

Impact of water and solution of glycerol on the treatment of sediment by cement

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An understanding of the behavior of sediment soils deposited in different chemical solutions is important as it affects their treatment and their application in field as construction material. In this paper the effect of glycerol solution on the behavior of a sediment of a clay soil and its treatment was investigated through a program of experimental tests. Laboratory tests were conducted to study settlement of the clay soil in water and in solutions of glycerol with different concentrations. Also, treatment of the sediments deposited in water and solutions of glycerol was investigated by adding 5, 8 and 10 % cement to these sediments. Atterberg limits, compaction and unconfined compression tests were conducted on treated and untreated sediments. Comparison of the results showed that the Atterberg limits and compaction characteristics of the sediments that were deposited in water and in different solutions of glycerol are not the same. The properties of the sediments that were formed in glycerol solution are a function of concentration of glycerol. The results also indicated that the cement is effective in treatment of sediments deposited in solutions of glycerol and for a given percent of cement and curing time, the degree of treatment is dependent on the percent of glycerol in the solution. Increasing the concentration of glycerol decreases the strength of the sediment with time. Based on SEM analysis, it was found that the fabric of the soil deposited in water is different from those of the soils deposited in solutions of glycerol. The soil fabric also affects the interaction between soil and cement.

Key words: Sediment, pore fluid, glycerol, treatment, cement

Introduction

Transportation of eroded soil particles and their deposition usually take place by surface water such as rivers and streams. The water in a river or a stream may be contaminated by industrial or urban sewage. The change in the quality of water affects the behavior of the suspended particles. The transported particles are deposited where the velocity of flowing water is reduced. The deposited particles are consolidated as a result of self weight of the soil particles. The form of fabric and structure of the deposited sediments is a function of the complex interaction between soil particles and the aqueous environment (Kaya *et al.*, 2006). Ohtsubo and Ibaraki (1991) and Sridharan and Prakash (1999) stated that the behavior of sediment is influenced by electro-chemical and physical properties such as composition and concentration of electrolytes, pH, particle size distribution and the solid concentration of the suspensions. The sediment may have a flocculated or dispersed fabric depending on the type of clay mineral, ionic strength, pH and solid to water ratio that control the process of deposition or suspension of soil particles. Melton and Rand (1977) showed that the behavior of a sediment of kaolin soil deposited in a solution of NaCl is a function of pH and NaCl concentration. On the other hand Palomino and Santamarina (2005) and Nasser and James (2006) stated that the sedimentation of kaolin suspension is a function of pH, ionic strength and type of used electrolytes. Mesri and Olson (1971), Anandarajah and Zhao (1996) and Chen and Anandrajah (1998) indicated that the stress-strain behavior, permeability, shear strength and fabric of soil may change when pore fluid composition is changed as a consequence of chemical composition. Yukselen-Aksoy *et al.* (2008) studied the effect of seawater on the physical characteristics (Atterberg limits, sediment volume and compressibility) of ten soils and

concluded that seawater has an important effect on soil parameters and the liquid limit, plastic limit and shrinkage limit of soils deposited in seawater would be more than 110, 70 and 104% respectively. Vitale *et al.* (2016) studied the behavior of kaolin and kaolin treated with lime during sedimentation and found that the fabrics of deposited soils are not the same and depend on the pH of the aqueous solution.

Studies on the treatment of soil by cement have been carried out for more than five decades (Moh, 1962 and Mateos, 1964). Cement is a chemical agent that is commonly used for stabilization of soils. Miller and Azad (2000), Bahar *et al.* (2004), Sezer *et al.* (2006), Modmoltin and Voottipruex (2009), Xing *et al.* (2009), Zhang *et al.* (2011), Estabragh *et al.* (2012) Ciancio *et al.* (2013) and Estabragh *et al.* (2017) showed that the role of cement is similar to lime in stabilization. By adding cement 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). These mechanisms include cation exchange and pozzolanic reaction. These reactions cause binding of the clay particles, reducing the clay content and increasing the percentage of coarse particles. The stabilization of contaminated soils by organic and inorganic substances has been investigated by a number of researchers such as Meegoda and Muller (1993) and Meegoda *et al.* (1998) who 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) increases the strength of petroleum-contaminated soil. Tremblay *et al.* (2002), Hassan *et al.* (2005), Estabragh *et al.* (2016) showed that adding cement to contaminated soil with organic substance can improve its mechanical behavior.

Sometimes deposited sediments can be considered as a borrow area for construction projects such as embankments, backfills and roads. Therefore the use of sediments that are deposited in organic aqueous solutions (such as organic hydrocarbons) and their stabilization can provide local construction materials 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. Often the use of local construction materials could be more economic in construction projects compared with more suitable materials that are located at far distances from the project. Therefore, understanding the mechanical behavior of these materials 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 soils. There has been no investigation on the stabilization of sediments that were deposited in organic aqueous solution for use as construction material. Therefore, the aim of this paper is to study the mechanical behavior of a clay sediment deposited in aqueous solutions with different percentages of glycerol and to evaluate the effect of cement on the treatment of the soil. The investigation is comprised of two stages. In the first stage, the mechanical behavior of sediment deposited in water is examined and then the treatment of the sediment by adding 5, 8 and 10% cement is studied. In the second stage the mechanical behavior of sediments that were deposited in solutions of glycerol with concentrations of 5, 10 and 15 % is studied their treatment by adding different percentages of cement (5, 8 and 10%) is investigated. The results are used of the two stages are compared to study the effect of different concentrations of glycerol on the

behavior of sediment and also 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 glycerol.

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 according to its grain size distribution as shown in Fig.1. 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 approximately 4100 cm²/g and specific gravity of 3.15. Table 3 shows the physical and mechanical properties of used 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.

Glycerol

Glycerol (propane-1,2,3-triol) is an oxygenated organic compound that has been widely used in the chemical industry in the last decades. Major applications of glycerol are in the detergents industry as well as in drugs and pharmaceuticals production.

According to the information obtained from the supplier, the dielectric constant, absolute viscosity and mass density of glycerol were 40.1, 1412 (cP) and 1258.02 (kg/m³) respectively. In this work solutions of glycerol with concentrations 5, 10, 15% and viscosities 1.04, 1.22 and 1.44 cP respectively were used. The selection of 5% as the concentration of glycerol 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 choice of 15% was based on the observations in the laboratory as the air dried sediments deposited in solutions with concentrations higher than 15% were oily and greasy and it was not possible to carry out the desired tests on them. Therefore, 15% was chosen as the upper limit. The choice of 5% increment was considered to study the variations of the soil properties with increasing the glycerol concentration in the sediments.

Sediment and sample preparation

The soil samples used in this study are natural soil, soil sediment deposited in water and soil sediment deposited in 5, 10 and 15% glycerol dissolved in water. 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). Therefore, the ratio of solid was chosen as 5% weight of mixture (fluid+solid) that is similar to the recommendation value for hydrometer testing (ASTM D 422-07). The required quantity of dry soil was then added to it in increments and mixed thoroughly to reach a dilute soil-water mixture. For the other test series, 5, 10 and 15% (by weight) glycerol was added to water and mixed thoroughly to reach water-glycerol 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. During the settlement, the transparency and limpidity of the liquid above the deposited soil was checked. It was found that for all solutions, after about two weeks the liquid above the sediments was totally clear and without any suspended particles. Therefore, it was decided to allow the dilute mixture to settle for two weeks. After that the excess liquid above the soil was drained off, the soil was then air dried for nearly between 7-10 days 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 sediments deposited in water and in different glycerol solutions. 5, 8 or 10% cement was added to the soil that was taken from each sediment and standard compaction tests were carried out on these mixtures as well. The choice of maximum 10% cement was based on the economic considerations and also to prevent the formation of tensile cracks due to the high percent of cement (Khattak and Alrashidi, 2006). Different percents of cement (below 10%) were used to study the effects of cement content on the behavior of treated soil. The maximum dry unit weight and optimum water content were determined for each of them from corresponding compaction curve. The samples for unconfined compression test were prepared from dry sediment 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. Static compaction was used for making 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 length and diameter of samples were 50 and 100 mm respectively. After preparing soil-cement samples they were stored in curing cabinet according to ASTM standard at constant temperature and relative humidity for curing times of 7, 14 and 28 days.

Test Program

Atterberg limits, compaction and unconfined compression tests were conducted on the samples of natural soil, soil sediment in water and soil sediment in different solutions of glycerol according to the ASTM standard. The tests were repeated three times and average of them was considered as final results. 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. In order to observe the microstructure of samples in different condition the Scanning electron microscopy (SEM) tests were performed on the samples. The typical samples that were deposited in water and solution of 10% glycerol were prepared according to the optimum water content and maximum dry unit weight. A curing time of 7 days was considered for the samples treated with 8% cement. After curing the samples were carefully cut with a sharp knife into small pieces of disk shape with 1 cm³ volume (as used by Tremblay et al. 2002 and Estabragh et al. 2016) and scanned under SEM.

Results

The results of liquid limit (LL) and plasticity index (PI) of sediments that were deposited in water and solutions with different percentages of glycerol are shown in Fig.2. As shown in Fig.2a the liquid limit of the sediment deposited in water is 53% but for the sediments deposited in 5, 10 and 15% glycerol it is changed to 36, 32 and 22% respectively. Fig.2b shows that the plasticity index of the sediments in water is 29% but for the sediments in solutions of 5, 10 and 15% glycerol it reached 19, 17 and 9% respectively. Fig.2 also shows the effect of 5, 8 and 10% cement on the LL and PI of different sediments. Fig.2a shows that there is an increase in the initial value of LL by adding cement to the sediment at different conditions. For the sample with 5% cement the value of LL is slightly more than those with 8 and 10% cement. For example for sediment that is deposited in solution of 15% glycerol, the initial value of LL (22%) is changed to 26, 25 and 24% by adding 5, 8 and 10% cement. Fig.2b shows the variations of PI for the sediments stabilized with different percents of cement. A reduction from initial value is observed for the sediments deposited in water and in solution of 5% glycerol, but there is an increase in the value of PI at 5% cement for sediments that were formed in 10 and 15% solutions of glycerol.

The results of compaction tests (maximum dry unit weight and optimum water content) on the sediments deposited in water and in different solutions of glycerol and sediments that were treated with 5, 8 and 10% cement are shown in Fig.3. As shown in Fig.3a the maximum dry unit weight of sediment formed in water is 16.2 kN/m^3 but for the sediments that were deposited in 5, 10 and 15% solutions of glycerol, their maximum dry unit weights are 17.8, 18.2 and 18.4 kN/m^3 respectively. These values of maximum dry unit weight show a considerable increase in comparison with soil deposited in water. The

maximum dry unit weight of sediments is also changed by adding cement to them. Fig.3a shows that adding different percentages of cement to the sediments deposited in water causes slight increase in the initial value of maximum dry unit weight (16.2 kN/m^3). There is a reduction in the maximum dry unit weight in the sediments formed in different percentages of glycerol by adding 5% cement. However, adding 8 and 10% cement results in increase in the value of maximum dry unit weight in comparison with the soil treated by adding 5% cement. For the sediments deposited in solutions of glycerol, by adding cement, the maximum dry unit weight decreases in comparison the untreated sediments. Fig.3b shows that the optimum water content of the sediment formed in water is 24.2% but for the sediments in 5, 10 and 15% solutions of glycerol it is changed to 14.3, 14 and 10.5% respectively. The results also show a significant reduction in optimum water content when the aqueous solution is water contaminated with different percentages of glycerol. Adding different percentages of cement to sediments formed in water causes a decrease in the value of optimum water content in comparison with the sediment without cement (Fig.3b). For the sediment deposited in glycerol solutions, the optimum water content increases in comparison with the untreated deposit (Fig.3b). The trend of increase in optimum water content is a function of the percent of cement used.

Fig.4 shows the stress-strain results for sediments formed in water and different solutions of glycerol. As shown in this figure, the final strength of sediment deposited in water is 190 kPa at strain of 4.6% but for the sediment in 5% solution of glycerol it reaches to maximum value of 343 kPa at strain of 5.6%. This shows an increase of 80.5% in the final strength when the soil is deposited in solution of 5% glycerol. For the sediments deposited in 10 and 15 % solutions of glycerol the final strengths of the samples are 146

and 80 kPa at strains of 10.2 and 11.8% respectively. There is a reduction in the final strength and increase in the failure strain for sediments deposited in 10 and 15% solutions of glycerol in comparison with the sediments deposited in water or 5% glycerol (Fig.4). Fig.5 shows typical results of stress-strain for the sample of sediment in water and the samples of this sediment treated with 5, 8 and 10% cement at curing time of 14 days. It is shown that the stress-strain curve evolves with increasing the percent of cement and the tests are continued until the failure of the sample. The final strength of the sediment is 190 kPa at 4.6% strain but it is changed to 1826, 2361.7 and 2481 kPa by adding 5, 8, and 10% cement. It is resulted that the peak strength is increased significantly with increasing the percent of cement. The strength of the mixture of sediment with cement is much greater than that of the sediment without cement. Therefore, the stress-strain relationship is dependent on the percent of cement. Fig.6 shows typical results of stress-strain for the sediment deposited in solution of 5% glycerol and the samples treated with 5% cement at curing times of 7, 14 and 28 days. It is seen that the final strength of the sediment sample deposited in 5% solution of glycerol (320.7 kPa) is changed to 1013, 1365 and 1789 kPa by adding 5% cement at curing times of 7, 14 and 28 days respectively. Therefore, the stress-strain curves evolve with increasing the curing time and the curing time is also effective in increasing the final strength of the samples. Similar results are shown in Fig.7 for the sediments formed in solution of 10% glycerol and treated with 5, 8 and 10% cement at curing time of 14 days. The final strength of the sediment deposited in 10% glycerol is 139 kPa and it is changed to 951, 1232 and 1387 kPa by adding 5, 8 and 10% cement respectively. Typical results for the sediment deposited in solution of 15% glycerol are seen in Fig.8. It is seen that the final strength of the sample is 70 kPa and it is

changed to 484, 689 and 1007 kPa by adding 10% cement at curing times of 7, 14 and 28 days respectively.

Discussion

Water and clay particles are not chemically inert, and they react with each other due to a strong attraction of water molecules and sorption onto the surface of the soil particles. These interactions influence the physical and physicochemical behavior of the mixture (Mitchell and Soga, 2005). Dry clays have adsorbed cations held tightly by negatively charged clay particles, with excess cations needed to neutralize the electro negativity of the clay particles and associated anions present as precipitated salts. When clay is placed in water, the precipitated salts go into solution, adsorbed cations produce higher concentration near the particle surface, and try to diffuse away in order to equalize concentrations. However, the freedom to do this is restricted by the negative electrical field originating on particle surface. This charged surface and adjacent phase of distributed ions make up the “Diffuse Double Layer” (Mitchell and Soga, 2005). The thickness of Diffuse Double Layer (DDL) is dependent on the electrolyte concentration, cation valency, dielectric constant, temperature and factors such as ion size, pH, etc.

The formation and behaviour of sediments from fine grained suspension particles is a function of different forces that exist in the depositing system. In general it is accepted that there are three kinds of force in the system of fine grained soil water system (Sridharan and Prakash, 1999). These are self weight, attractive and repulsion forces. The two latter forces have an important role in the behavior of sediments (Sridharan, 1991). Attractive forces are divided into Coulombic attractive forces and London-van der Waals forces (Sridharan and Prakash, 1999). Coulombic forces are inversely proportional to the

square of distance between the particles and to the dielectric constant of pore fluid (Mitchell and Soga, 2005). The second attractive forces are affected by change in quality of pore fluid and they are inversely proportional to the dielectric constant of pore fluid (Mitchell and Soga, 2005). Repulsive force is formed by the interaction between diffuse double layers (Seed *et al.*, 1960). Therefore, the nature and process of sediment formation is dependent on the predominant attractive or repulsive forces during the process of settling of the suspended particles in solution (Sridharan *et al.*, 2001 and Kaya *et al.*, 2006).

The dielectric constants of water and glycerol are 80 and 40 and for solutions of 5, 10 and 15% glycerol are 78, 76 and 74 respectively (Ratnaweera and Meegoda, 2006). Since the thickness of DDL is dependent on the square root of dielectric constant, the change in the thickness of this layer results in different soil fabrics; reduction in the thickness of DDL leads to flocculation of the soil particles (Bowder and Daniel, 1986). For organic fluids with lower dielectric constant than water, the thickness of DDL layer around clay particles is reduced and this leads to reduction in the space between particles. Therefore, increasing the concentration of organic fluid causes reduction in the value dielectric constant. Hence, this layer is shrunk which leads to increase in the degree of flocculation of sediment.

The results of Atterberg limits (Fig.2) show that when the soil is deposited in water, its LL and PI are 53 and 29% but when the sedimentation is formed in solutions of glycerol these values are reduced. For the solution of 5% glycerol the values of LL and PI are 36 and 19% and this reduction is also seen for solution of 10 and 15% glycerol. The reduction of Atterberg limits can be attributed to the reduction of thickness of DDL due

to the lower dielectric constant of these solutions compared with water. The shrinkage of DDL leads to pasting of the particles to each other and formation of coarse particles. The water adsorption capacity of coarse particles is less than fine particles because of reduction in their specific surface which causes reduction in the values of Atterberg limits. These results are consistent with the results that were reported by Kaya and Fang (2000), Singh *et al.* (2009), Olung and Yildis (2010) and Khosravi *et al.* (2013).

The results (Fig.2) show that by adding different percentages of cement to the sediment deposited in water, the variations of the Atterberg limits is not significant in comparison with the soil without cement but reduction in PI is significant. For the sediments deposited in solutions of glycerol the value of LL is increased by adding 5% cement but for 8 and 10% cement there is a reduction in the value of LL in comparison with the sediment mixed with 5% cement. A similar trend is seen for the variation of PI with the percent of cement used. It can be said that there might be some cement in the soil that does not contribute to the chemical actions and adsorbs more water due to its high specific surface which results in increase in the value of LL. Estabragh *et al.* (2016) reported that adding 5% cement to a CL soil contaminated with MEG increased the value of LL but for 8 and 10% cement, reduction of LL was observed. Du et al. (2013) reported that adding 8% cement to a clay soil contaminated with different percent of zinc caused reduction in the value of LL.

As shown in Fig.3 the maximum dry unit weight ($\gamma_{d_{max}}$) and optimum water content (wopt) for the sediment deposited in water are 16.2 kN/m³ and 24.2% respectively. They are changed to 17.6, 18.2, 18.4 kN/m³ and 14.3, 14, 10.5% for the sediments that were deposited in 5, 10 and 15% solutions of glycerol. It is seen that $\gamma_{d_{max}}$ is increased and

w_{opt} is decreased. It can be said that the solution of glycerol facilitates the slippage of the particles over one another in comparison to the sediment deposited in water. This results in the voids between the particles being reduced, leading to increase of maximum dry unit weight and decrease of optimum water content. These results are consistent with the results that were reported by Singh *et al.* (2009) and Estabragh *et al.* (2016) for CL soil that was contaminated with Mono Ethylene Glycol (M,E.G.) and used motor oil (U.M.O.). Al-Sanada (1995) and Hassan *et al.* (2005) reported similar results for a granular soil that was contaminated with 10% petroleum and 2% crude oil respectively.

The results of the compaction tests for 5, 8 and 10% cement added to the sediments deposited in water or different glycerol solutions are shown in Fig.3. As shown in this figure, for samples with 5, 8 and 10% cement the value of $\gamma_{d_{max}}$ is nearly the same as the sediment without cement. For this sediment there is a reduction in w_{opt} for the samples with 8 and 10% cement. This could be due to reduction in plasticity of the soil due to the chemical reactions that occur between cement and the soil particles. For the sediments that were deposited in 5, 10 and 15% solutions of glycerol and mixed with various percents of cement, the values of $\gamma_{d_{max}}$ are nearly the same as the soil deposited in these solutions but w_{opt} is increased from its initial value (sediment without cement). This may be due to a small amount of cement that could exist between the particles which is not able to do chemical reaction with soil particles due being covered by glycerol. This cement can adsorb water and cause an increase in optimum water content. These results are not in agreement with those that were presented by Estabragh *et al.* (2018) who reported that adding 20% cement to a clay soil contaminated with anthracene did not change the optimum water content and maximum dry unit weight but adding 30% cement

caused only increase in maximum dry unit weight. Estabragh *et al.* (2016) showed that for a clay soil contaminated with MEG (at constant percent of MEG), adding 3, 6 and 9% cement caused increase in the value of maximum dry unit weight but the change in the amount of optimum water content is not considerable. Kogbara *et al.* (2013) reported that adding mixture of cement and fly ash to a soil contaminated with metal and organic matters increased the maximum dry unit weight while the optimum water content was nearly constant. Hassan *et al.* (2005) indicated that adding cement to petroleum-contaminated soil causes reduction in maximum dry unit weight and optimum water content. This difference may be due to the type of the contaminating matter, type of soil and interaction between contamination and soil.

Fig.4 shows the stress-strain curves for the sediments at different conditions of deposition. As shown in this figure the final strength of the sample deposited in solution of 5% glycerol (343 kPa) is more than the sediment deposited in water (190 kPa). The final strengths of the sediments with 10 and 15 % glycerol are less than the sediment in water. It is expected that the final strength of samples with 10 and 15 % glycerol would be more than the samples formed in water and in 5% glycerol solution. The dielectric constant of glycerol solution is less than water which leads to a flocculated fabric for soil and the final strength is increased as shown for the sample with 5% glycerol. This finding is supported by the results that were presented by Moore and Mitchell (1974) and Sridharan and Rao (1979). In addition to dielectric constant, the viscosity of the chemical solution also affects the strength of the soil. The results for samples with 10 and 15% solution of glycerol are consistent with the results that were reported by Ratnaweera and Meegoda (2006). They conducted compressive strength tests on samples of a cohesive soil

contaminated with different concentrations of glycerol and found that the strength is reduced by increasing the concentration of contaminant. They also found that viscosity has a significant effect on the strength of the soil. The pore fluid viscosity changes the properties of minerals and pore fluid contacts, thereby facilitating the displacement of particles relative to each other and displaying reduction in strength. These findings are supported by the results that were reported by Ratnaweera and Meegoda (2006) and Cabalar and Clayton (2010 and 2016). Therefore, the main reason for the reduction of strength due to 10 and 15% glycerol is viscosity. These results are similar to the results that were reported by Estabragh et al. (2016 and 2018). They showed that although adding cement causes increase in the strength of clay soil contaminated with anthracene or MEG, but at a constant percent of cement, increasing the percent of contaminant causes reduction in strength. Kogbara et al. (2013) reported similar results to this work. They showed that adding cement-fly ash increases the strength of contaminated soil and the rate of increase is dependent on the percent of cement. They argued that the presence of high amount of contamination can be expected to reduce the strength.

Fig.9 shows the final (peak) strength of various sediments that were treated with 5, 8 and 10% cement against curing time. As shown in this figure, at a given curing time the strength is increased with decreasing the percent of glycerol in the solution in which the sediment is formed. Therefore, the strength of the sediment deposited in water is higher than the strength of the sediments deposited in glycerol solutions. This variation is observed for all percents of cement that were used in this work. The curve of strength against curing time is evolved with reduction in the percent of glycerol in the solution. Increasing curing time increases the sediment strength. The rate of increase in strength

for the sediment deposited in solution of glycerol is less than the one deposited in water (Fig.9). By increasing the percent of glycerol in the solution, reduction is observed in the rate of increase in strength. The final strength of the treated sediments against percent of glycerol for different cement contents is shown in Fig.10. It is seen that increasing the curing time causes increase in the strength; so the curve for curing time of 28 days is located at the top and the one for curing time of 7 days is at the bottom. Particularly for the curing time of 28 days, the strength is decreased by increasing the percent of glycerol in the solution. At a low constant percent the glycerol (e.g., 5%) the increase in strength with curing time is considerable but for 10 or 15% glycerol it is not significant in comparison with 5% glycerol.

When cement is mixed with a cohesive soil, the calcium ions released during the initial hydration reaction of cement are marked to reduce the soil plasticity. The mechanism is most likely the cation exchange or crowding of additional cations onto the soil. These processes that change the electrical charge density around the soil particles cause changes in the behavior of aggregated soil. After this stage the cementation stage begins where chemical bonds develop between adjacent cement grain surface and between cement grain and soil particle interfaces (Mindess and Young, 1981 and Williamson and Cortes, 2014). In clay soils cement hydration develops strong linkages between the minerals and the particles of soil can no longer slide over each other (Tang *et al.*, 2007). Therefore, not only the cement reduces the plasticity of soil but also increases the shear strength and reduces the water holding capacity of clayey soil.

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 decreases

the strength and compressibility compared with the sediment deposited in water and treated with cement. Therefore, the strength of samples from sediment in glycerol solutions treated with cement is decreased and this reduction is a function of increase in the concentration of glycerol. By increasing the amount of glycerol in the solution, it tends to cover the cement particles and prevent from hydration of the cement. The results show that at a constant percentage of cement, the strength of sediment deposited in solution of glycerol is increased with increasing the curing time. When cement is added to sediment that is deposited in solution of glycerol, different reactions may occur due to this 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 in water, surfaces of more particles are covered by glycerol which reduces the friction between the particles and results in the reduction of strength compared with the sample of soil cement. Figs 11a and 11b show the micrograph for soil deposited in water and water with glycerol at concentration of 10%. As shown in Fig.11a the flocculating structure is very obvious for the soil deposited in water but Fig.11b shows a flocculated structure in which the pores between particles have been increased and the particles paste to each other. It can be said that the solution of glycerol caused the increase in the degree of flocculation the fabric of soil in comparison with the fabric of soil deposited in. A micrograph of mixture of soil deposited in water with 8% cement is shown in Fig.11c. 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.11d shows a monograph of treated soil deposited in solution of 10 % glycerol with 8% cement. As shown in this figure the soil appears in granular shape; a part of the cement appears to have linked some soil particle together and another part cover the surface of particles.

Conclusion

This paper presented the results of an experimental study to investigate the mechanical properties and treatment of sediments formed in water and in glycerol solutions. The following conclusions can be drawn from the results presented:

1. The results reveal that it is possible to treat sediments that are deposited in water or solutions with different concentrations of glycerol and use them as construction materials by considering the potential environmental problems (leaching contaminant to underground or evaporation to air).
2. For a sediment that is formed in a solution of glycerol, the Atterberg limits (LL and PL) decrease with increasing the glycerol concentration. The maximum dry unit weight increases and the optimum water content decreases with increasing the glycerol concentration.
3. The strength of sediments deposited in solutions of glycerol at concentrations of 10 and 20% is decreased in comparison with the sediment deposited in water.

4. The strength of sediments deposited in water or in solutions of glycerol is increased by addition of cement and the amount of increase is dependent on the percent of cement and curing time.

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Table 1. Physical and mechanical properties of soil

Property	Standard designation	Value
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, γ_{dmax} (kN/m ³)		19.0

Table. 2 Physico-chemical components of soil

Chemical component	Amount	Chemical component	Amount
pH	8.4	Cl ⁻ (meq/L)	49.0
EC ^a (dS/m)	13.90	HCO ₃ ⁻ (meq/L)	7.5
Na ⁺ (meq/L)	142.0	SO ₄ ²⁻ (meq/L)	112.0
Ca ²⁺ (meq/L)	21.0	CO ₃ Ca (%)	10.2
Mg ²⁺ (meq/L)	6.0	O.C. ^b (%)	0.11

a- Electrical Conductivity

b- Organic content

Table. 3 Properties of cement

Properties	Standard designation	Value
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	ASTM C 348-14	5.2

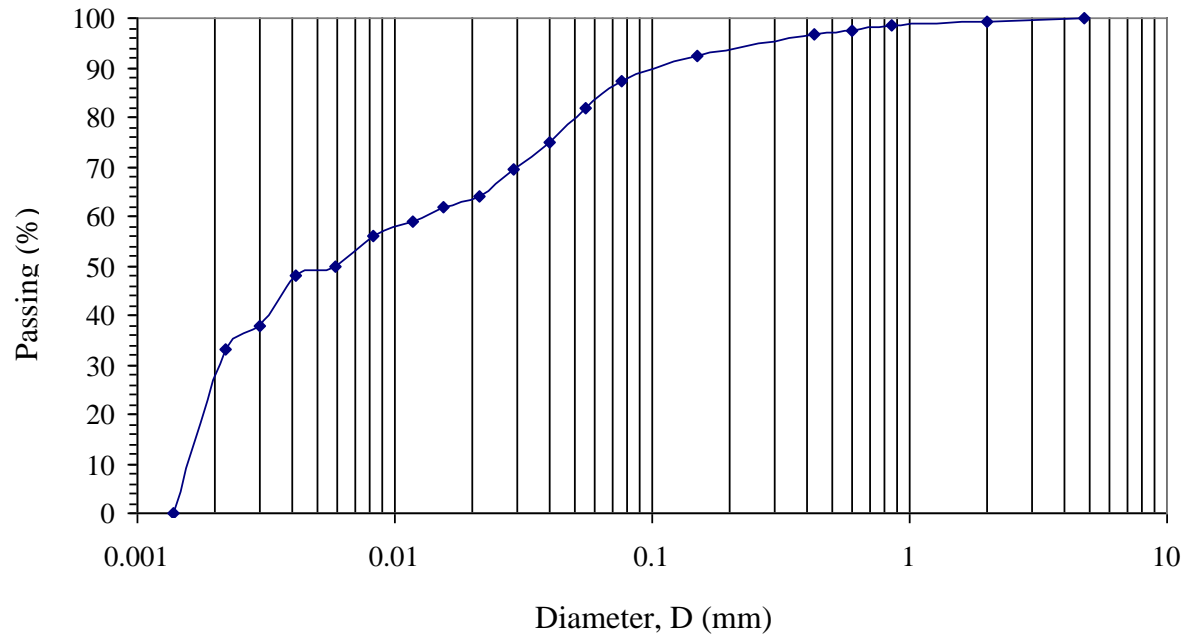
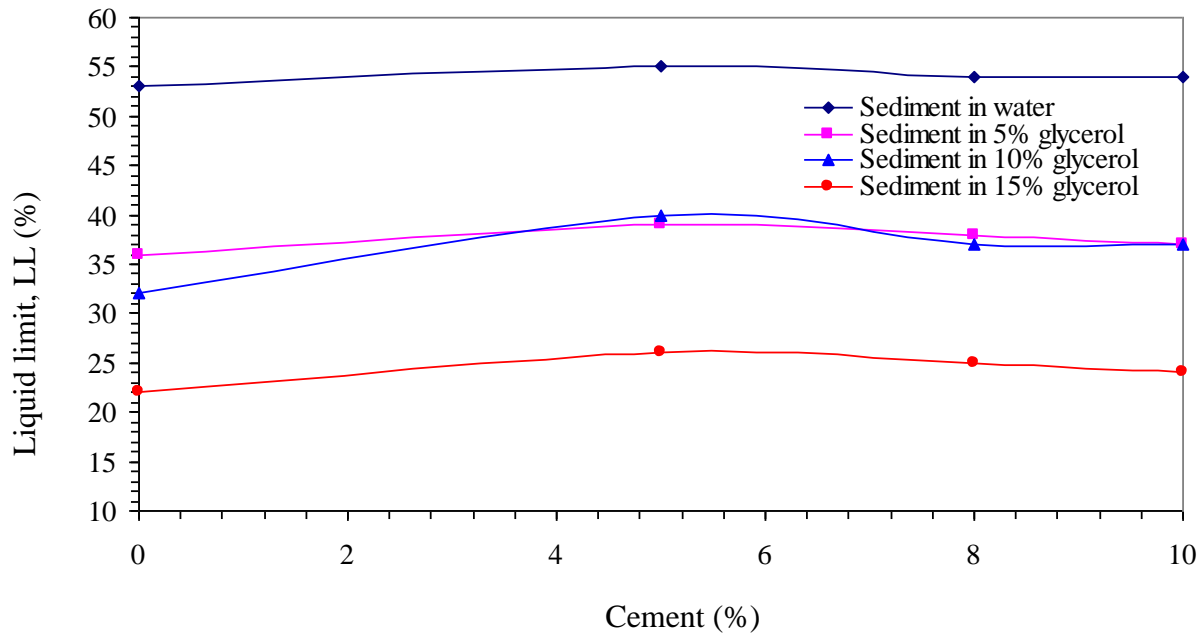
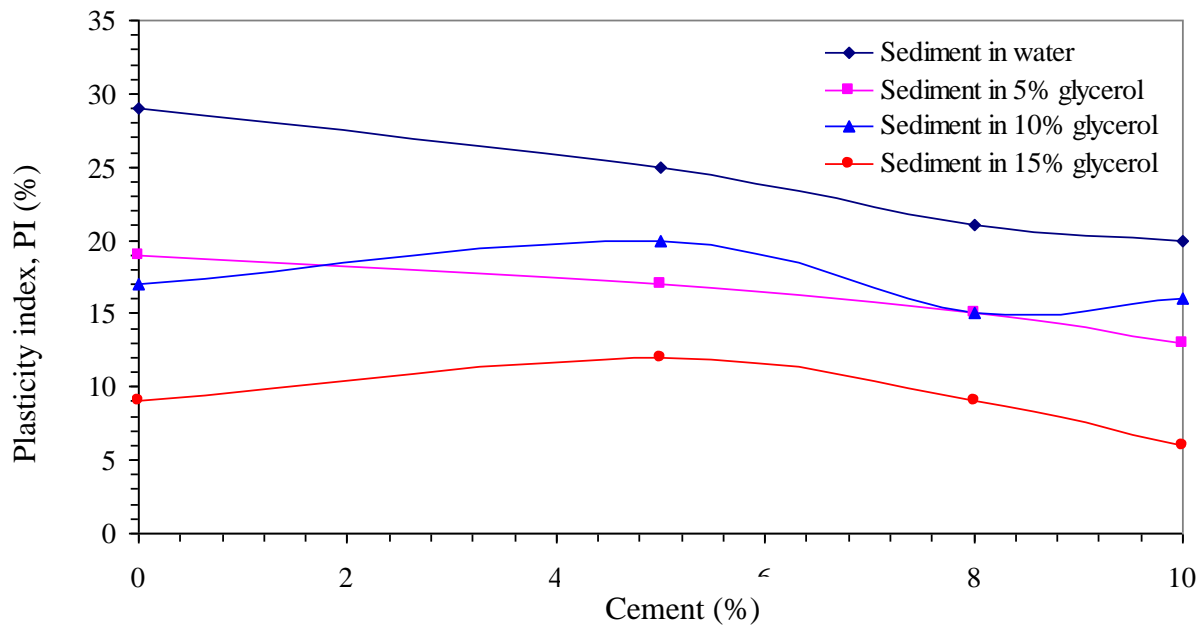


Fig.1. Grain size distribution

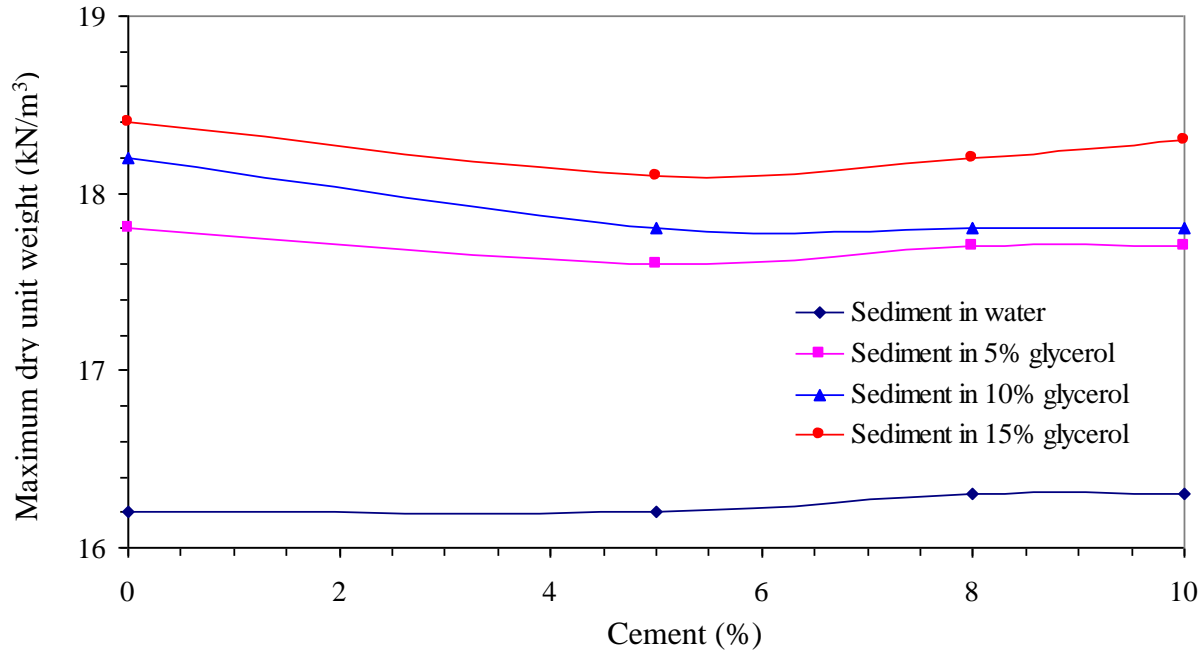


(a)

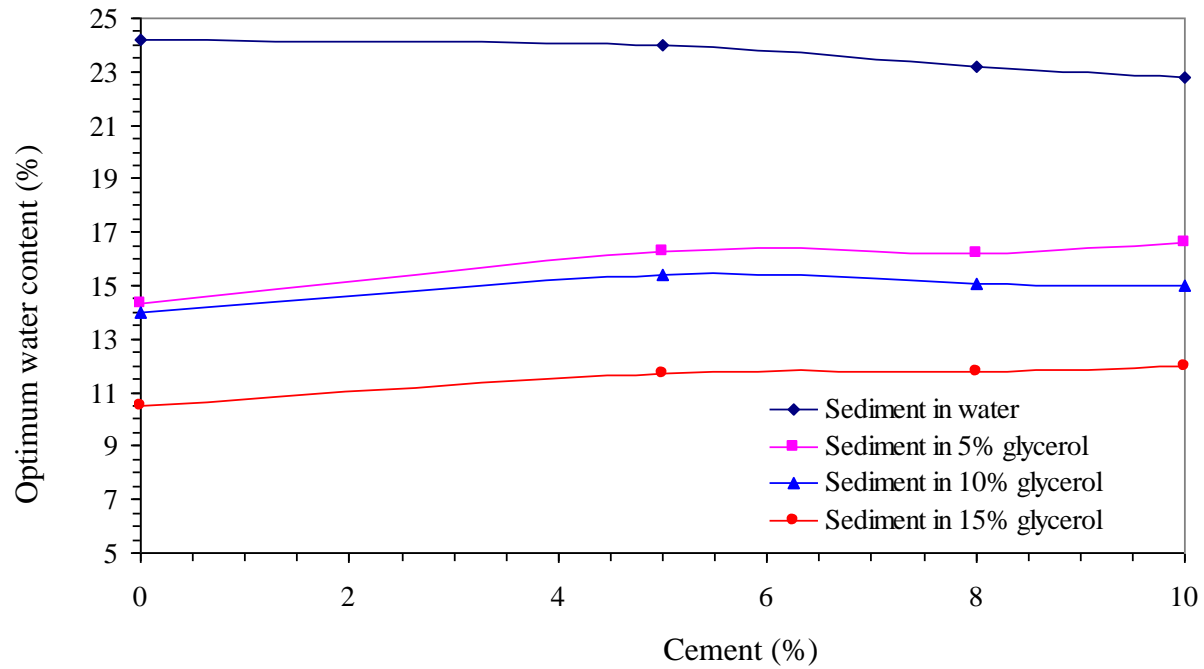


(b)

Fig.2. Variations of Atterbeg limits for different sediments treated with cement. (a): Liquid limit, (b): Plasticity index



(a)



(b)

Fig.3. Variations of maximum dry unit weight and optimum water content for different sediments treated with cement. (a): Maximum dry unit weight (b): Optimum water content

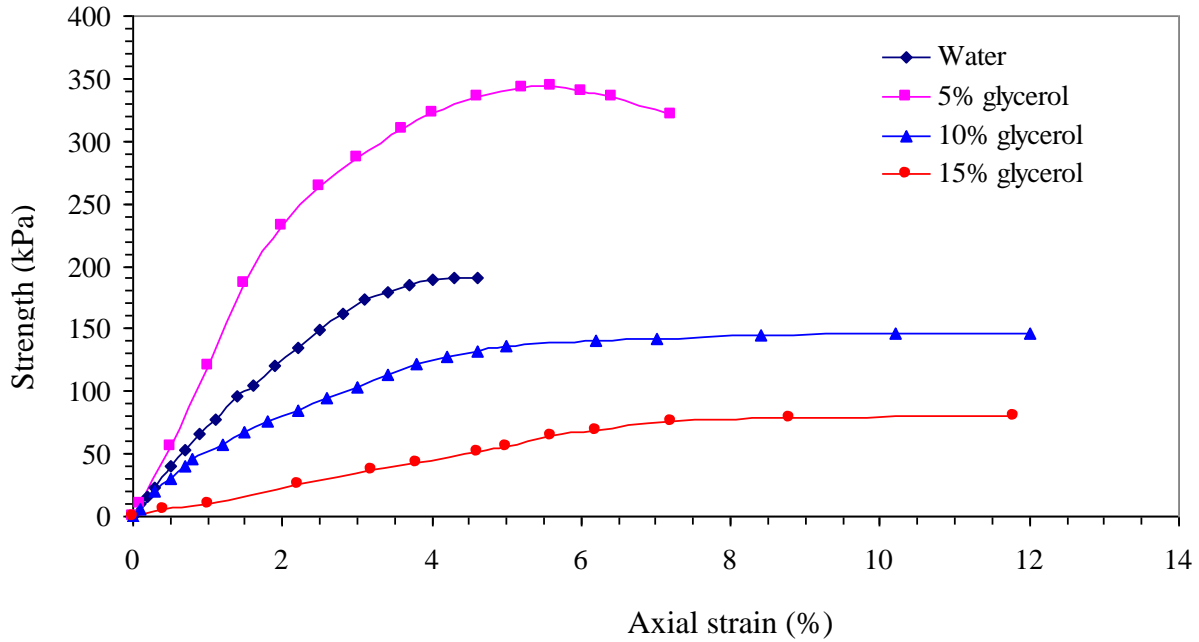


Fig.4. Stress-strain curves for sediments deposited in different solutions

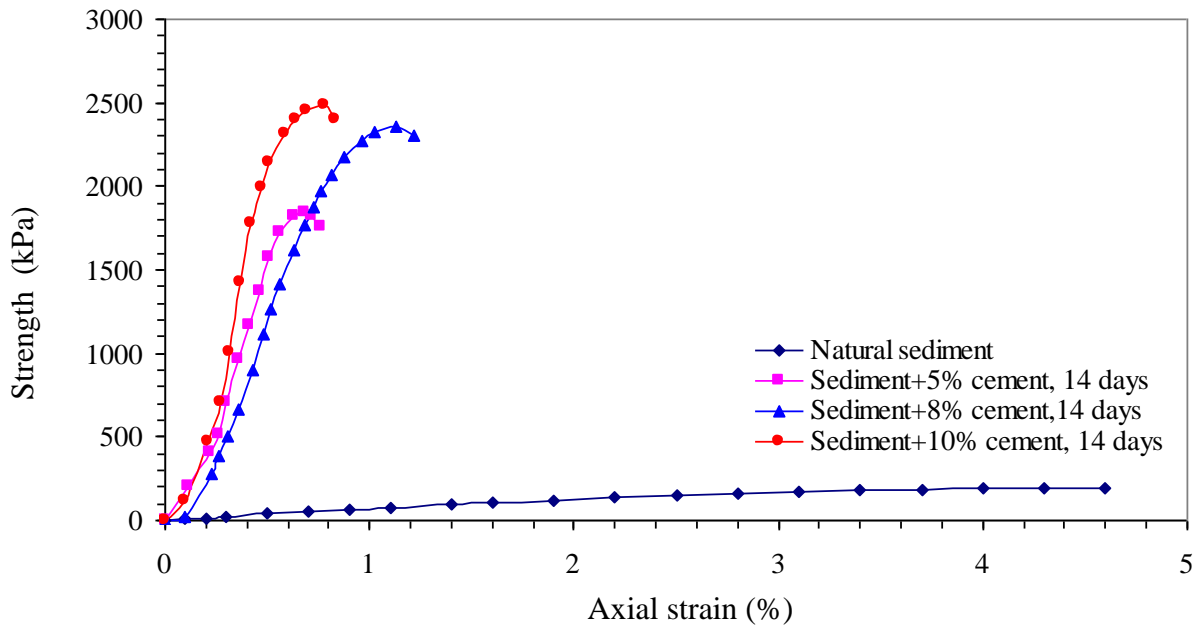


Fig.5. Stress-strain curves for sediments in water and those treated with different percents of cement at constant curing time

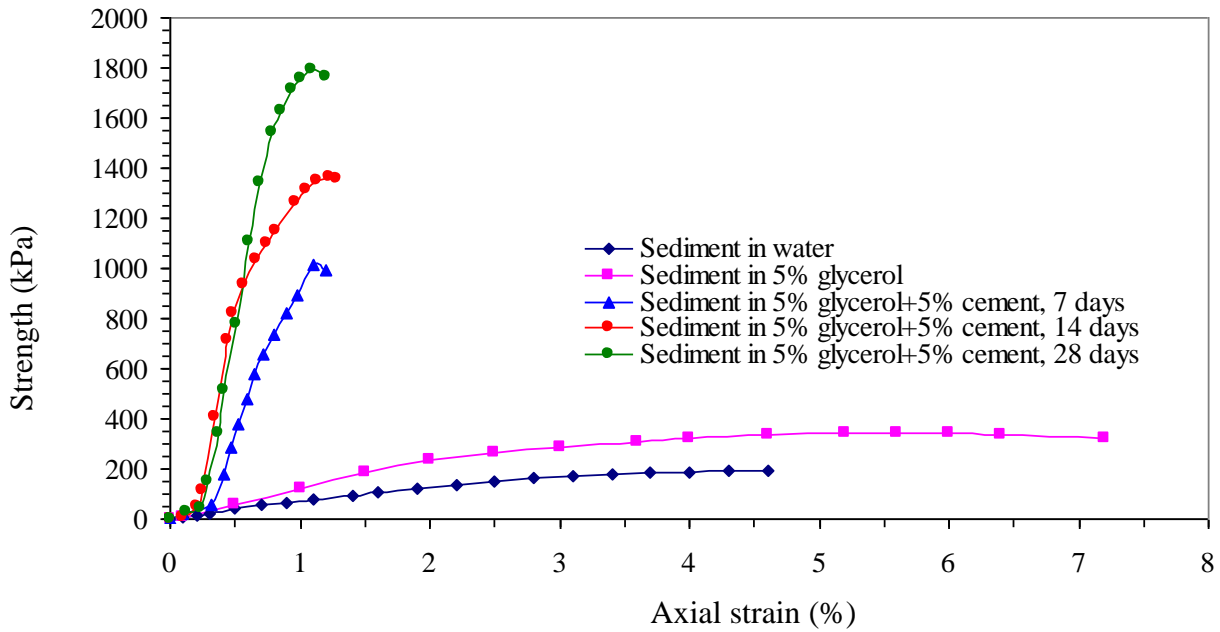


Fig.6. Stress-strain curves for sediments and treated sediments deposited in 5% glycerol at constant percent of cement with different curing times

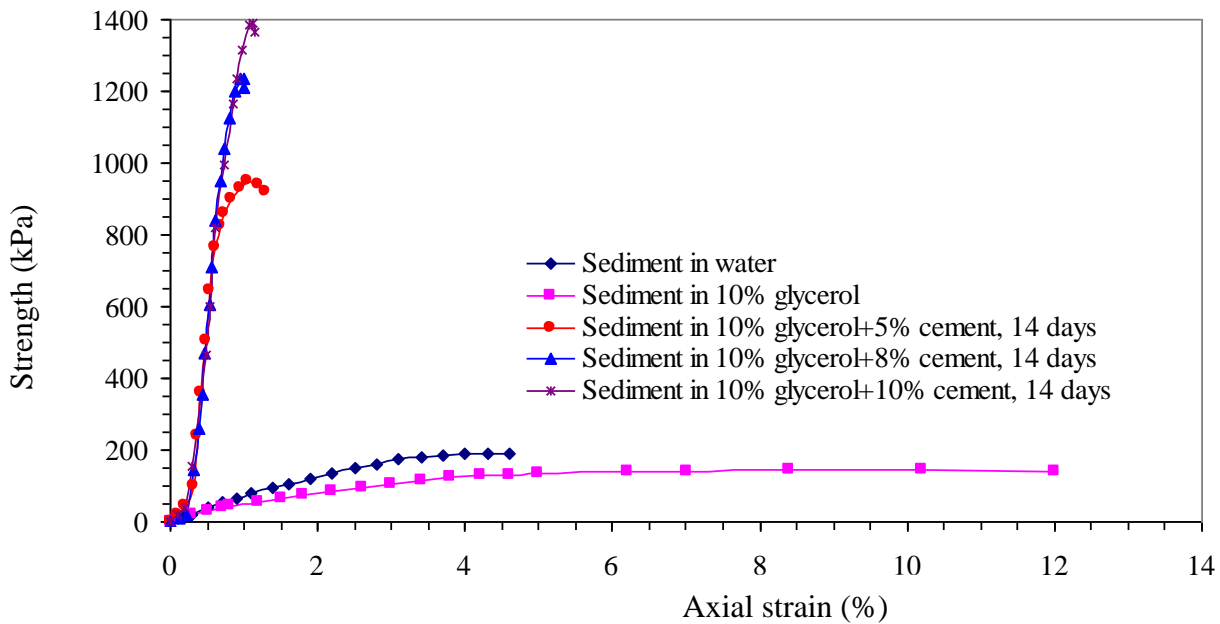


Fig.7. Stress-strain curves for sediments and treated sediments deposited in 10% glycerol at constant curing time with different percent of cement

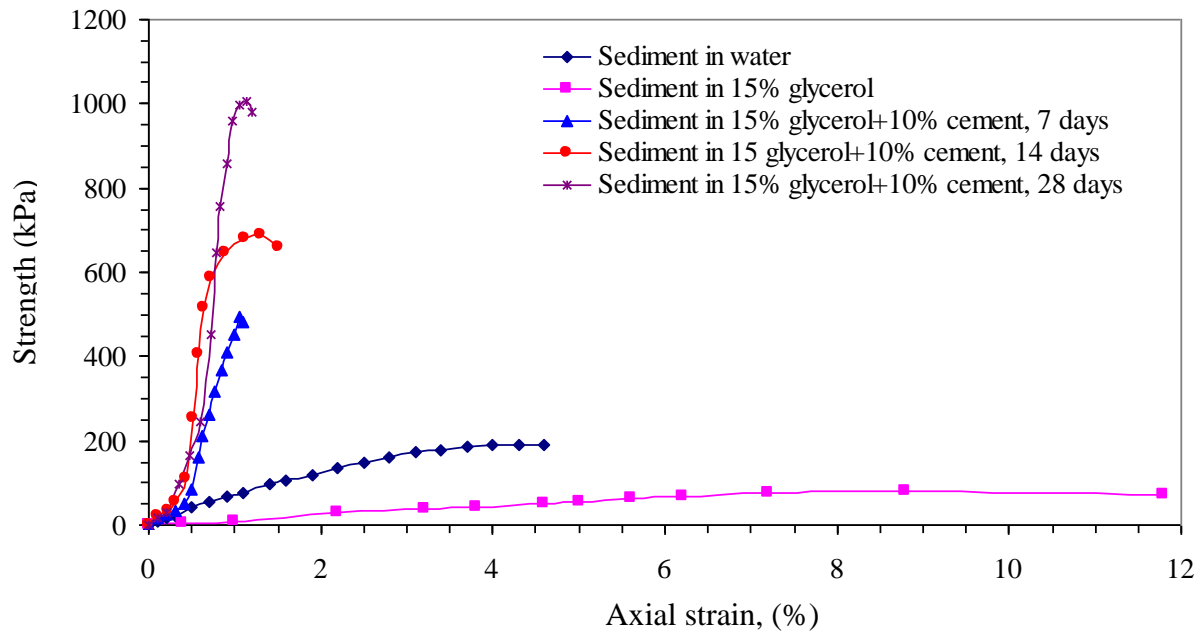
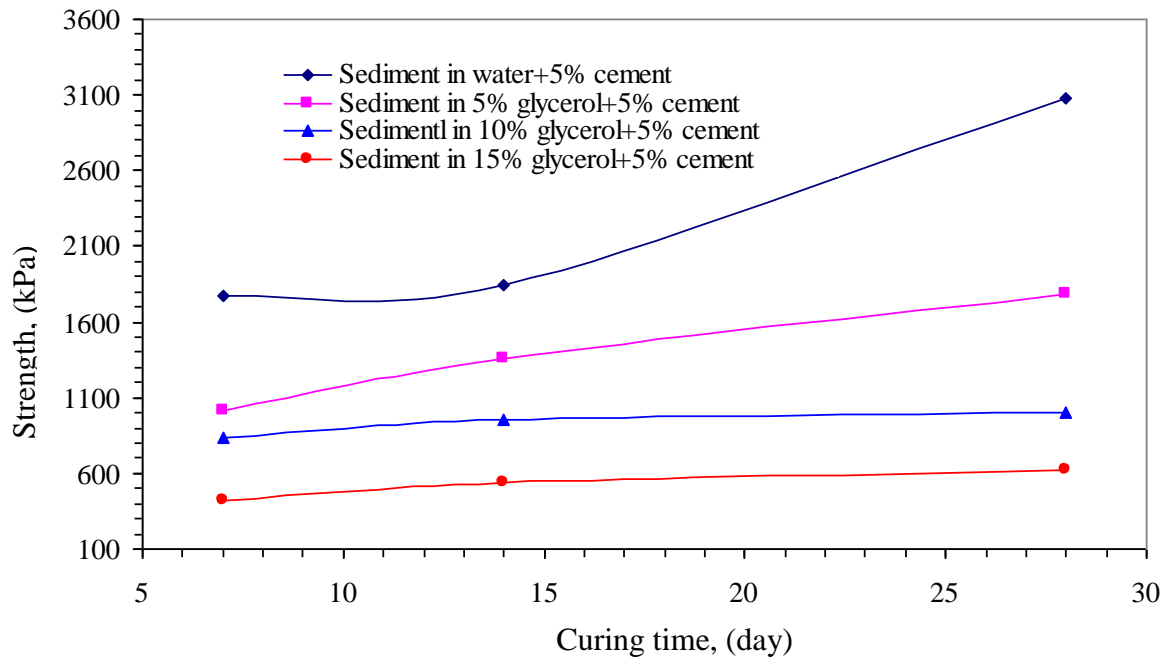


Fig.8. Stress-strain curves for sediments and treated sediments deposited in 15% glycerol with constant percent of cement and different curing times



(a)

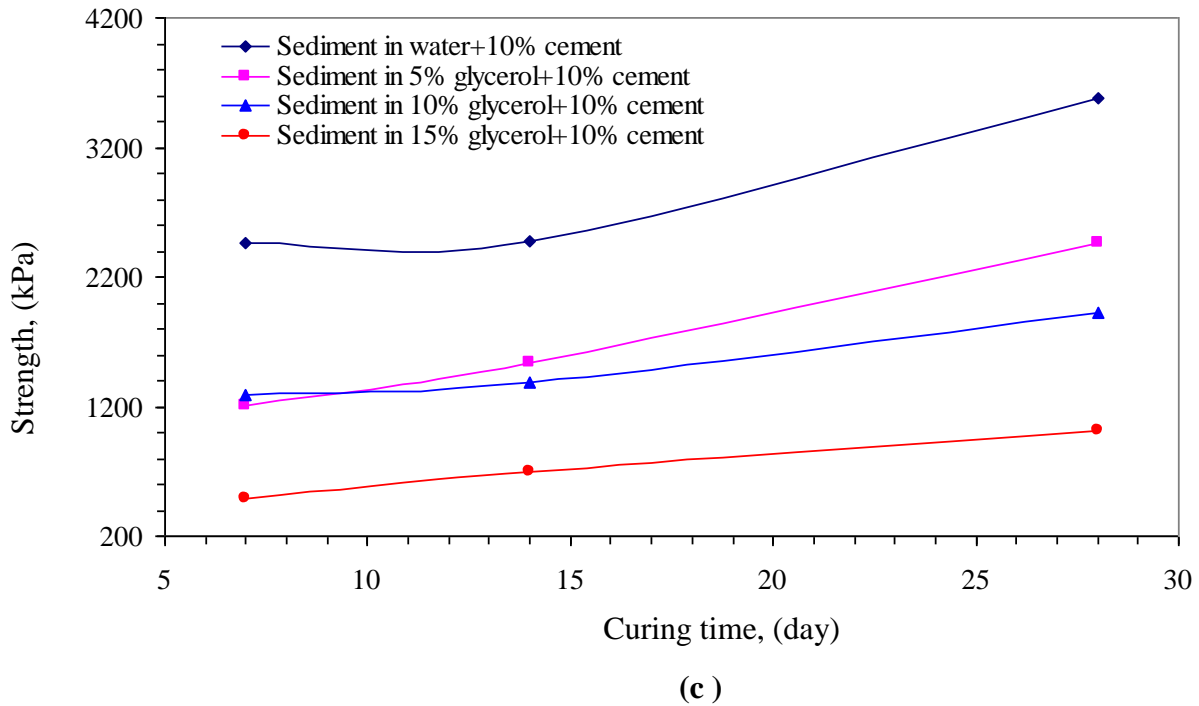
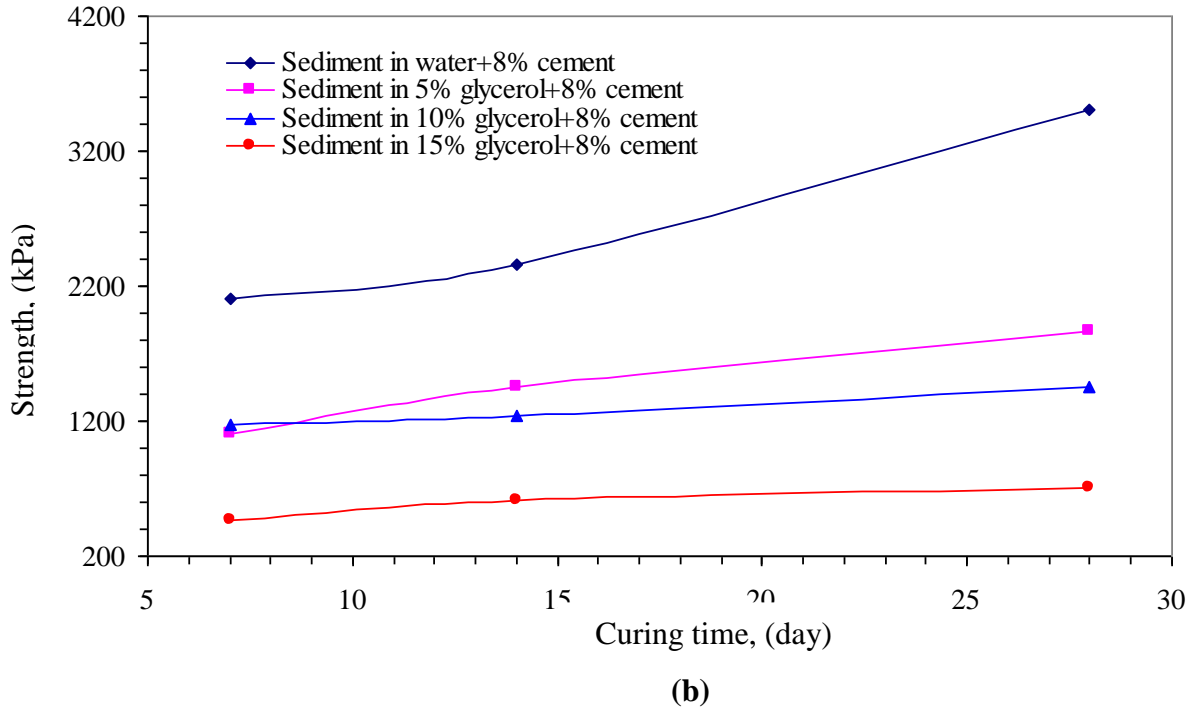
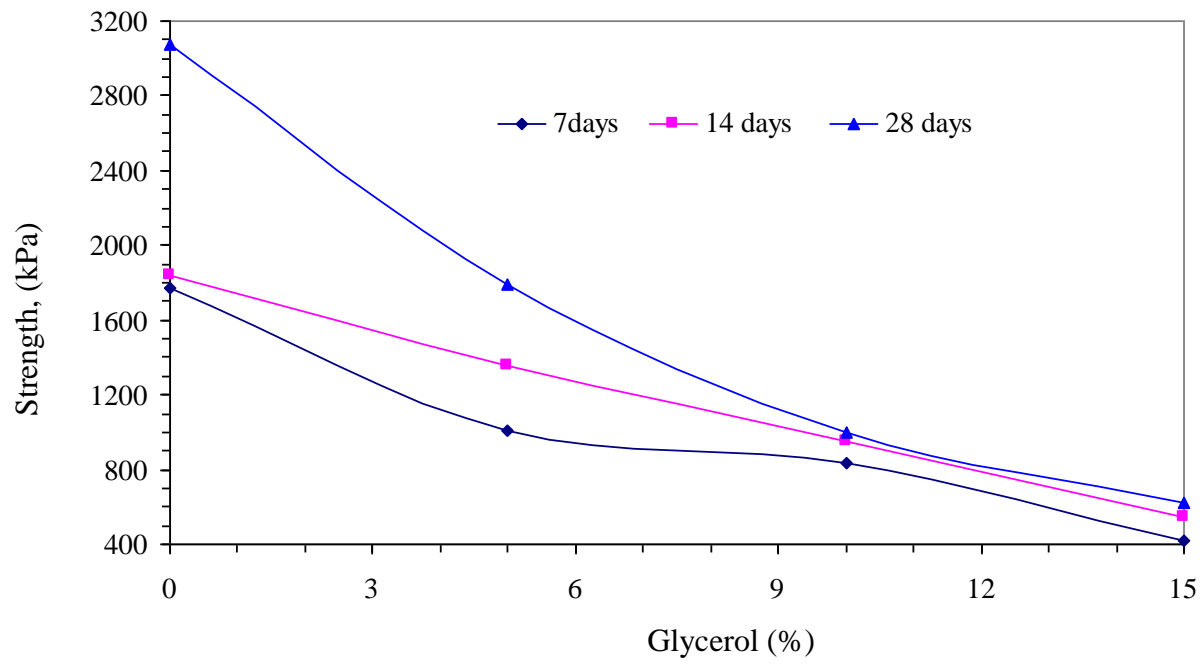
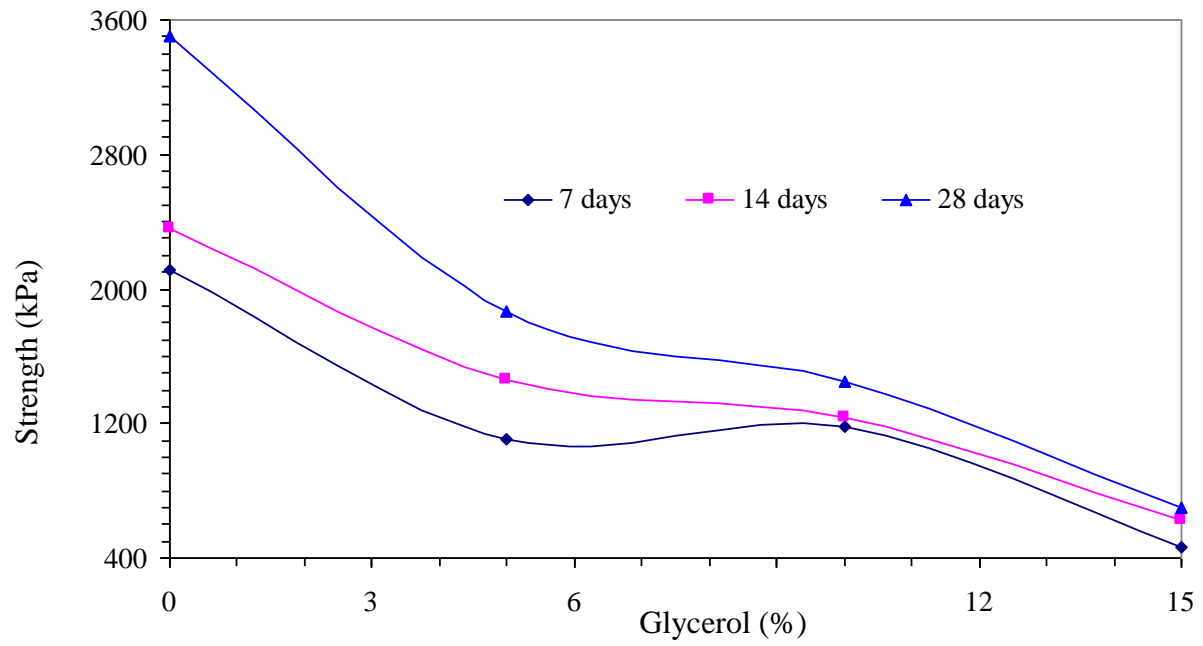


Fig.9. Strength-curing time for treated sediments. (a): 5% cement, (b): 10% cement and (c): 15% cement



(a)



(b)

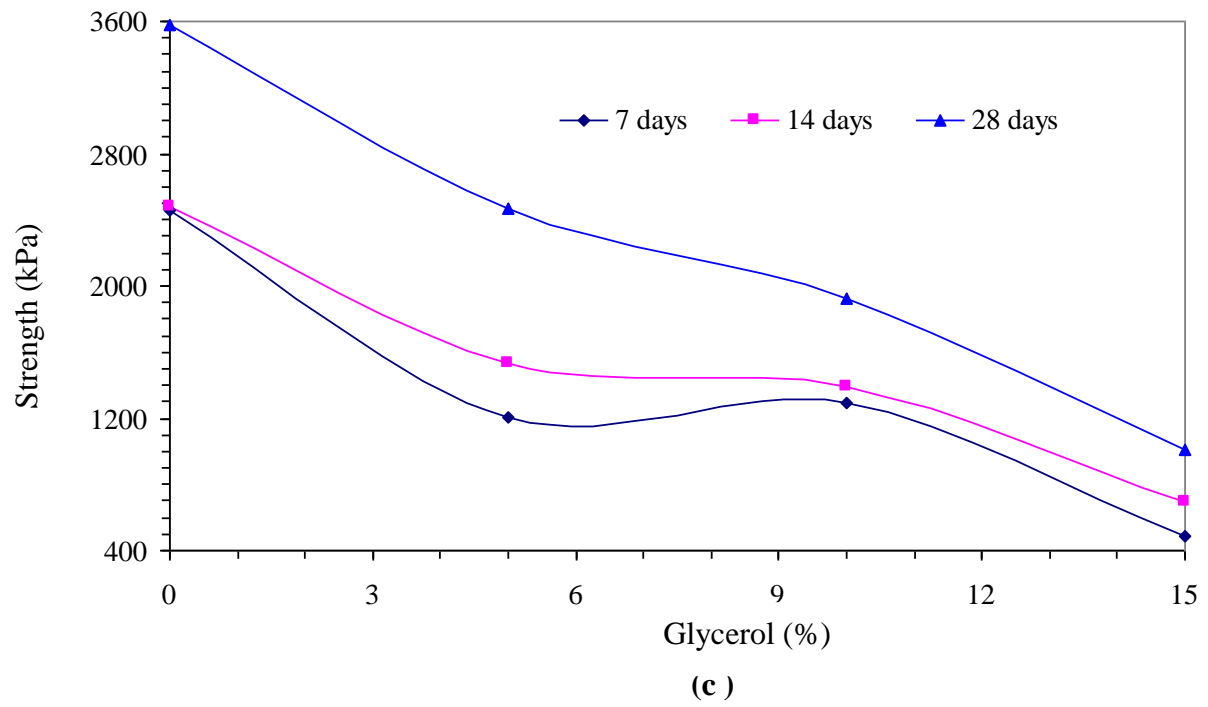


Fig. 10. Strength-percent of glycerol curves for treated sediments (a): 5% cement, (b): 8 % cement, (c): 10% cement

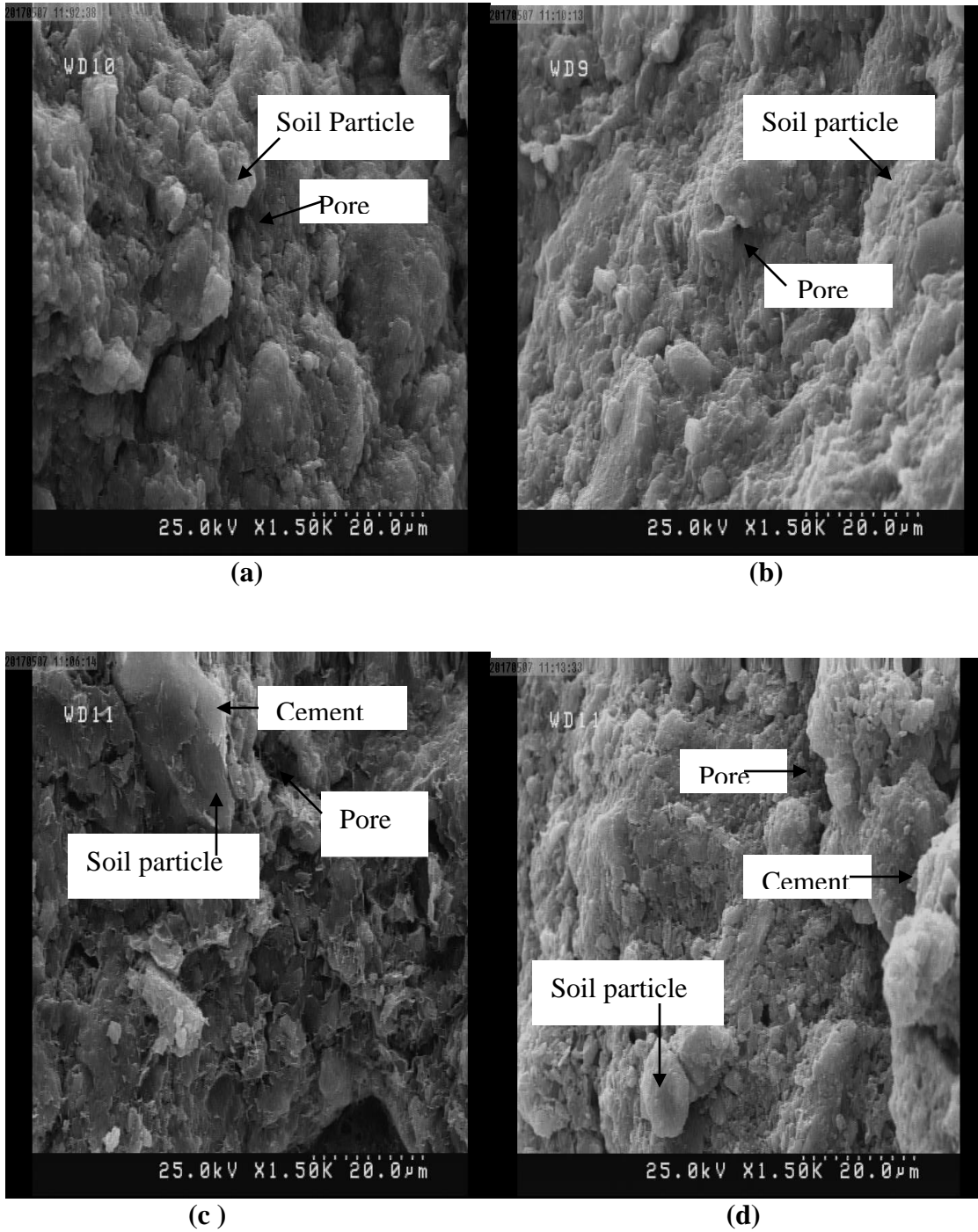


Fig. 11. SEM images of (a) deposited soil in water, (b) deposited soil in water and 10% glycerol (c) deposited soil in water +8% cement (d) deposited soil in water and 10% glycerol+8% cement