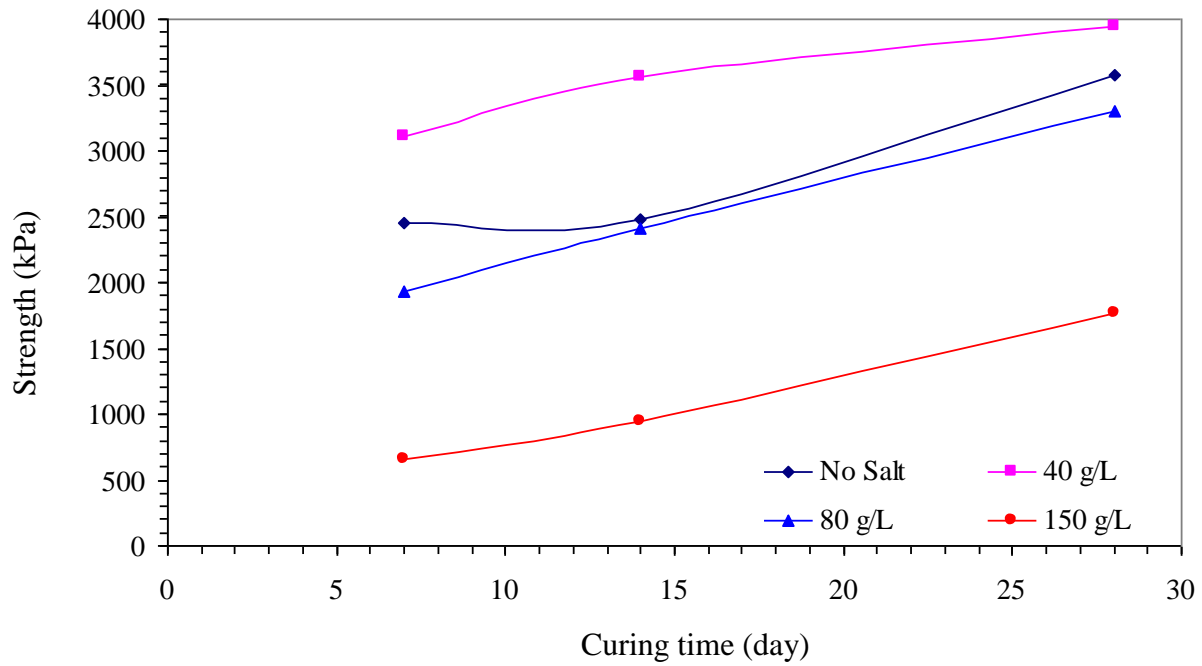
**Fig.9.** Stress-strain curves for soil deposited at 150 g/L salt solution and treated with different percentages of cement at curing time of 28 days



(a)

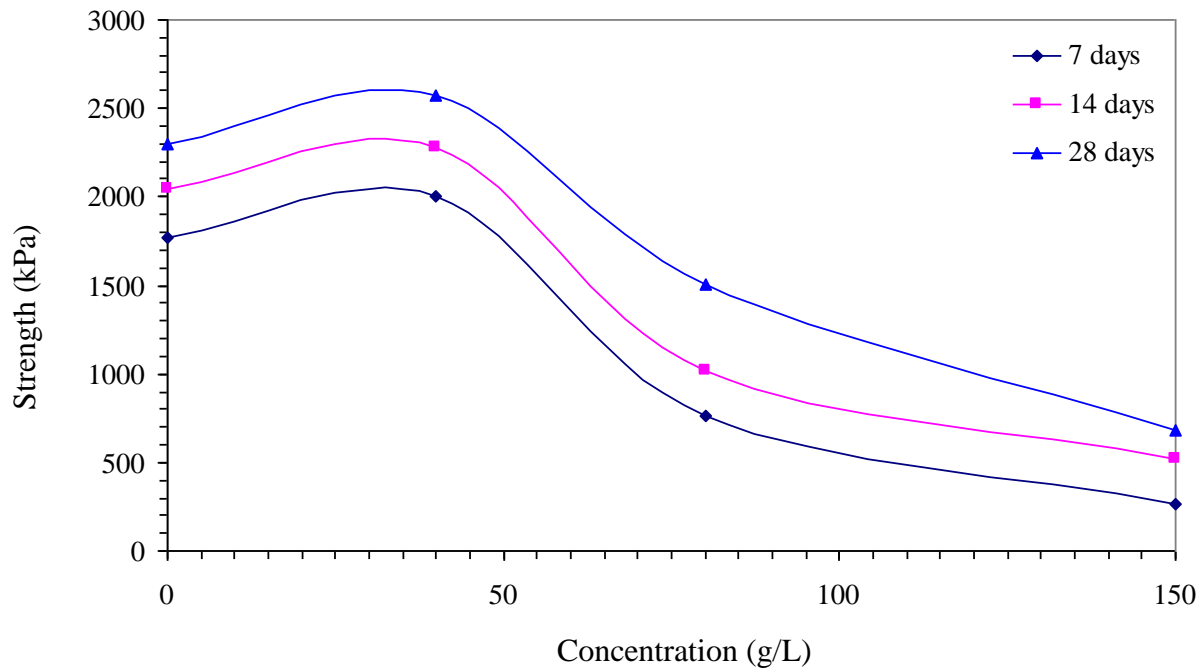


(b)

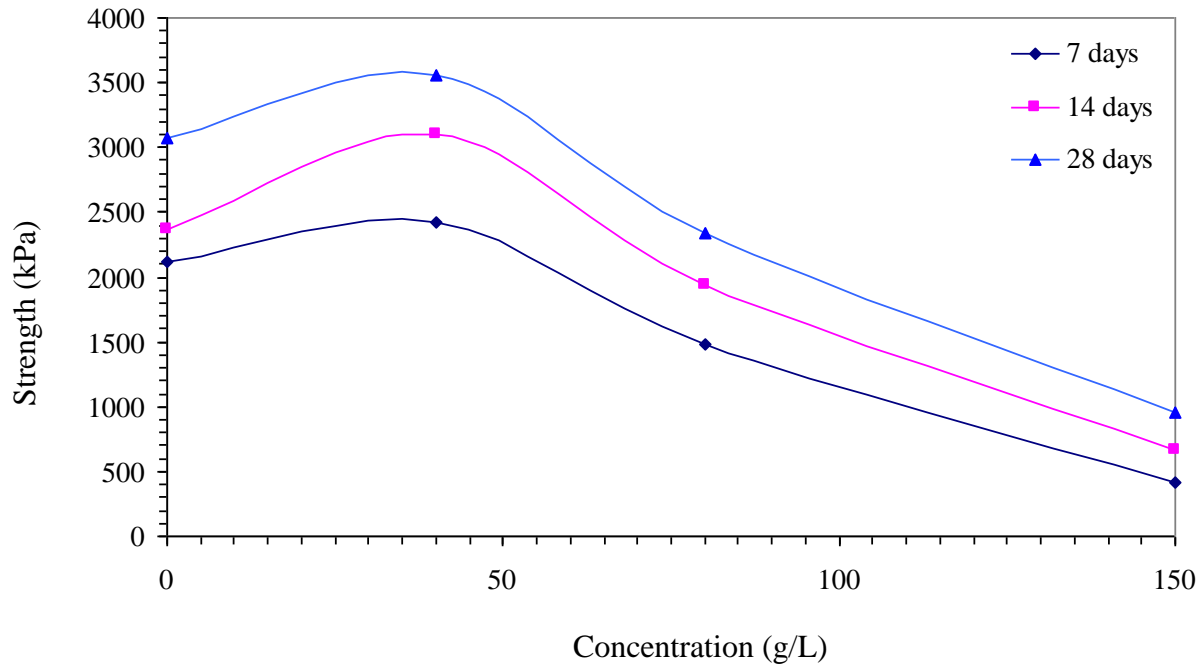


(c)

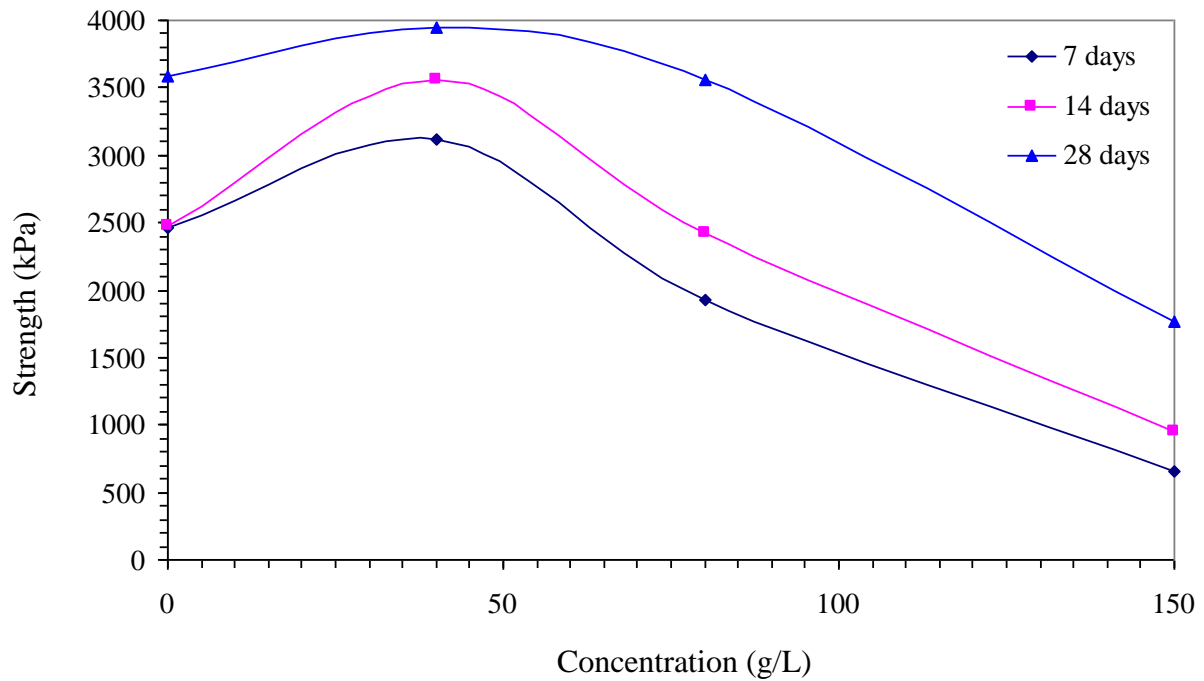
**Fig.10.** Strength-curing time curves for treatment of deposited soil with a) 5% cement, b) 8% cement c) 10% cement



(a)



(b)



(c)

**Fig.11.** Strength-concentration curves for treatment of deposited soil at different curing times a) 5% cement, b) 8% cement c) 10% cement