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Effect of cement on treatment of a clay soil contaminated with glycerol

Abstract

An investigation into the behaviour of a contaminated clay soil and its treatment was carried out through a program of experimental tests. The contaminated soil samples were prepared with different percentages (3, 6 and 9%) of a glycerol solution with 40% concentration. The samples were prepared as mixtures of clean or glycerol-contaminated soil with different cement contents (3, 6 and 9%). Atterberg limits and unconfined compressive strength (UCS) tests were conducted on the samples. The results showed that Atterberg limits are reduced by adding glycerol or cement or adding glycerol to soil-cement. Both the strength and stiffness of the contaminated soil are reduced by increasing the degree of contamination. The results of treated soil showed that adding cement to contaminated soil increases the strength and the amount of increase in strength is dependent on the percent of cement, curing time and degree of contamination. Based on SEM analysis, it was found that the presence of glycerol prevents from interaction between soil and cement.

Key Words: Contaminated soil, Glycerol, Treatment, Soil-cement, Strength, SEM

Introduction

Improving the mechanical behaviour of clay soils by stabilization is a means of fulfilling geotechnical design criteria. The methods of stabilization can be divided into chemical and mechanical techniques. Chemical stabilization includes the addition of additives such as lime, cement and fly ash to the soil. These chemical agents cause chemical reactions to occur in the soil water that stabilizes the soil. The use of lime as a stabilizing agent has been a popular method during the last few decades because it decreases the volume change of expansive soil and improves the mechanical behaviour of soil (Chen 1975; Bell 1993; Muntohar and Hantoro 2000). By adding lime to clay soil a number of mechanisms may be responsible for changes in the properties of soil (such as plasticity index, liquid limit, swelling potential and strength). They include cation exchange and pozzolanic reaction. These reactions cause binding of the particles of clay, reducing the clay content and increasing the percentage of coarse particles. Cement is another chemical agent that is used for stabilization. Sezer et al. (2006), Bahar et al. (2004) and Miller and Azad (2000) showed that the role of cement is similar to lime in stabilization.

Soil can be contaminated by organic materials due to leakage from underground or aboveground storage tanks and accidental spills. The response of soil to the contaminants not only depends on the local environment but it is also influenced by factors such as particle size, bonding characteristics between particles and ion exchange capacity. The transport of contaminant components from soil into ground water can cause serious problems. Stabilization of contaminated soil can be achieved by adding agents such as fly ash, lime and cement or combination of them. The stabilization of contaminated soil is usually performed to prevent from contaminant

transport to ground water, to reduce the mobility of the contaminant in soil, or to change the contaminant into a non-toxic form. This procedure is called stabilization and solidification of contaminated soil. The ultimate aim of this method is to reduce the concentration of contaminant in soil (Wiles 1987; Cullinane and Jones 1989 and Vipulanandan 1995). Young (1972) reported that all organic compounds can prevent from cementation. Tremblay et al. (2002) showed that humic acid can effectively retard the hydration process of cement. On the other hand, some studies have indicated that organic soil can be successfully treated by using cementing agents (e.g., Ogino et al. 1994; Parkkinen 1997; Hoikkala et al. 1997 and den Haan 1998). Meegoda and Muller (1993) and Meegoda et al. (1998) studied the use of petroleum contaminated soil as construction material. Tuncan et al. (2000) concluded from experimental tests on petroleum-contaminated soil with 5% cement and 10% fly ash that adding these chemical agents (cement and fly ash) causes increase in the strength of petroleum-contaminated soil. Tremblay et al. (2002) studied the effect of cement on treatment of two types of clay soil contaminated with different organic matters (e.g., acetic acid, humic acid, kersone). Their results showed that some of these organic matters prevent from treatment of soil by cement. Tremblay et al. (2002) concluded that the effect of pH of the pore solution and the coating of the soil particles by organic matter are important factors that influence the strength of stabilized soil. Gussoni et al. (2004) conducted experimental tests by proton nuclear magnetic resonance (NMR) imaging to investigate the cementation and hardening of cement in the absence and presence of organic matters in the soil. They found that a considerable delay occurs in the cement hardening when organic matters are present in the soil. Organic compounds affect the cement hydration by retarding reaction via formation of a protective film around the cement grain, hindering the production of

calcium hydroxide and accelerating the reaction via modification of colloidal C-S-H ($C=CaO$, $S=SiO_2$, $H=H_2O$) gel precipitated at very early stages around cement grains (Edmeades and Hewlett 1988). Hassan et al. (2005) studied the behaviour of a petroleum-contaminated soil and concluded that the contaminated soil can be stabilized with cement as an agent and used for road construction.

The engineering behaviour of soil, soil-cement, or soil-cement mixed with contaminant depends upon its existing structure. The term structure is used to mean the geometrical arrangement of different particles within a soil mass. Clay soils have two structures namely micro- and macro-structures. The physical and chemical interactions influenced by active clay minerals occur within microstructure. Significant information about the structure of soil can be obtained with advent of scanning electron microscopy (SEM). SEM is now widely used for explanation of different types of soil behaviour (Collins and McGown 1974). Some researchers such as Tremblay et al. (2002), Botta et al. (2004), Cai et al. (2006) and Yazdandoust and Yasrobi (2010) used the SEM analysis for observing the microstructure of soil samples under different conditions (contaminated, mixed with cement, etc) and for explaining their observed behaviours.

The use of contaminated soil and its stabilization can be considered in earthworks such as embankments, backfills and roads 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. In some areas the native soil is contaminated with hydrocarbon substances. For performing projects in such areas, because of the haulage distance to suitable soil and economic considerations, often the use of local soil is dictated for construction. Thus, the treatment and stabilization of local soil must be considered. On the other hand, in some areas where the soil has been contaminated and the

treatment is not economic, for the design of a project in these areas the effect of the contaminating substance on the soil behavior should be evaluated. Therefore, understanding the mechanical behavior of contaminated soils and their treatment is important.

Review of the literature shows that there has been considerable amount of research on the effect of chemical agents on the stabilization and solidification of contaminated soil. However, there has been very limited research on the stabilization of this kind of soil as a construction material for construction of roads, backfills and embankments. Therefore, the aim of this work is to evaluate the effect of cement on the treatment of a clay soil contaminated with different percentages of glycerol. The investigation is comprised of two stages. In the first stage, the mechanical behaviour of a clay contaminated with different amounts of glycerol (3, 6 and 9%) with concentration of 40 % is studied and the results are compared with natural soil. In the second stage different percentages of cement (3, 6 and 9%) are added to natural and contaminated soil and the results are compared to study the effect of different cement contents on the behaviour of contaminated soil for different amounts of contamination and different curing times.

Material and testing programme

The main materials used in this work were soil, cement and glycerol. The properties of these materials are described in this section.

Soil

The soil used in this experimental work was a clay. It was composed of 23% sand, 52% silt and 25% clay. It had a liquid limit of 47.0% and plasticity index of 22.6%. The optimum water content in standard compaction test was 16.33% dry unit weight was 17.75 kN/m³, and the specific gravity of solids (G_s) was 2.70. According to the

Unified Soil Classification System (USCS), the soil can be classified as clay with low plasticity (CL). The chemical properties of the soil are shown in Table 1.

Cement

The cement used in this study was Portland type 1 with specific gravity of 3.15. It had a Blaine fineness of approximately 4100 cm²/g. The physical and mechanical properties of the cement and its chemical composition are shown in Tables 2 and 3.

Glycerol

Glycerol was considered as the contaminating organic material. Glycerol (propane-1,2,3-triol) is an oxygenated organic compound that has been successfully and widely used in the chemical industry in the last decades. Major applications of glycerol can be found in the detergents industry as well as in drugs and pharmaceuticals production. The dielectric constant, absolute viscosity and mass density of glycerol were 40.1, 1.31 (cp) and 1258.02 (kg/m³) according to the information provided by the supplier. In this work a solution of glycerol with concentration of 40% was used.

Preparation of samples

The samples that were used consisted of natural soil, soil-cement, soil contaminated with glycerol and soil contaminated with cement. In preparation of the samples contaminated with glycerol, the degree of contamination was specified as the percentage weight of contaminant with respect to mixture of air-dried soil with contaminant. The degrees of contamination of 3, 6 and 9% were considered for preparing the contaminated samples. The selection of 3% as degree of contamination was according to the State of New Jersey classification of soil with an oil concentration above 3% as hazardous waste (Pincus et al. 1995). The calculated weight of glycerol with 40% concentration with degrees of contamination of 3, 6 and 9% was sprayed on 6 kg of soil. The soil was poured in flat layers with thickness of

about 50 mm in a tray. A pre-specified volume of fluid was sprayed on each layer and mixing was done carefully. The soil was then flattened and the next layer with the same thickness was added on it and spraying and mixing was repeated. This procedure was repeated until the last layer. After that, all layers were mixed and covered with a nylon to prevent evaporation. After a few days a number of samples were taken randomly and their water contents were measured to ensure the homogeneity and uniform distribution of moisture in the whole soil. The mixing was done in a covered tray. The mixture was then kept in sealed plastic bags for one week so that the soil and glycerol came to equilibrium condition. The natural soil was also mixed with different percentages (3, 6 and 9% of mixture of air-dried soil with cement) of cement. The mixtures of soil, glycerol and cement were prepared by mixing the contaminated soil (that was prepared previously) with 3, 6 and 9% cement. Standard compaction tests were conducted on these mixtures (natural soil, contaminated soil, soil-cement and soil-cement with glycerol). The maximum dry unit weight and optimum water content were determined for each of the materials. The samples for the main tests were prepared by static compaction in three layers at their respective maximum dry unit weight and optimum water content that were obtained from standard compaction test. In order to prepare the different samples for unconfined compression tests, the natural soil, glycerol, cement and water were weighted with accuracy of 0.1 gr. They were mixed in a container and water was added up to optimum water content. All mixing was done manually and proper care was taken to prepare homogenous mixtures at each stage of mixing. Static compaction was used for preparing cylindrical samples. The mixtures were compacted under the predefined target pressure in three layers at the rate of 1.5 mm/min until the maximum dry unit weight (according to standard compaction test) was achieved. The

length and diameter of the prepared samples were 100 and 50 mm respectively. After compaction the soil-cement samples with and without glycerol were stored in a curing cabinet at constant temperature and relative humidity according to the ASTM D1632 (2007) standard for curing times of 3, 7, 14 and 28 days. Three samples were prepared for each specific soil (natural soil, contaminated soil, soil-cement with and without contaminant) and different curing times.

Experimental tests

Atterberg limit tests were conducted according to ASTM D4318 (2010) on natural soil, contaminated soil, soil-cement and contaminated soil after adding different percents of cement. Unconfined compression tests were performed on the prepared samples according to the ASTM D1633 (2007) standard. The rate of loading was selected as 1mm/min (as used by many researchers such as Kumar et al. 2007 and Estabragh et al. 2012 for mixtures of fly ash with clay soil and soil-cement respectively). The applied load was recorded continuously and the test was continued until failure of the sample was attained and the compressive strength of the sample was determined.

Scanning electron microscopy (SEM) tests were performed on the samples in order to observe the microstructure of the samples in different conditions. The samples were prepared according to the optimum water content and maximum dry unit weight. A curing time of 7 days was considered for the samples of soil-cement and the cement-treated contaminated soil. After curing the samples were carefully cut with a sharp knife into small pieces of disk shape with 1 cm³ volume (as used by Yazdandoust and Yasrobi 2010 and Tremblay et al. 2002) and scanned under SEM.

Results

Atterberg limits according to the ASTM standard were determined on samples of contaminated soil and soil cement with different percentages of glycerol. The results are shown in the Table 4. Comparison of the results with Atterberg limits of natural soil shows that Atterberg limits are decreased by adding glycerol, or cement to the natural soil. This reduction is observed for contaminated soil after adding cement to it. Typical results of standard compaction tests on the natural soil, soil contaminated with different percentages of glycerol and soil-cement with 6% cement and different percentages of glycerol are shown in Fig.1. As shown in Fig.1a, adding 6 and 9% glycerol to the soil changed the maximum dry unit weight of the natural soil from 17.75 kN/m³ to 17.98 and 18.1 kN/m³. The optimum water content also changed from 16.3% to 16.0% and 15.0% respectively. The results for the soil with 3% glycerol show a decrease in maximum dry unit weight from 17.75 kN/m³ to 17.53 kN/m³ and increase in optimum water content from 16.33 to 17.8%. Table 4 shows the results of the compaction tests for natural soil, contaminated soil, soil cement and contaminated soil cement. Comparison of the results shows that, in all cases, the variations of the compaction characteristics (optimum water content and maximum dry unit weight) are insignificant.

Fig. 2 shows the stress-strain curves for the soil and the soil with different percentages of glycerol (3, 6 and 9%). As shown in this figure, adding glycerol to the soil resulted in increasing ductility of the soil and decreasing its strength. The strength of the soil sample before failure was 417.5 kPa at 2.46% strain, but for the samples with 3, 6 and 9 % glycerol the strength changed to 265.2, 215.7 and 188.5 kPa at axial strains of 3.62, 5.9 and 5.14 % respectively. The results show that although adding glycerol caused a reduction in strength but the ductility of the soil was increased. The initial slope of the stress-strain curves was reduced by adding glycerol to the soil which

shows reduction in stiffness of the contaminated soil. The position of the stress-strain curves is in the order of the percent of glycerol; so, the higher the percent of glycerol the greater is the reduction in the strength of the soil.

Typical stress-strain curves for the soil and the soil-cement with 3% cement at different curing times are shown in Fig.3. It can be observed that the addition of cement and the resulting cementation of soil particles increased the strength of the soil. Failure was defined as the peak point of the stress-strain curves. The peak strengths were 417.5 kPa for the soil and 556.5 kPa for the soil-cement at 28 days curing time at strains of 2.46 and 1.6 % respectively. Similar results are shown in Fig.4 for different percentages of cement (3, 6 and 9%) at curing time of 14 days; so the strengths for 3% and 9% cement were 561 and 1678 kPa, respectively. These data show that the peak strength and brittleness of the soil-cement increased with increasing the percent of cement. As shown in this figure (Fig.4) the axial strain for soil-cement is less than the soil. This condition is observed for the soil-cement in comparison with the natural soil and contaminated soil. This is more obvious with increasing the percent of cement and also with increasing the curing time at constant cement content. This is due to the brittle behavior that develops in the soil by adding cement or increasing the curing time that causes the failure to occur at small strains. This behavior was also reported by Estabragh et al. (2012). Fig.5 shows the stress-strain curves for natural soil and soil contaminated with 3% glycerol after adding 3% cement for different curing time. As shown in this figure, with increasing the curing time the strength and stiffness of the soil increased. The effect of different cement contents (3, 6 and 9%) on contaminated soil with 3% glycerol for curing time of 7 days is shown in Fig.6. The strengths of the contaminated soil with 3, 6 and 9% cement are 558, 915 and 1420 kPa respectively. It is resulted that the strength of the

soil-cement contaminated with 3% glycerol increased with increasing the curing time and percent of cement.

Discussion

As shown in Table 4 the liquid limit (LL), plastic limit (PL) and plasticity index (PI) of soil contaminated with different percentages of glycerol are decreased in comparison with the natural soil. This reduction is dependent on the percent of glycerol; so, more reduction is observed by increasing the percent of added glycerol. These results are in agreement with the results that were published by Singh et al. (2008) for contaminated soil by different percents of kerosene. The values of liquid limit and plastic limit for soil cement and soil cement contaminated with different percentages of glycerol are shown to decrease by increasing glycerol. As shown in this table, by adding 3% cement to the soil the values of LL and PL are increased in comparison with natural soil. By adding 6 or 9 % cement to the soil there is a reduction in LL and PI in comparison with mixture of soil with 3% cement. It is seen from this table that Atterberg limits have no specific trend by increasing the percent of cement in the soil. These results are similar to the results that were reported by Al-Rawas et al. (2005). The results show that adding cement to the contaminated soil causes reduction in the values of LL, PL and PI. This reduction at constant percent of glycerol is dependent on the percent of cement so, the higher the percent of cement, the greater is the reduction in the consistency limits. Table 4 also shows that adding cement to the soil contaminated by glycerol causes reduction in the liquid limit and plasticity index. It is resulted that the cohesive behaviour of soil is reduced.

Table 5 shows the maximum dry unit weight and optimum water content for the materials that were used in this study. As shown in this table, the maximum dry unit weight increased and optimum water content decreased for the soil contaminated with

6 and 9% glycerol but an opposite trend was observed for the soil contaminated with 3% glycerol. It can be said that adding 6 or 9% glycerol caused easy slippage of the particles over one another which resulted in the voids between the particles being reduced leading to increase of maximum dry unit weight and decrease of optimum water content. This trend was not observed for the mixture of soil with 3% glycerol. It can be said since the compaction energy was the same for different mixtures of glycerol with soil, for the soil with 3% glycerol more energy would be needed because the friction between the particles is more than the soil with 6 and 9% glycerol.

The results in Table 5 show that adding cement in different percentages (3, 6 and 9%) caused decrease in maximum dry unit weight and increase in optimum water content compared with the natural soil but the amount of change is relatively small. The addition of cement causes flocculation of the clay particles which leads to decrease in maximum dry unit weight and increase in optimum water content. Similar results were reported by some other researchers such as Shen and Mitchell (1966) and Estabragh et al. (2011). The variations of maximum dry unit weight and optimum water content for the contaminated soil with glycerol after adding different percents of cement are also shown in Table 5. The results show that at a constant percentage of glycerol and different percentages of cement there is no significant variation in maximum dry unit weight but the variation of optimum water content is considerable. The results show that the optimum water content decreases with increasing the percent of cement, particularly for 6 and 9% glycerol. The reduction in specific surface can cause reduction in optimum water content. These results are not in agreement with the results that were reported by Hassan et al. (2005) who indicated that adding cement to petroleum-contaminated soil causes reduction in maximum dry

unit weight and optimum water content. However, dry unit weight that is resulted from compaction is a function of soil minerals, texture of clay soil, interaction of particles with pore fluid and the applied compaction energy (Croft 1967).

Fig.2 shows the stress-strain curves for the soil and mixtures of soil with different percentages of glycerol. As shown in this figure, the strength of the soil is reduced by increasing the percentage of glycerol. The addition of glycerol increases the compressibility of the soil and reduces its stiffness and strength. The values of E (Young' Modulus) were calculated from the slope of the initial linear part of the stress-strain curves for different conditions of test. The value of E for natural soil was 363 kPa but for the samples of soil with 3, 6 and 9% glycerol it changed to 165, 150 and 136.5 kPa respectively. This shows that the adding glycerol causes the reduction of stiffness of soil and the amount of reduction is dependent on the percent of glycerol. The higher the glycerol content, the greater is the reduction in the stiffness of soil. The presence of glycerol in the pore fluid decreases the friction between the particles, facilitating the displacement of the particles. These findings are consistent with the results that were presented by Ratnaweera and Meegoda (2005) who concluded (from experiments on clay samples mixed with different percentages of glycerol and propanol) that adding glycerol or propanol to the soil causes reduction in both stiffness and initial slope of the stress-strain curves of contaminated soil with glycerol or propanol.

The surface charges on clay particles are negative (anions). These negative surface charges attract cations and the positively charged side of water molecules from surrounding water. Consequently, a thin film or layer of water (called adsorbed water) is bonded to the mineral surfaces. The thin layer of water is known as the diffuse double layer (DDL). The thickness of this layer is dependent on a number of factors

such as dielectric constant, absolute temperature, etc. The dielectric constants for water and for the glycerol solution with 40% concentration (that were used in this work) are 78.5 and 67.1 respectively. This shows that the dielectric constant is lower for the glycerol solution than water. Sridharan and Rao (1979) and Moore and Mitchell (1974) argued that the reduction in the dielectric constant causes a reduction in the physico-chemical interactions between pore fluid and clay particles which results in increase in strength of soil. Ratnaweera and Meegoda; (2005) reported reduction in soil strength and ductility behaviour in stress-strain curves as a result of decrease in dielectric constant in long term when the thickness of diffuse double Layer (DDL) was decreased. The conditions in which the samples were prepared in this study do not represent long-term conditions. Therefore, not all the pores between the particles of sample were filled with glycerol. It can be said that the viscosity of glycerol is an important factor in reducing the strength and increasing the ductility of the soil. The viscosities of water and the glycerol solution with 40% concentration are 0.894 and 4.31 CPS respectively. Meegoda and Ratnaweera (1994) concluded from their experiments that increasing in the viscosity of glycerol solution results in compressibility of soil.

The variations of strength of the soil-cement (with 3, 6 and 9% cement) with different curing times are shown in Fig.7. As shown in this figure, for a given curing time the soil strength is increased with increasing the percentage of cement. For example, for 7 days curing time the strengths for 3, 6 and 9% cement content are 525, 815.5, and 1311 kPa respectively. The results also show that, for a constant cement content the strength is increased with increasing the curing time. The strength for the sample with 9% cement at curing time of 3 days is 1207 kPa and for 28 days curing time it changes to 1492 kPa that shows an increase of 23.6%. The values of E were also

calculated for soil-cement with different percentages of cement and different curing times. The results show that for the samples with 6% cement for curing times of 3, 7, 14 and 28 days the value of E is 800, 847, 868 and 111 kPa respectively. It is seen that for a given percent of cement, the values of E are more than the natural soil (363 kPa) and are dependent on the curing time. This is because the chemical reaction continues with time. The results also show that at a constant curing time, the value of E is increased with increasing the percent of cement (at 14 curing time the values of E for 3, 6 and 9% cement are 430, 868 and 1004 kPa).

The basic structural units of most clay minerals consist of a silica tetrahedron and an alumina octahedron. Silicon and aluminium may be partially replaced by other elements in these units. When cement is mixed with a clay soil, during the initial hydration of cement calcium ions are produced and cause a reduction of plasticity of the soil. The mechanism is most likely cation exchange or crowding of additional cations on the soil. These processes that change the electrical charge density around the soil particles cause changes in the properties of soil, resulting in reduction of plasticity. The units of silica and alumina then gradually react with the released calcium ions. This reaction is known as the pozzolanic reaction in which chemical bonds develop between adjacent cement grains surfaces and interfaces between cement grains and soil particles. In cohesive soils cement hydration develops strong linkages between the mineral and the aggregates to form a honeycomb type structure whereby the particles of soil can no longer slide over each other. Therefore, not only cement reduces the plasticity of soil but it also increases the strength and reduces the water holding ability of cohesive soils

Figs. 8a , 8b and 8c show the variations of compressive strength with curing time for 3, 6 and 9% cement and different percentages of glycerol. As shown in these figures

increasing the curing time causes increase in strength, particularly for different percentages of cement with 3% glycerol. The compressive strength of the soil contaminated with 3% glycerol mixed with different percentages of cement is more than that of the corresponding soil-cement mixtures. By increasing the percentage of glycerol beyond a certain limit (6 and 9%) there is a reduction in the strength of the contaminated soil with different cement contents. The values of E were also calculated for contaminated soil-cement. For example for soil-cement with 9% cement and contaminated with 9% glycerol the values of Young's modulus are 243, 274, 314 and 360 kPa for curing times of 3, 7, 14 and 28 days respectively. It is shown that by increasing the curing time, the value of E is increased but is much less than soil-cement without contaminant.

In this case the glycerol produces an organic phase in a gel form that links the particles together and fills the pores between the particles (Tremblay et al. 2002). This increases the soil's stiffness and strength decreases its compressibility compared with the soil-cement without glycerol. Therefore, the strength of soil-cement is changed by adding glycerol. This is because by increasing the glycerol, it tends to cover the cement particles and prevent from hydration of the cement. Therefore, it is resulted that there is a reduction in the strength of soil-cement contaminated with glycerol by increasing the percentage of cement. At a constant percentage of cement the strength is increased with increasing the curing time.

It is generally accepted that the increase in strength of mixture of soil-cement is due to the hydration of cement and production of cementing materials. When cement is added to soil contaminated with hydrocarbons, different reactions may occur due to the organic matter that influence the strength of the soil. Pollard et al. (1991) and Vipulanandan (1995) concluded from experimental tests on contaminated soils that

hydrocarbons tend to coat the cement particles and this delays the hydration process and consequently the setting time, nonetheless, they do not significantly affect the ultimate strength. This is not in agreement with the results obtained in the present work. By increasing the percentage of glycerol surfaces of more particles are covered by glycerol which reduces the friction between the particles and results in the reduction of strength compared to the sample of soil cement.

Tremblay et al. (2002) indicated that the pH of pore fluid can be responsible for the cementing process and gaining strength of the sample. pH of the pore solution is important because when its value is lower than 9 hydration products are dissolved and produce no hardening or little hardening in the soil (Tremblay et al. 2002). The addition of glycerol can decrease the pH of pore solution and reduce the cementation process which results in reduction of the strength of soil. The pH of pore fluid was measured for soil with 9% glycerol and for mixture of soil-cement with 9% cement as 8.3 and 12.1 respectively. On the other hand the values of pH for samples with 9% cement with 3, 6 and 9% glycerol and also those with 3 and 6% cement with different percentages of glycerol are in the range of 11.6 to 12. Since the value of pH is more than 9 it cannot be effective in the reduction of strength of the mixture of soil-cement with different percentages of glycerol. Therefore adding glycerol to the soil-cement does not produce acid environment in the mixture for softening and reduction of the strength of samples. Fig.9 shows similar results of compressive strength at different curing times for different amounts of glycerol at constant cement content. As shown in Fig.9a, for the soil cement with 3% cement content, the strength is increased by increasing the amount of glycerol up to 3% beyond which, further increase in glycerol leads to reduction in strength. Up to a certain limit (3%) glycerol helps to increase the strength by filling the pores of the soil and linking the particles. This trend is also

observed in Fig.9b for the mixture of soil with 6% cement where the increase in strength is observed up to 3% glycerol. However for the mixture of 9% cement (Fig.9c) there is a slight increase in strength up to 3 % glycerol and beyond 3 % glycerol a similar trend of reduction in strength is observed. As mentioned above, in these cases the reduction in pH reduces the hardening of the sample and results in reduction of strength. These findings are in agreement with the results that were reported by Hassan et al. (2005). They concluded from strength tests on a petroleum contaminated soil mixed with 5, 10 and 15% cement for different curing times (7, 14 and 28 days) that the strength is increased for 5% cement. They found that there is no considerable increase in strength for other curing times; even for curing time of 28

Figs 10a and 10b show the micrograph for natural soil and soil contaminated with 6% glycerol. As shown in Fig.10a the flocculating structure is very obvious for the natural soil but Fig.10b shows a flocculated structure in which the pores between particles have been reduced. It can be said that the viscosity of glycerol caused the reduction in friction between particles and allowed them to move more easily. A micrograph of mixture of soil with 6% cement is shown in Fig.10c. This micrograph shows the flocculated structure of soil cement where the cementing products with lamellar form create trellis like structure on and between the particles of soil. They are mainly calcium silicate hydrates as reported by Choquette et al. (1987). Fig.10d shows a monograph of treated contaminated soil with 6% cement. As shown in this figure the soil appears in lamellar shape; a part of the cement appears to have linked some soil particle together.

This study shows that it is possible to treat clay soils contaminated with organic matters. An important factor that should be considered is the different percentages of organic contaminating matter that can change the results and treatment. A high degree

of contamination may produce a harmful effect, while at low degree of contamination there is no effect on the process of cementation and treatment of soil.

Conclusion

Behaviour of a contaminated clay soil and its treatment with cement was studied.

Based on the experimental results the following conclusions can be drawn:

- 1- The strength and stiffness of contaminated soil are decreased with increasing the degree of contamination.
- 2- Adding cement to contaminated soil increases its strength. The amount of increase in strength is dependent on the percent of cement, curing time and degree of contamination.
- 3- For a constant cement content, increasing the degree of contamination beyond 3 % caused a reduction in strength of the soil.

References

- Al-Rawas, A. A., Hago, A. and Al-Sarmi H.,(2005). "Effect of lime, cement and sarooj (artificial pozzolan) on the swelling potential of an expansive soil from Oman." *Build. Environ.*, 40(5), 681-687.
- ASTM (2010). "Standard test method for normal consistency of hydraulic cement." ASTM C187, West Conshohocken, PA.
- ASTM (2008). "Standard test method for for time setting of hydraulic cement by Vicat needle." ASTM C191, West Conshohocken, PA.
- ASTM (2008) ." Standard test method for compressive strength of hydraulic cement mortars." ASTM C109, West Conshohocken, PA.
- ASTM (1985). " Methods of test for tensile strength of hydraulic cement mortars." ASTM C190. West Conshohocken, PA.
- ASTM (2007). "Standard practice for making and curing soil-cement compressive and flexure test specimens in the laboratory." *D1632*, west Conshohocken, PA.
- ASTM (2007). "Standard test method for compressive strength of moulded soil-cement cylinders" *D1633*, west Conshohocken, PA
- ASTM (2010). "Standard test methods for liquid limit, plastic limit and plasticity index of soil " *D 4318*, west Conshohocken, PA.
- Bahar, R., Benazzoug, M., and Kenai, S. (2004). "Performance of compacted cement stabilized soil." *Cem. Concr. Compos.*, 24(7),811-820.
- Bell, F.G. (1993). "*Engineering treatment of soils.*" London: Chapman and Hall.
- Botta, D., Dotelli, G., Biancardi, R., Pelosato, R. and Sora, N.I. (2004). "Cement-clay pastes for stabilization/solidification of 2-chloroaniline." *Waste Manage*, 24, 207-216.

- Cai, Y., Shi, B., Ng, C.W.W., and Tang, C-S. (2006). “Effect of polypropylene fiber and lime admixture on engineering properties of clayey soil.” *Eng. Geol.*, 87, 230-240.
- Chen, F.H.(1975). “*Foundation on expansive soils.*” Amsterdam: Elsevier Science
- Choquette, M., Bérubé, M.A. and Locat, J. (1987). “Mineralogical and microtextural changes associated with lime stabilization of marine clays from Eastern Canada.” *Appl Clay Sci*, 2, 215-232.
- Collins, K., and McGown, A. (1974). “The form and function of microfabric features in a variety of natural soils.” *Geotechnique*, 24 (2), 223–254.
- Croft, J.B. (1967). “The influence of soil mineralogical composition on cement stabilization.” *Geotechnique*, 17(2, 119-135.
- Cullinane, J.M., and Jones, L.W. (1989). “Solidification and stabilization of hazardous waste.” Part 1. *Hazard. Mater. Contr.* 2(1), 9-19.
- den Haan, E.J. (1998). “Cement based stabilizers for Dutch organic soils.” *In Proc. Intl. Conf. on Problematic Soils*. Sendai, Japan, A.A. Balkema, Rotterdam, Vol.1,, 53-56.
- Edmeades R.M., Hewlett, P.C. (1998). “Cement admixtures.” In: Hewlett PC, editor. *Lea’s chemistry of cement and concrete*. London: Arnold, p. 837–96.
- Estabragh, A.R., Namdar, P., and Javadi, A.A. (2012). “Behavior of cement-stabilized clay reinforced with nylon fiber.” *Geosynthetics Int.*,19(1), 85-92.
- Estabragh, A.R., Beytolahpour, I., and Javadi, A.A. (2011). “Effect of resin on the strength of soil-cement mixture.” *J. Mater. Civ. Eng.*,23(7), 969-976.
- Gussoni, M., Greco, F., Bonazzi, F., Vezzoli, A., Botta, D., Dotelli, G., Natali Sora, I., Pelosato, R. and Zetta, L. (2004). “¹H NMR spin-spin relaxation and imaging in porous system: an application to the morphological study of white

- Portland cement during hydration in the presence of organics.” *Magn Resonance Imaging*, 22, 877-889.
- Hassan, H.F., Taha, R., Al Rawas, A., Al Shandoudi, B., Al Gheithi, K., and Al Barami, A.M. (2005). “Potential uses of petroleum-contaminated soil in highway construction.” *Constr. Build. Mater.*, 19, 646-652.
- Hoikkala, S., Leppänen, M., and Tanska, H. (1997). “Blockstabilization of peat in road construction.” *Proc. 14th Int. Conf. on Soil Mechanics and Foundation Engineering (ICSMFE)*, Hamburg, Germany, 1693-1696.
- Kumar, A., Walia, B.S., and Bajaj, A. (2007). “Influence of fly ash, lime and polyester fibres on compacted and strength properties of expansive soil. *J. Mat. In. Civil Eng.* 19(3), 242-248.
- Meegoda, J.N., and Muller, R.T. (1993). “Petroleum contaminate soils in highway construction.” *Proc. Recovery and effective reuse of discarded and by-products for construction of highway facilities*, Denver, CO, 4-83-4-95.
- Meegoda, N.J., and Ratnaweera, P. (1994). “Compressibility of contaminated fine-grained soils.” *Geotech. Test. J.*, 17(1), 101-112.
- Meegoda, J.N., Chen, B., Gunasekera, S.D., and Pederson, P. (1998). “Compaction characteristics of contaminated soils-reuse as a road base material.” *Proc. of the geocongress: geotechnical special publication no. 79: recycled materials in geotechnical applications*, Boston, M.A., 195-209.
- Miller, G. and Azad, S. (2000). “Influence of soil type on stabilization with cement kiln duct.” *Constr. Build. Mater.*, 14(2), 89-97.
- Moore, C.A., and Mitchell, J.K. (1974). “Electromagnetic forces and soil strength.” *Geotechnique*, 24(4), 627-640.

- Muntohar, A.S. and Hantoro G. (2000). "Influence of rice husk ash and lime on engineering properties of clayey subgrade." *Electric J. Geotech. Eng.*
- Ogino, T., Goto, T., Kataoka, K., and Kuroda, M. (1994). "Utilization of stabilized dredged waste for construction material." *Proc. of the 1st Int. Congr. on Environmental Geotechnics (ICEG)*, 10-15 July, edited by W.D. Carrier, III. Edmonton, Canada, 49-56.
- Parkkinen, E. (1997). "Utilization of industrial by-products to strength soft clayey and organic soils." *Proc. of the 14th Int. Conf. on Soil Mechanics and Foundation Engineering (ICSMFE)* Hamburg, Germany, 1701-1704.
- Pincus, H.J., Meegoda, N.J., and Ratnaweera, P. (1995). "Treatment of oil contaminated soils for identification and classification." *Geotech. Test. J.*, 18(1), 41-49.
- Pollard, S.J.T., Montgomery, D.M., Sollars, D.M., and Perry, R. (1991). "Organic compounds in the cement-based stabilization/solidification of hazardous mixed wastes-mechanistic and process considerations." *J. Hazard. Mater.*, 28, 313-327.
- Ratnaweera, P., and Meegoda, J.N. (2005). "Shear strength and stress-strain behaviour of contaminated soils." *Geotech. Test. J.*, 29(2), 1-8.
- Sezer, A., Inan, G., Yilmaz, H.R. & Ramyar, K. (2006). "Utilization of a very high lime fly ash for improvement of Izmin clay." *Build. Environ.*, 41 (2), 150-155.
- Singh, S.K., Srivastava, R.K. and John, S. (2008). "Settlement characteristics of clayey soils contaminated with petroleum hydrocarbons." *Soil Sediment Contam.*, 17, 290-300.
- Shen, C.K., and Mitchell, J.K. (1966). "Behaviour of soil-cement in repeated compression and flexure." *Highway Res. Rec.*, 128, 68-100.

- Sridharan, A., and Rao, G. (1979). "Shear strength behaviour of saturated clays and role of the effective stress concept." *Geotechnique*, 2, 177-193.
- Tremblay, H., Duchesne, J., Locat, J., and Leroueil, S. (2002). "Influence of the nature of organic compounds on fire soil stabilization with cement." *Can. Geotech. J.*, 39(3), 535-546.
- Tuncan, A., Tuncan, M., and Koyuncu, H. (2000). "Use of petroleum contaminated drilling wastes as sub-base material for road construction." *Waste Manage. Res.*, 18, 489-505.
- Vipulanandan, C. (1995). "Effect of clays and cement on the solidification/stabilization of phenol-contaminated soils." *Waste Manage.*, 15(5/6), 399-406.
- Wiles, C. (1987). "Review of solidification/stabilization technology." *J. Hazard. Mater.*, 14, 5-21.
- Yazdandoust, F. and Yasrobi, S.S. (2010). "Effect of cyclic wetting and drying on swelling behaviour of polymer-stabilized expansive clays." *Appl Clay Sci*, 50, 461-468.
- Young, J.F. (1972). "A review of the mechanisms of set-retardation in Portland cement pastes containing organic admixtures." *Cem. Concr. Res.*, 2, 415-433.

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Table 1. Chemical composition of soil

Chemical component	Amount	Chemical component	Amount
pH	7.8	Mg ²⁺ (meq/L)	11.25
EC ^a (dS/m)	13.2	Cl ⁻ (meq/L)	62.5
Na ⁺ (meq/L)	108.69	CO ₃ ²⁻ (meq/L)	0.6
K ⁺ (meq/L)	0.20	HCO ₃ ⁻ (meq/L)	5.0
Ca ²⁺ (meq/L)	35.0	SO ₄ ²⁻ (meq/L)	72.91
Ca CO ₃ (%)	10.2	O.C. ^b (%)	0.11
		C.E.C. ^c (meq/100g)	8.42

a-Electrical Conductivity

b- Organic Content

c- Cation Exchange Capacity

Table 2. Physical and mechanical properties of cement

Properties	Standard Designation	Value
Normal consistency (%)	ASTM C 187-10	29.2
Primary setting time (min)	ASTM C 191-08	108
Final setting time (min)	ASTM C 191-08	180
Compressive strength (MPa)	ASTM C 109-08	
7days		23
28 days		34
Tensile strength (MPa)	ASTM C 190-85	
7 days		1.6
28 days		2.4
Flexure strength (MPa)		
7 days		3.1
28 days		4.2

Table 3. Chemical composition of cement

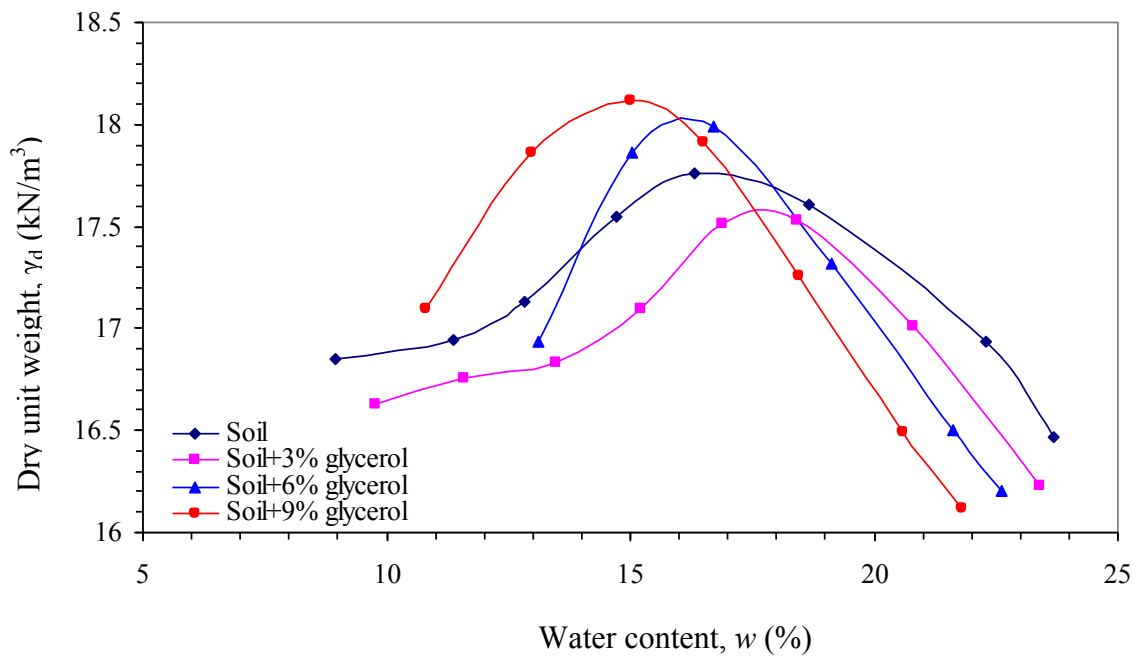
Chemical name	Chemical formula	Percent by weight
Silicon dioxide	SiO ₂	-
Aluminum oxide	Al ₂ O ₃	-
Ferric oxide	Fe ₂ O ₃	-
Magnesium oxide	MgO	max, 5.0
Sulfur trioxide	SO ₃ When C ₃ A < 8% When C ₃ A > 8%	max, 3.0 max, 3.5
Loss on ignition		max, 3.0
Insoluble residue		max, 0.75
Tricalcium silicate (C ₃ S)		-
Dicalcium silicate (C ₂ S)		-
Tricalcium aluminate (C ₃ A)		-
Tetracalcium aluminoferrite plus twice the tricalcium aluminate ((C ₄ AF+2(C ₃ A)) or solid solution (C ₄ AF+C ₂ F) as applicable		-

Table 4. Atterberg limit for natural soil, contaminated soil and contaminated soil after adding cement

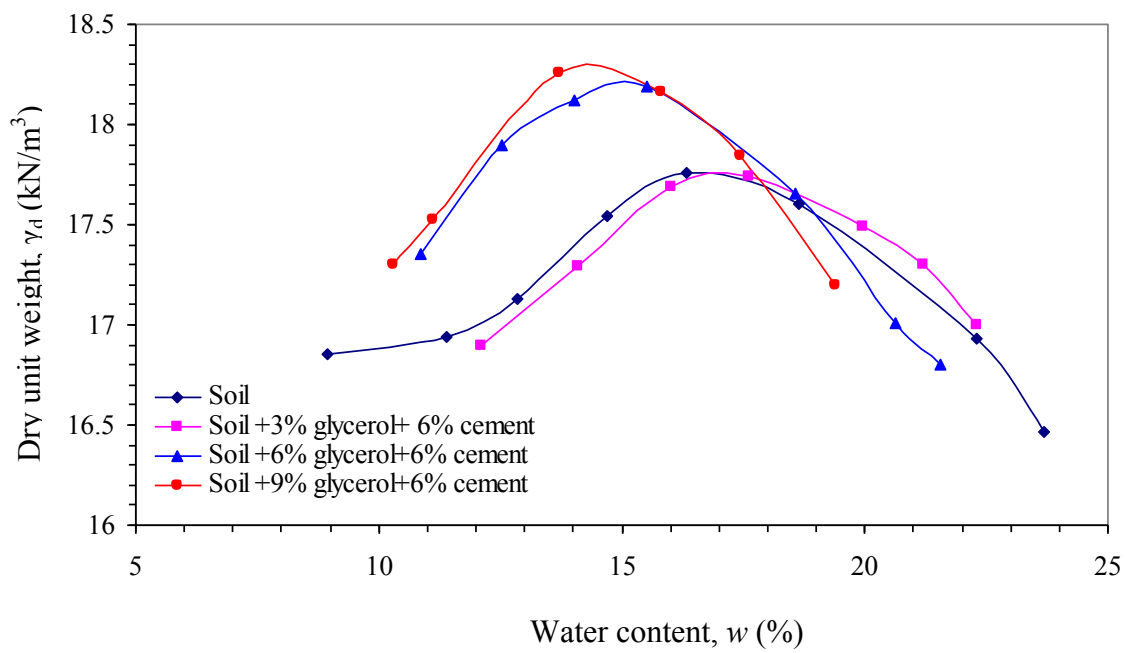
Soil (%)	Cement (%)	Glycerol (%)	LL (%)	PL (%)	PI (%)
100	-	-	47.0	24.4	22.6
97.0		3.0	44.0	22.2	21.8
94.0	-	6.0	42.5	21.2	21.3
91	-	9.0	41.5	20.4	21.1
97.0	3.0	-	55.0	28.0	27.9
94.0	6.0	-	47.5	26.1	21.4
91.0	9.0	-	50.0	27.5	22.5
94.0	3.0	3.0	46.8	29.8	17.0
91.0	6.0	3.0	45.7	29.6	16.1
88.0	9.0	3.0	44.12	29.5	14.62
91.0	3.0	6.0	45.5	27.2	18.3
88.0	6.0	6.0	45.0	28.2	16.8
85.0	9.0	6.0	44.5	28.4	16.1
88.0	3.0	9.0	45.8	23.4	22.4
85.0	6.0	9.0	45.6	23.4	22.2
82.0	9.0	9.0	43.2	24.2	19.0

Table 5. Compaction parameters for soil, soil-cement, soil with glycerol and soil-cement with glycerol

Soil (%)	Cement (%)	Glycerol (%)	w_{opt} (%)	γ_{dmax} (kN/m ³)
100	-	-	16.33	17.75
97	3	-	18.5	17.38
94	6	-	19.5	17.12
91	9	-	18.13	17.53
97	-	3	17.8	17.57
94	-	6	16.0	17.98
91	-	9	15.0	18.1
94	3	3	18.0	17.32
91	3	6	17.0	17.82
88	3	9	16.1	17.90
91	6	3	17.6	17.7
88	6	6	15.5	18.2
85	6	9	14.2	18.29
88	9	3	19.0	17.57
85	9	6	15.5	17.78
82	9	9	13.7	17.97



(a)



(b)

Fig. 1. Compaction curves (a) for soil and soil with different percent of glycerol, (b) for contaminated soil with different percent of glycerol after the addition of 6% cement

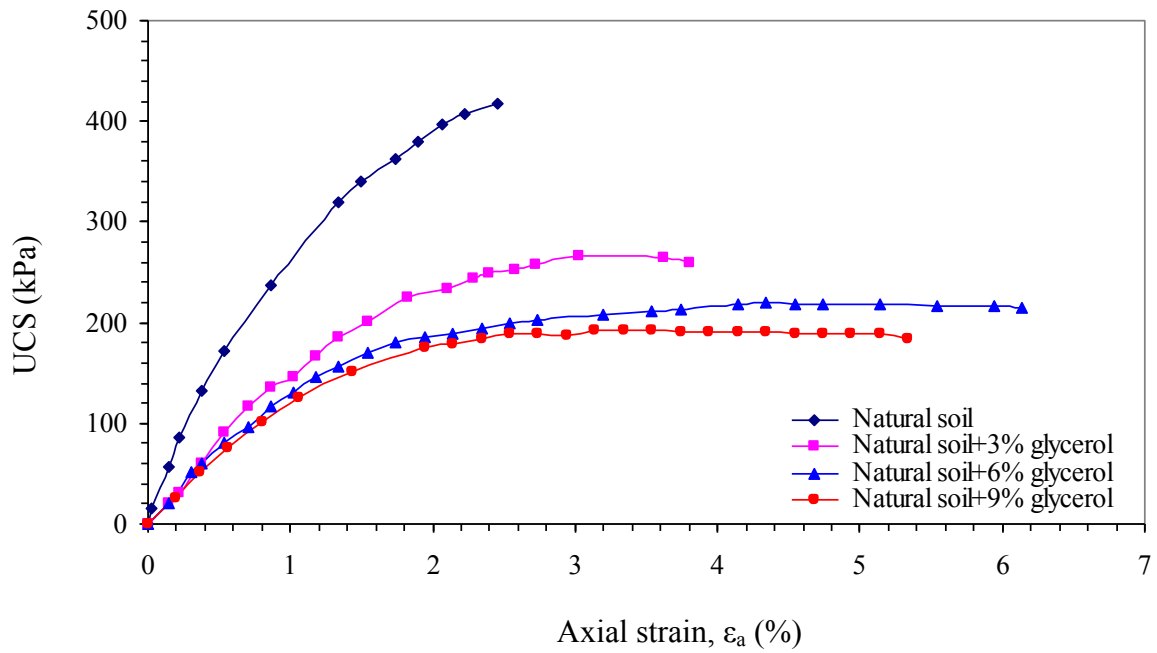


Fig.2. Stress-strain curves for natural soil and soil with different percent glycerol

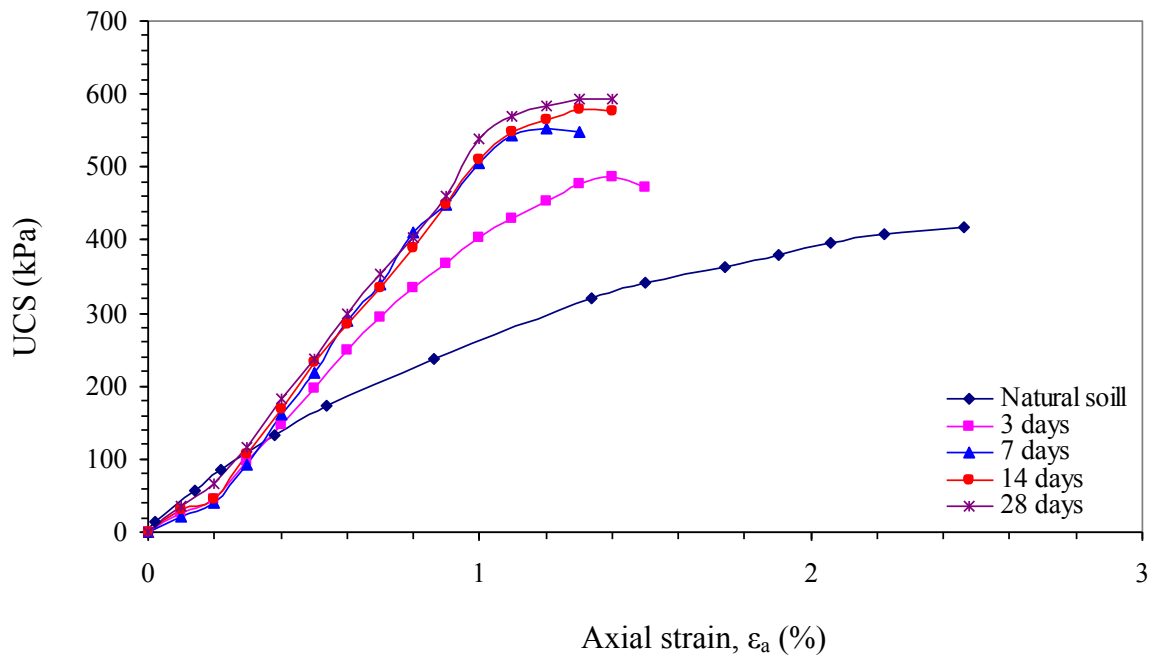


Fig.3. Stress-strain curves for natural soil and soil-cement with 3% cement at different curing time

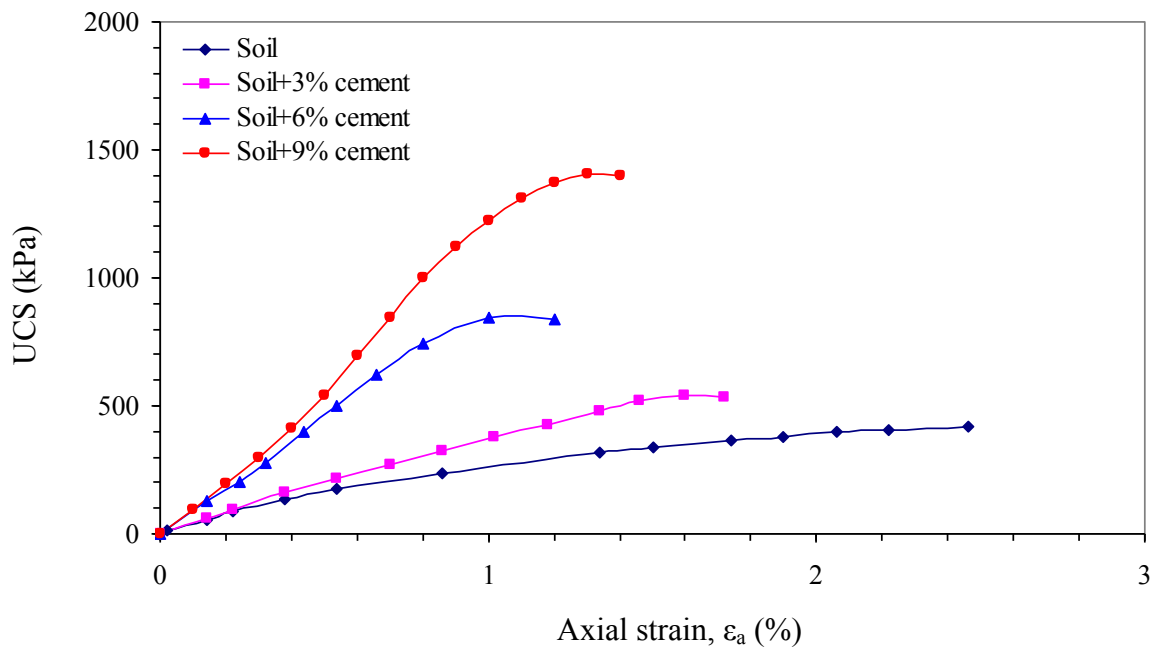


Fig.4. Stress-strain for natural soil and soil cement with different percent cement for curing time 14 days

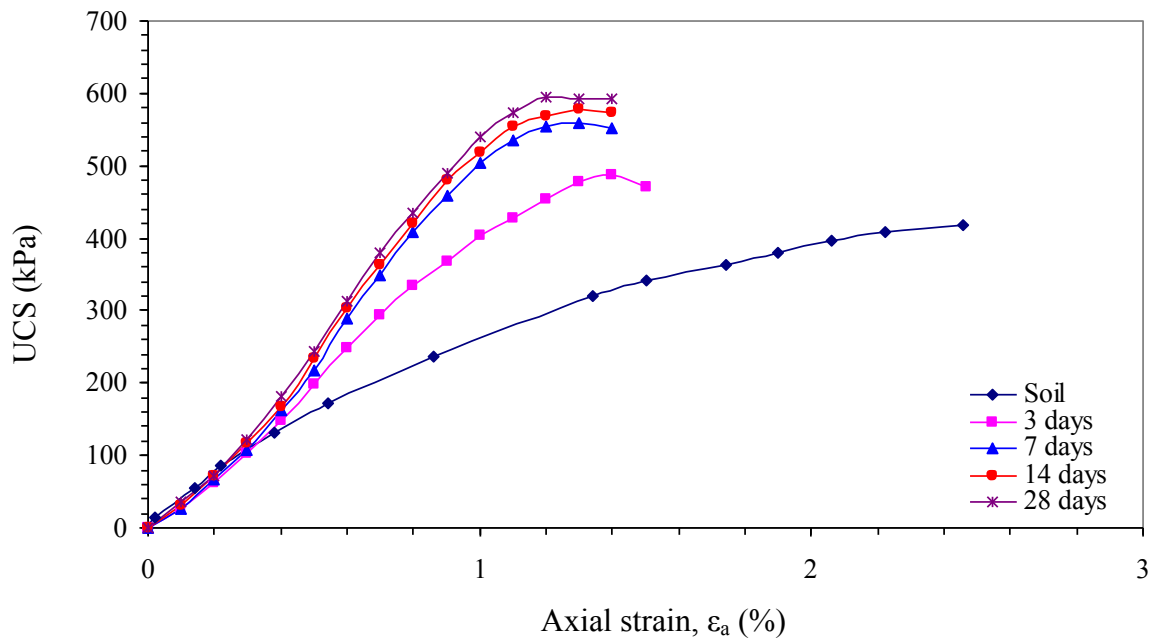


Fig.5. Stress-strain curves for natural soil and mixture of soil cement with 3% cement and 3% glycerol at different curing times

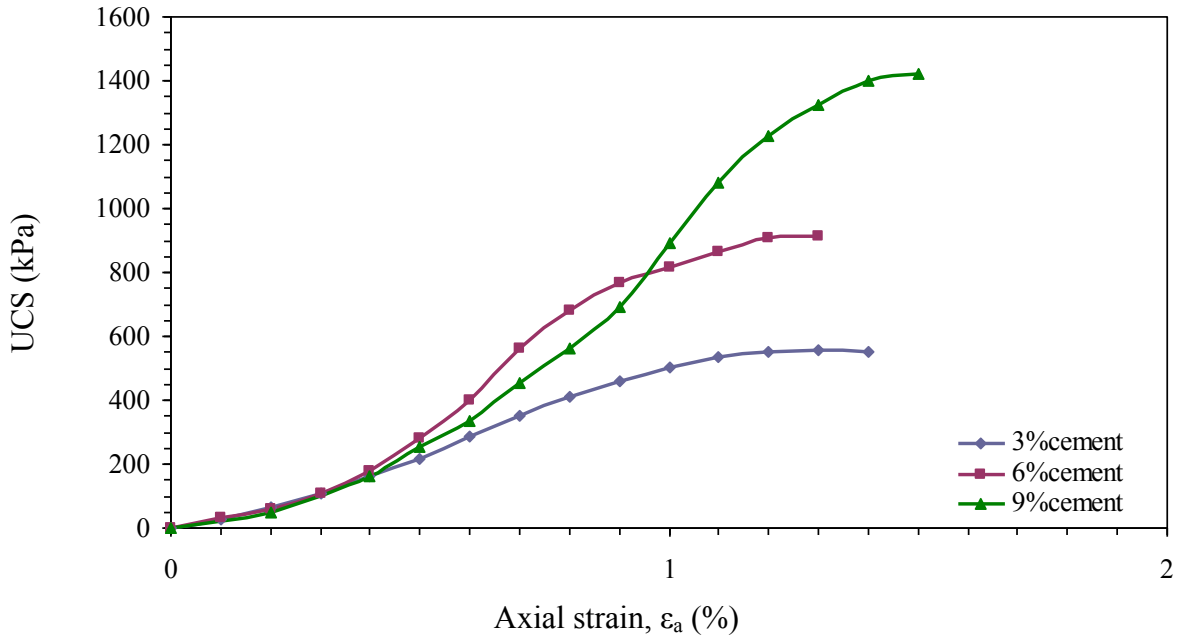


Fig.6. Stress-strain curves for soil contaminated with 3% glycerol after the addition of various cement and curing time of 7 days

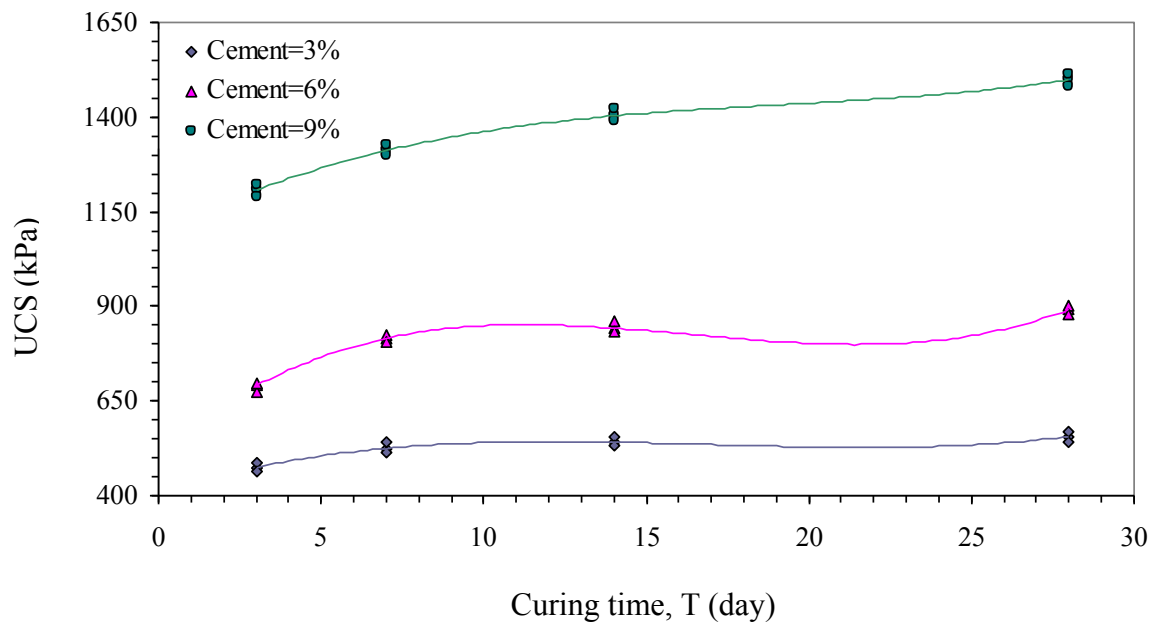
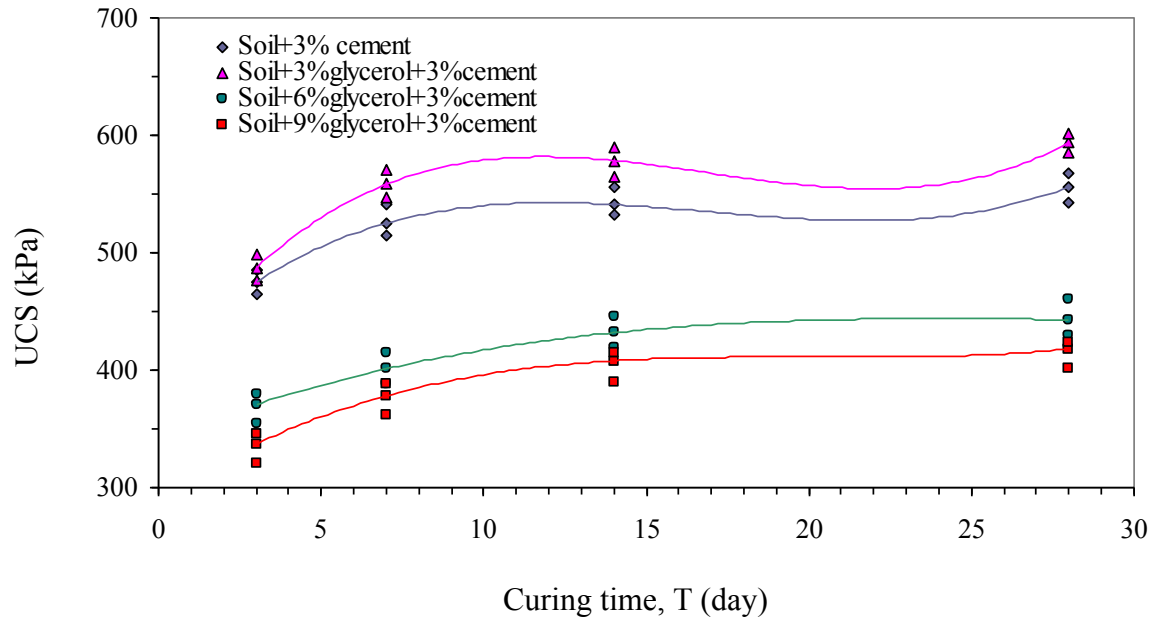
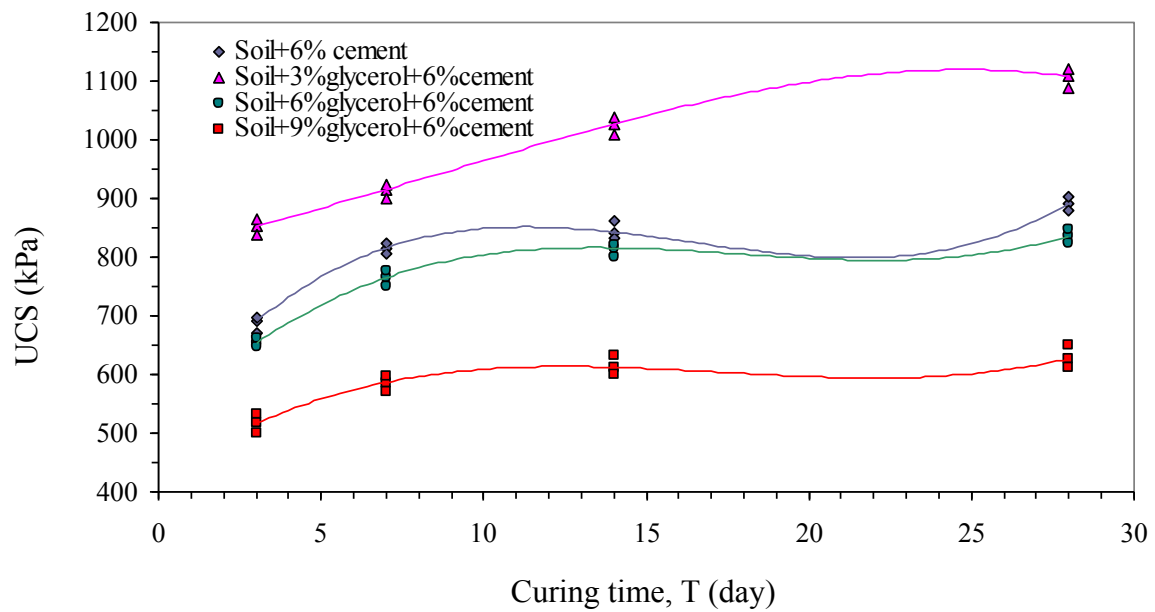


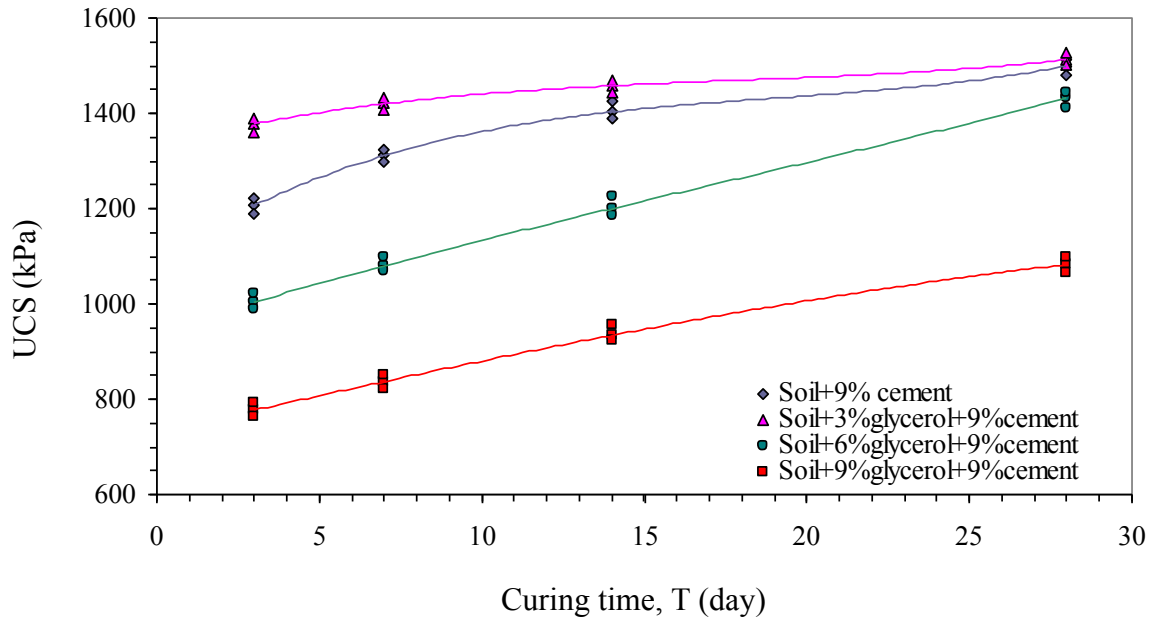
Fig.7. Compressive strength with curing time for soil-cement with different percentage of cement



(a)

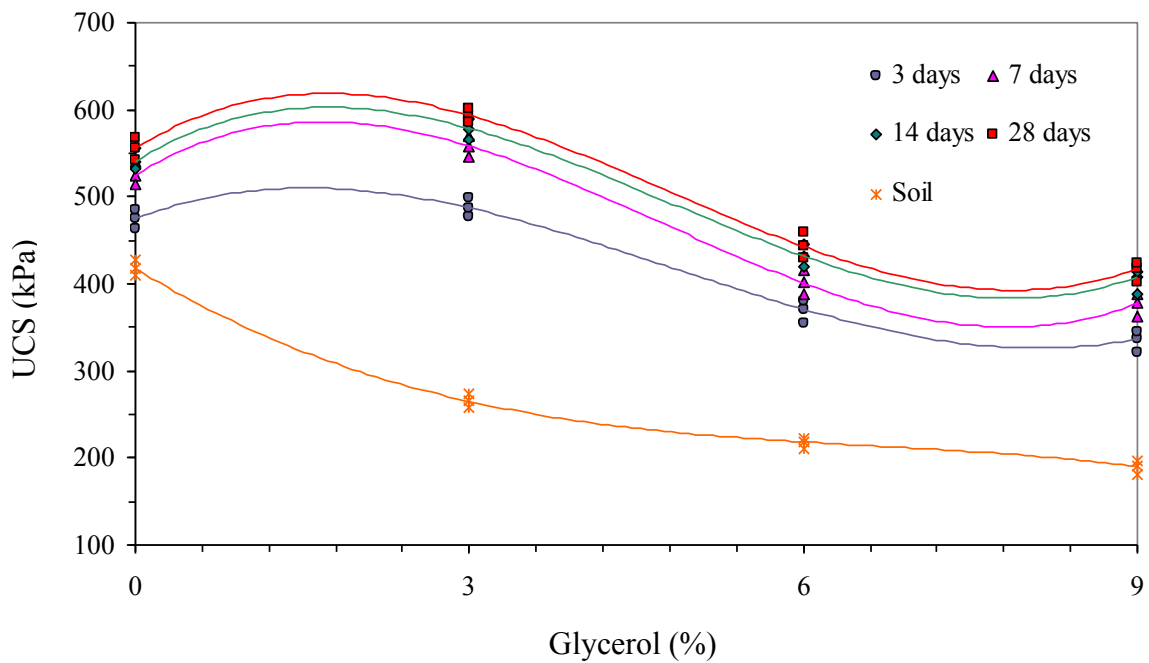


(b)

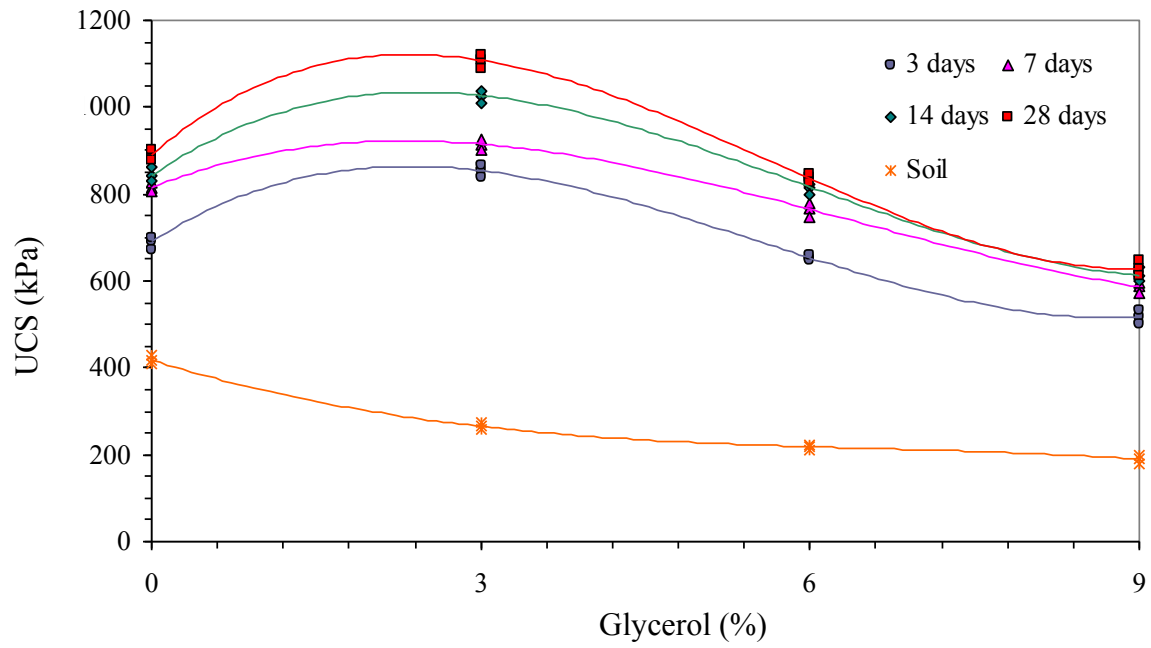


(c)

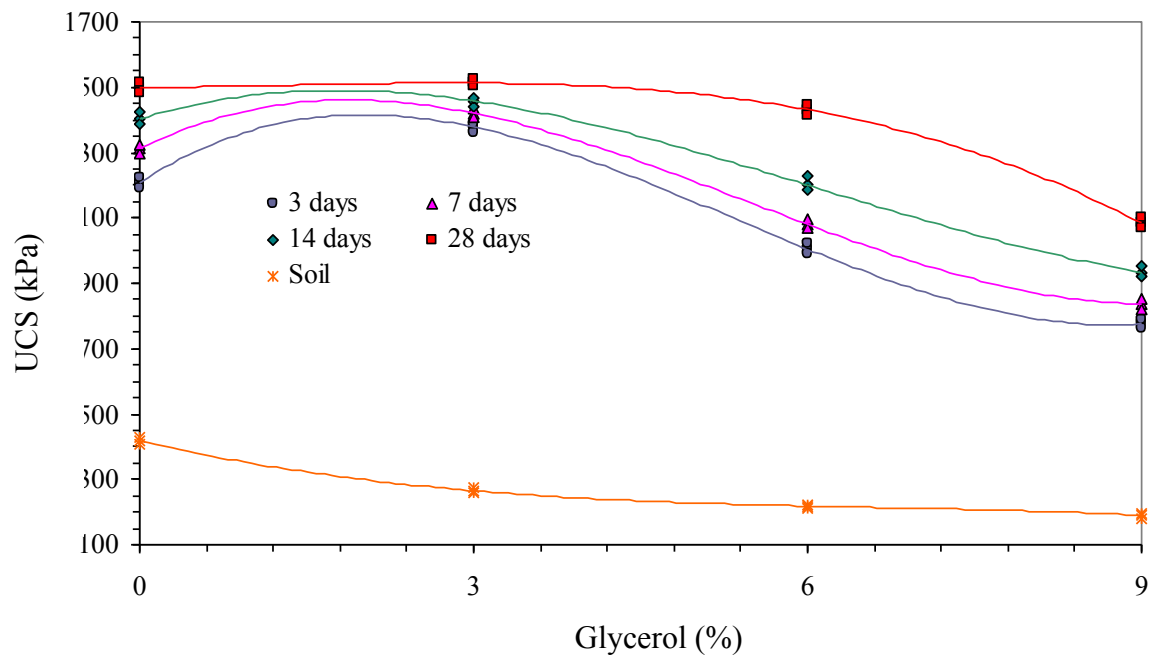
Fig.8. Compressive strength against curing time for contaminated soil with different percent of glycerol after the addition of different cement content (a) 3% cement, (b) 6% cement, (c) 9% cement



(a)



(b)



(c)

Fig.9. Compressive strength -percent of glycerol for different curing times (a) soil and soil-cement with 3% cement (b) soil and soil-cement with 6% cement (c) soil and soil cement with 9% cement