Effect of cement on the mechanical behaviour of a soil contaminated with Mono Ethylene Glycol (MEG)

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ABSTRACT

This paper presents a study on the mechanical properties of a contaminated clay soil and its treatment by cement. One group of unconfined compression (UC) tests was performed on samples of natural soil, and soil contaminated by Mono Ethylene Glycol (MEG) with 40% concentration at different degrees of contamination (3, 6 and 9%). Another group of UC tests was conducted on the samples that were prepared as mixtures of clean or MEG contaminated soil with different cement contents (3, 6 and 9%) at different curing times. The results show that the strength and stiffness of the soil contaminated with MEG is reduced increasingly by the degree of contamination. In addition, by adding cement to the contaminated soil, the strength of the soil is increased as a function of degree of contamination, percent of cement and curing time.

Key Words: Contaminated soil, mono ethylene glycol, treatment, soil-cement, strength

INTRODUCTION

Clay soils are generally well known for their low strength and high compressibility. Usage of this kind of soil in construction projects would require stabilization. There are two major methods for stabilization of clay soils, chemical and mechanical methods. Chemical stabilization is associated with modification of the actual chemical make up of the soil matrix. Chemical stabilization can be carried out by adding calcium-based chemical agents such as lime, class c fly ash or cement to the soil[1-3]. When cement is added to soil, the chemical and physical properties of soil are changed. Cement reduces the plasticity and water holding capacity of the soil and increases its strength. The degree of stabilization depends upon the type of the cement used, the type of soil, and some other factors such as water content, proportion of mixing, degree of compaction and curing. Another use of cement is in treatment of contaminated soil through solidification and stabilization. This technique is one of the most effective methods for treatment of contaminated soils[4,5].

Contaminants can be divided into two broad categories: organic and inorganic. Many organic compounds originate from crude oil, including motor oils, lubricating oils, heating oils, detergents and antifreeze. These products must be partially separated by distillation and if needed, modified prior to being used. Many types of organic contaminants (petroleum contaminants) can result from this process and can be found polluting the environment. Sources of petroleum and its products in the environment will also include accidental spills and from ruptured oil pipelines. Today the international oil and gas pipelines span several million kilometres and this is growing yearly. Just like any

other technical apparatus, pipelines are subject to wear and tear and degradation with time. All the petroleum contaminants released on the ground finally find their way to the soil system due to gravity until an impervious horizon is met such as bedrock.

MEG is an organic compound that is also known as glycol or glycol alcohol. It is a clear, colorless, syrupy liquid without any odour. It is used as chemical intermediate in the manufacture of polyesters for fibers, film, bottle, etc. It is also used as antifreeze in engine coolants. The spread of MEG to the environment can occur by leakage from the relevant plants to surface water and soil[6-8] and also leakage from coils of heating pump[9]. It can also spread following a spill on surface water or soil. When MEG enters the soil it has little or no capacity to bind to the particles and will be mobile in soil and penetrate to underground water[9]. Dobson[10] (2000) indicated that existence of MEG in run off of airport is harmful and may cause serious environmental damage.

The contaminants in the soil are held in either by chemical adsorption or entrained within pore space surrounding the soil particles. The reaction of soil to contaminant depends on the local environment, soil mineralogy, particle size, bonding and ion exchange capacity. Fang[11] introduced an index, namely sensitivity index, that shows the interaction of soil with contaminant. The value of the sensitivity index is between 0 and 1 with higher values showing more interaction between soil and contaminant. The value of sensitivity index is between 0.01-0.1 for coarse-grained soils and 0.6-0.9 for fine-grained soils.

Meegoda et al.[12,13] studied the use of contaminated soil as the construction material. They conducted compaction tests for improving a soil contaminated with 3, 6 and 12% motor oil and concluded that using 2.5% glycol can improve the mechanical behavior of this kind of soil. Meegoda and Muller[14] investigated the use of petroleum contaminated

soil in hot mix asphalt concrete in New Jersey. They found that it is possible to use about 35% petroleum contaminated soil in the mixture of asphalt concrete. Tuncan et al.[15] conducted a number of tests on the treatment of petroleum contaminated soil. They mixed 5% cement, 10% fly ash and 20% lime with a petroleum contaminated soil and found that the treated soil gained the highest strength. Hassan et al.[16] performed an experimental study on the use of petroleum contaminated soil in construction of highways and concluded that petroleum contaminated soil mixed with crushed stones can be used as base and sub base material in highways.

RESEARCH SIGNIFICANCE

In construction projects where the local soil is contaminated with petroleum products, transportation of suitable soil from another area may or may not be economical (many projects have to import better-quality soils for construction, subgrade, etc.). However, the more important point might be that excavating, treating, and transporting the contaminated soil to a hazardous waste site might be prohibitively expensive. Appropriately treating the products on-site, improving their properties so that they can be used in construction (which would include traditional properties such as strength, PI, etc., as well as environmental, such as leachability and chemical stability once treated), and placing them back in an environmentally suitable manner (which may include encapsulation) might be significantly more cost-effective. In this work the mechanical behavior of a clay soil contaminated with different percentages of contamination is studied and the effect of cement on stabilization of the contaminated soil is investigated for different percentages of contaminant, cement contents and curing times.

EEPERIMENTAL PROCEDURE

Material and testing programme

Soil, cement and Mono Ethylene Glycol (MEG) are three basic materials that were used in this work. The properties of these materials are explained in this section.

MATERIALS

Soil

A clay soil was used in this experimental work. The main physical, mechanical and chemical properties of the soil are summarized in Tables 1 and 2. Based on the index properties the soil can be classified as clay with low plasticity (CL) according to the Unified Soil Classification System (USCS). The result of standard compaction test showed that the values of optimum water content and maximum dry unit weight were 16.3% and 17.7 kN/m^3 (112.7 pcf) respectively. XRD (X-ray diffraction) tests were conducted on samples of the soil and the results are shown in Fig.1. As shown in Fig.1a the minerals of the soil include quartz, calcite, feldspar (Na, Ca) and feldspar (K). The results also show that the clay minerals of the soil are Illite, Chlorite and Montmorillonite (Fig.1b).

Cement

The cement that was used in this study was Portland type 1. It had a specific gravity of 3.15 with Blaine fineness of approximately 4100 cm^2/gr. The properties of the cement are shown in Table 3.

Mono Ethylene Glycol (MEG)

MEG is an organic compound. It is primarily used as a raw material in the manufacture of polyester fibers and fabric industry, and polyethylene terephthalate resins (PET) used in bottling. A small percent is also used in other applications such as antifreeze and other products. MEG is used in the natural gas industry to remove water vapor from natural gas before further processing. Ethylene glycol is moderately toxic. It breaks down in air in about ten days, and in water or soil in a few weeks. It enters the environment through the dispersal of ethylene glycol-containing products, especially at airports where it is used in deicing agents for runways and airplanes. It is produced from ethylene, via intermediate ethylene oxide. The chemical formula for MEG is $C_2H_6O_2$. It is totally miscible with water. The dielectric constant, absolute viscosity and mass density of MEG were 37.7, 1631 (cP) and 1132.2 Kg/m^3 (70.74 pcf) at 25^oC (77^oF) according to the information provided by the supplier. In this work a solution of MEG with concentration of 40% was used.

SAMPLES

The main materials used in preparing the samples were natural soil, cement, water and MEG. The samples that were used in this study were natural soil, soil-cement, soil contaminated with MEG and soil-cement contaminated with MEG. In preparation of the samples contaminated with ethylene, the degree of contamination was defined as the percentage weight of contaminant with respect to dry weight of the soil. The degrees of contamination of 3, 6 and 9% were considered for preparing the contaminated samples. The initial degree of contamination was considered at 3% because soil with more than 3% oil concentration can be considered as hazardous waste[17,18]. The calculated weight of MEG with 40% concentration with degrees of contamination of 3, 6 and 9% was sprayed

on 6 kg (13.230 lb) of 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 MEG could reach equilibrium condition. Different mixtures of natural soil with different percentages of cement (3, 6 and 9% of dry weight of soil) were prepared. The mixtures of soil, ethylene and cement were prepared by mixing the contaminated soil (that was prepared previously) with 3, 6 and 9% cement. The above materials (natural soil, contaminated soil, soil-cement and soil-cement with MEG) were compacted according to the standard compaction test procedure. The maximum dry unit weight and optimum water content were determined for each of the materials. The static compaction method was used for preparing cylindrical samples. Static compaction was achieved by applying a static pressure, using a loading machine, on the material placed in three layers at their respective maximum dry unit weight and optimum water content that were obtained from standard compaction test. Each layer was compacted with a fixed displacement rate of 1.5 mm/min (0.059 in/min). In order to prepare the different samples for unconfined compression tests, the natural soil, MEG, cement and water were weighed with accuracy of 0.1 gr ($2.205*10^{-4}$ lb). They were then 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. All the samples had a height to diameter ratio of 2 (length and diameter of the prepared samples were 100 and 50 mm (3.93 and 1.96 in) respectively). After compaction the soil-cement samples with and without MEG were stored in a curing cabinet at constant temperature and relative humidity according to the ASTM D1632 standard for curing times of 3, 7, 14 and 28 days.

Experimental tests

Atterberg limits 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 standard. The rate of loading was selected as 1mm/min (0.059 in/min) as used by many researchers such as Kumar et al.[19] and Estabragh et al.[20] 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.

RESULTS

The results of the Atterberg tests are shown in the Table 4. The results show that Atterberg limits are decreased by adding MEG, or cement to the natural soil. This reduction is observed for contaminated soil after adding cement to it.

Typical results of the compaction tests for the soil and soil-cement with different percentages of MEG are shown in Fig.2. As shown in Fig.2a the maximum dry unit weight and optimum water content of natural soil are 17.7 kN/m^3 (112.7 pcf) and 16.3% respectively and for the soil mixture with 3% MEG they are changed to 17.8 kN/m^3 (113.3 pcf) and 15.6%. A similar trend is also observed for other percentages of MEG. So, the higher the percentage of MEG, the greater is the increase and decrease in the values of maximum dry unit weight and optimum water content. Fig.2b shows the compaction curves for soil-cement with 9% cement and mixture of soil with 9% cement and different percents of MEG (3, 6 and 9%). As shown in this figure the maximum dry unit weight and optimum moisture content for mixture of 9% cement with soil are 17.5 kN/m^3 (111.4 pcf) and 18.1% respectively. They are changed to 17.7 kN/m^3 (112.7 pcf)

and 16.4% for mixture of 3% MEG with the soil-cement. It is seen from this figure that increasing the amount of MEG (i.e, 6 or 9%) in the mixture of soil-cement causes increase in maximum dry unit weight and decrease in optimum moisture content. Table 5 also shows the results of compaction tests for mixtures of soil-cement with 3, 6 and 9% cement and mixtures of soil-cement with various percentages of MEG. It is seen from this table that adding 3% cement to the natural soil causes the maximum dry unit weight and optimum moisture content of the soil to change from 17.8 kN/m^3 (113.3 pcf) and 16.3% to 17.5 kN/m^3 (111.4 pcf) and 18.1% respectively. This trend of reduction in maximum dry unit weight and increase in optimum moisture content is also seen for the samples with 6 and 9% cement. As shown in this table, adding the 3, 6 or 9 % MEG to the different soil-cement mixtures (with 3, 6 or 9% cement) increases the maximum dry unit weight and decreases the optimum moisture content compared with the relevant soil-cement compaction parameters.

Figure 3 shows the stress-strain curves for the natural soil and the mixtures of soil with different percentages of MEG (3, 6 and 9%). The results show that the strength of the natural soil is 417 kPa (60.5 psi) at 2.46% strain. By adding 3% MEG to the natural soil the strength of the mixture is changed to 282 kPa (40.9 psi) at strain of 2.94%. The strength of the soil with 6 and 9% MEG is 266 and 221 kPa (38.6 and 32.1 psi) at strains of 3.2 and 3.5% respectively.

Typical results of stress-strain curves for the soil-cement are shown in Figs 4 and 5. Fig.4 shows the stress-strain curves for the natural soil and mixture of soil-cement with 6% cement at different curing times (3, 7, 14 and 28 days). It is seen from this figure that by adding 6% cement to the natural soil, the strength of the soil changed from 417 kPa

(60.5 psi) at strain of 2.46% to 689 kPa (100 psi) at strain of 1.2%. It shows that adding 6% cement to the soil caused an increase of about 65.2% in strength and 51.0% reduction in strain of the failure point after 3 days curing time. At curing times of 7, 14 and 28 days the strength of the soil-cement was changed to 815, 842 and 891 kPa (118.2, 122.1 and 129.2 psi) respectively. The results show that both the percent of cement and also the curing time are effective in increasing the strength of soil-cement. These results are in agreement with findings that were reported by Kézdi[21]. The effect of different percentages of cement (3, 6 and 9%) on the strength of soil after 7 days curing time is shown in Fig.5. It is shown that the strength of the natural soil changed from 417 kPa (60.5 psi) to 525, 815 and 1540 kPa (76.1, 118.2 and 223.2 psi) by adding 3, 6 and 9 % cement after 7 days curing time. The results show that adding 3, 6 and 9% cement increases the strength of natural soil by 26.0 and 95.4% and 270% respectively. Therefore, increasing the percent of cement is an important factor in increasing the strength of soil-cement as indicated by Khattak and AlRashidi[22], Bahar et al.[2] and American Concrete Institute (ACI)[23].

Figure 6 shows the stress strain curves for the natural soil, soil-cement with 3% cement and mixture of soil-cement with 3% cement and different percentages of MEG for curing time of 3 days. It is seen from this figure that the final strength of the soil-cement is 525 kPa (76.0 psi) at strain of 1.72%. The strength and strain at failure for the soil-cement sample with 3% MEG were changed to 537 kPa (77.9 psi) and 1.4% respectively showing a relatively small increase in strength. The samples that were prepared with 6 and 9% MEG showed a reduction in strength of about 21 and 26.5% compared to the sample of soil-cement that was prepared with natural soil. The results indicate that the

strength of the sample with 3% MEG is about 28.7% more than the natural soil. The strength of the sample with 6% MEG is nearly the same as the natural soil but that of the sample with 9% MEG is less than the natural soil. Similar results for natural soil, soil-cement with 9% cement and mixture of soil-cement with different percentages of MEG are shown in Fig.7 for curing time of 28 days. As shown in this figure, the strength of the sample with 3% MEG is nearly 7% more than the sample that was prepared from soil-cement with natural soil. This figure also shows that the final strength of the samples that were made of soil with 6 and 9% MEG are nearly 21 and 43% less than the strength of soil-cement. The results show that the strength of the samples with 3, 6 and 9% MEG is more than the natural soil. For a given cement content, the strength increases with decreasing the MEG content. Figure 8 shows the stress-strain curves for the natural soil and the mixtures of soil with 3% MEG and 3, 6 and 9% cement at curing time of 28 days. As shown in this figure, increasing the percent of cement at constant percent of MEG increases the strength and the initial slope of the stress-strain curve,

DISCUSSION

As shown in Table 4, the liquid limit (LL), plastic limit (PL) and plasticity index (PI) of the soil contaminated with different percentages of MEG are decreased in comparison with the natural soil. This reduction is dependent on the percent of MEG; so, more reduction is observed by increasing the percent of the added MEG. These results are in agreement with the results that were published by Singh et al.[24] for a soil contaminated with kerosene. The values of liquid limit and plastic limit for the soil-cement and soil-cement contaminated with different percentages of MEG are shown to decrease by increasing MEG. As shown in this table, by adding 3% cement to the soil the values of

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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 the mixture of soil with 3% cement. It is seen from this table (Table 4) 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.[25]. The results show that adding cement to the contaminated soil causes reduction in the values of LL, PL and PI. For a constant percent of MEG, this reduction is dependent on the percent of cement; 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 MEG causes reduction in the liquid limit.

The results of compaction tests on the natural soil and the mixtures of soil with different percentages of MEG showed that the maximum dry unit weight is increased but the optimum water content is decreased by adding MEG. By increasing the amount of MEG in the soil the maximum dry unit weight increased and optimum water content decreased (Table 5 and Fig.2a). It may be that adding MEG to soil causes reduction in the friction between the particles, facilitating the slippage of the particles which results in reduction of voids between the particles, increase in maximum dry unit weight and decrease in optimum water content. Al-Sanad et al.[26] reported similar results for granular soil that was contaminated with 2% crude oil. Hassan et al.[16] reported increase in maximum dry unit weight and reduction in optimum water content for a granular soil contaminated with 10% petroleum.

Table 5 shows the results of the compaction tests for the soil-cement with different cement contents. As shown in this table, a reduction in the maximum dry unit weight and an increase in optimum moisture content is observed for the mixture of soil-cement

compared to the natural soil. Croft[27] indicated that mixing of cement with soil tends to create a flocculated structure in the mixture of soil-cement that is dependent on the type of clay mineral, pH of pore fluid and cement content of the soil. Similar results were reported by Shen and Mitchell[28] and Estabragh et al.[20]. The results of compaction tests for the mixtures of soil-cement with different percentages of MEG are shown in Table 5. The results show that at a constant cement content, by adding different amounts of MEG, the maximum dry unit weight is increased and optimum water content is decreased. The authors postulate that a part of the volume of MEG fills the pore between the clay particles and a part of it surrounds the clay or cement particles. This prevents the particles from having direct contact with water and results in increase in maximum dry unit weight and decrease in optimum moisture content.

Figure 3 shows the stress-strain curves for the natural soil and the mixtures of soil with different percentages of MEG. As shown in this figure adding MEG to the soil causes decrease in strength of the mixture. The decrease in strength is dependent on the amount of MEG. Increasing the MEG content of the mixture increases the amount of reduction in strength and increases the ductility of the mixture. The basic structural units of most clay minerals consist of a silica tetrahedron and alumina octahedron. The surfaces of clay minerals carry negative charges mainly as a result of the isomorphous substitution or due to disassociation of hydroxyl. Isomorphous substitution in which lower positive valence elements replace the existing higher positive valence elements in clay crystals, results in a net negative charge on clay crystals. This negative charge attracts cations (positive ions) towards the surface of the clay. These cations, attached to the clay surface are termed exchangeable cations as they can be exchanged with other cations. The replicability of

one type of cation by another type depends upon many factors such as valence and ion size. The total amount of exchangeable cations is called cation exchange capacity. Cation exchange capacity of a clay is influenced by particle size, grinding, temperature and exchange reaction environment[29].

When water is added to the dry particles, the adsorbed cations will try to diffuse away from the surface in order to equalize concentrations[29,30]. However, their movement will be restricted by the surface's negative electric field and this will result in the formation of a micelle of ions in suspension next to the particle surface. A hydrated clay particle will, therefore, have an associated micelle in which the adsorbed ions are scattered in space and separated from the particle surface. The charged particle surface and the ion micelle form an electrostatic system known as the diffused double layer (DDL). The concentration of ions will diminish with increasing distance from the particle surface, until it becomes similar to that of the bulk water. The thickness of DDL is an important controlling factor for the structural development and other physico-chemical and mechanical properties of soils[29-32]. Van Olphen[32] indicated that the thickness of DDL around clay particles depends on the concentration of salt and type of cations in the soil water. According to the Gouy-Chapman theory the thickness of the DDL decreases as ion concentration increases, resulting in flocculation of clay particles and large space between them[29,33] . Bowders and Daniel[34] stated that many chemicals tend to reduce the thickness of the DDL, causing the soil skeleton to shrink and resulting in a decrease in repulsive forces. This in turn leads to flocculation of clay particles and formation of granular particles. The thickness of DDL is dependent on parameters such as the dielectric constant of pore fluid, cation valance and electrolyte concentration. The dielectric constant of MEG solution with a defined concentration is less

than that of water. Therefore, the thickness of DDL is reduced compared with the case of water as pore fluid and causes flocculation of the soil particles.

As mentioned above, the thickness of DDL is dependent on the value of dielectric constant. The value of dielectric constant of MEG (37.7) is less than that of water (78). Adding MEG to soil causes the DDL around the particles to shrink. This provides an opportunity for the clay particles to orient into a flocculated structure. In the flocculated structure of clay, due to reduction in DDL thickness, the strength of the soil mass is increased[35-37]. The present results show the opposite of the above assumption. These results are in agreement with the results that were reported by Ratnaweera and Meegoda[38]. This can perhaps be explained by the difference between the viscosities of ethylene and water. The viscosity of MEG solution was 1252 cp that is more than water. Proctor[39] reported changes in the measured friction angle for samples in dry and wet conditions. He indicted that water plays the role of lubricating agent to make the particles reach closer in packing. The action of lubrication at particle contact level is formed by the viscose behavior of pore fluid. Sherif and Burrous[40] state that the majority of soils experience reduction in shear strength with increase in temperature. Viscosity is generally dependent on temperature and it decreases with increasing temperature. This supports the assumption that an increase in pore fluid viscosity changes the properties of mineral to pore fluid contacts and shows softening in stress-strain behavior. Thereby the effect of viscosity of the pore fluid can be considered as a factor that influences the variations of soil strength. The adsorption of MEG to the soil particles is very low[9]. It can concluded that the effect of MEG on soil behavior is more mechanical than physico-chemical. Therefore viscosity has an important effect on mechanical behavior of contaminated soil with MEG. This mechanism is concluded from the experimental results. Ratnawwera and

Meeegoda[38] 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 found that viscosity has a significant effect on the strength of the soil. Therefore, the main reason for the reduction of strength due to MEG is its viscosity. The viscosity of MEG with concentration of 40% was 1252.4 cP that is more than water.

Typical results of stress-strain curves for soil-cement are shown in Figs. 4 and 5. The results show that adding cement to soil causes its strength and brittleness to increase. Increasing the percent of cement and curing time are important factors in increasing the strength and brittleness of soil-cement mixture as also shown by[2,22].

The effect of cement on soil can be divided into three stages, namely cation exchange, cement hydration and pozzolanic reaction. The cation exchange stage starts when the cement is mixed with soil. In this stage calcium ions are released during the initial cement hydration. The reaction of calcium ions is likely to lead to cation exchange, so the electrical charge density around the particles is changed which results in reduction of soil plasticity. The hydration stage leads to a rise of pH value of the pore water. The strong bases dissolve the soil silica and alumina from both the clay minerals and amorphous materials on the clay particle surfaces. In the pozzolanic stage the cementation of the soil mass occurs. In this stage the calcium hydroxide in the soil water reacts with silicates and aluminates (pozzolans) that were liberated in previous stage form cementing materials. Calcium ions react with dissolved SiO_2 and Al_2O_3 form hydrated gel of calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH). These gels bind the soil particles in a manner similar to that produced by the hydration of cement and form a hard structure

that particles of soil can no longer slide over each other. This increases the strength and reduces the water holding capacity. Therefore, the increase in strength of soil-cement with time is mainly due to pozzolanic reaction. These results are consistent with the results that were reported by[21,41,42].

The results of the tests on mixtures of soil, cement and MEG show that at a constant percent of cement (3, 6 or 9%), increase of strength is only observed for 3% MEG (see Fig.9). However, for 6 and 9% MEG reduction of strength is observed. Comparing the results for different percentages of cement shows that at 3% MEG greater strength is attained by increasing the percent of cement. When adding 3% MEG solution to the soil, the degree of flocculation of the soil structure is increased which leads to larger voids in comparison with the natural soil. Hence the cement can make more pozzolanic reactions with soil particles which results in the formation of more CSH and CAH components than the natural soil. This leads to binding of the soil particles and results in a solid mass with high strength. By increasing the percent of cement at this amount of MEG (3%), more pozzolanic products are formed which leads to greater increase of strength. On the other hand, the curing time is another factor in increasing the strength. When adding 3% MEG, the majority of it fills the voids between the particles because the adsorption of it to soil particles is very low. At a constant percent of cement, by increasing the percent of MEG (6 or 9%) decrease in strength is observed for different percentage of cement (Fig.9). This is because when a higher percent of MEG is added to soil, a part of it may fill the pores between the particles and the rest of it covers the particle surfaces of soil. This prevents from formation of enough pozzolanic products between cement and soil and hence causes reduction in strength of the sample. Comparing Figs 9a, b and c shows

that at a constant percent of MEG (for example 6%) and for a given curing time (for example 7 days) the strength is increased with increasing the percent of cement. It is likely that the increase of strength is dependent on the pozzolanic reactions that are in turn dependent on the time and percent of cement. It may be concluded that only a portion of MEG can cover the soil particles that may be nearly constant. Therefore, by increasing the cement content the rest of the cement particles can produce pozzolanic products and increase the strength.

The stabilization of MEG-contaminated soil with cement showed significant improvement in performance through laboratory experimental tests. The effect of various addictive agents for treatment of contaminated soil should be tested and the most appropriate agent (e.g., lime or cement) chosen. However the performance should also be evaluated under actual field conditions. Other mechanical tests such as CBR (California Bearing Ratio), direct shear, triaxial and resilience and leaching tests should be carried out on the samples of the tested soil to assess their suitability for use in the field conditions.

CONCLUSIONS

This paper presented the results of an experimental study to investigate the mechanical properties of soil-cement-MEG mixtures. The following conclusions can be drawn from the results presented:

1- The results show that it, in principle, is possible to treat contaminated soils and use them as construction materials by considering the potential environmental problems (leaching contaminant to underground or evaporation to air).

1- The results of compaction tests showed that for a soil contaminated with different percentages of MEG and for a mixture of soil contaminated with MEG with various percents of cement, the maximum dry unit weight is increased and optimum water content is decreased in comparison with natural soil.

2- Strength and stiffness of soil contaminated with MEG are decreased compared with natural soil and this reduction is dependent on the percent of MEG.

3- Strength, stiffness and brittleness of soil are increased by addition of cement and the amount of increase is dependent on the percent of cement and curing time.

4- Increase of strength is only observed for mixture of contaminated soil with 3% MEG for various percent of cement and this increase is also a function of curing time.

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List of tables

Table 1. Physical and mechanical properties of soil

Property	Standard Designation	Value
Specific gravity, G_s	ASTM D 854-10	2.70
Particle distribution		
Gravel (%)		8.0
Sand (%)		27.0
Silt (%)		53.0
Clay (%)		12.0
Consistency limits		
Liquid limit, LL (%)	ASTM D 4318-10	53.3
Plastic limit, PL (%)	ASTM D 4318-10	26.1
Plastic index, PI (%)	ASTM D 4318-10	27.2
Shrinkage limit, SL (%)	ASTM D 427-04	13.0
USCS classification	ASTM D 2487-11	CL
Compaction characteristics		
Optimum water content, w (%)	ASTM D 698-07e	16.30
Maximum dry unit weight, γ_{dmax} (kN/m^3)[a]		17.70

a- kN/m^3 = 3.685*10^{-3} pcf

Table. 2 Chemical composition of soil

Chemical component	Amount	Chemical component	Amount
pH	8.0	Mg^{2+} (meq/L)	10.0
EC^b (mmhos/cm)	10.74	Cl^- (meq/L)	60.0
Na^+ (meq/L)[a]	114.0	CO_3^{2-} (meq/L)	0.6
K^+ (meq/L)	0.23	HCO_3^- (meq/L)	4.0
Ca^{2+} (meq/L)	24.0	SO_4^{2-} (meq/L)	83.0
CO_3Ca (%)	10.2	O.C.^{c} (%)	0.11

a- (meq/L) = 3,78* (meq/gal)
b-Electerical Conductivity
c- Organic content

Table. 3 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)[a] 7days 28 days	ASTM C 109-08	 23 34
Tensile strength (MPa) 7 days 28 days	ASTM C 190-85	 1.6 2.4
Flexure strength (MPa) 7 days 28 days		 3.1 4.2

a- MPa = $1.45*10^2$ psi

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

Soil (%)	Cement (%)	MEG (%)	LL (%)	PL (%)	PI (%)
100	-	-	53.3	24.4	22.6
97.0		3.0	42.4	22.2	21.8
94.0	-	6.0	41.2	21.2	21.3
91	-	9.0	40.9	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	44.6	28.5	16.1
91.0	6.0	3.0	43.9	27.9	16.0
88.0	9.0	3.0	41.4	26.1	15.3
91.0	3.0	6.0	43.2	27.3	15.9
88.0	6.0	6.0	40.9	26.5	14.4
85.0	9.0	6.0	38.7	26.1	12.6
88.0	3.0	9.0	42.1	26.8	15.3
85.0	6.0	9.0	39.0	26.5	12.5
82.0	9.0	9.0	37.7	26.1	11.6

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

| Soil (%)	Cement (%)	MEG (%)	w_{opt} (%)	γ_{dmax} (kN/m^3)[a]
100	-	-	16.3	17.7
97	3	-	18.1	17.5
94	6	-	18.7	17.1
91	9	-	18.1	17.5
97	-	3	15.6	17.8
94	-	6	14.5	18.3
91	-	9	13.4	18.4
94	3	3	15.6	17.5
91	3	6	15.8	17.9
88	3	9	14.2	18.1
91	6	3	17.2	17.6
88	6	6	15.0	17.9
85	6	9	14.8	18.0
88	9	3	16.4	17.8
85	9	6	15.9	18.0
82	9	9	14.0	18.2

a- kN/m^3 = 3.685*10^{-3} pcf

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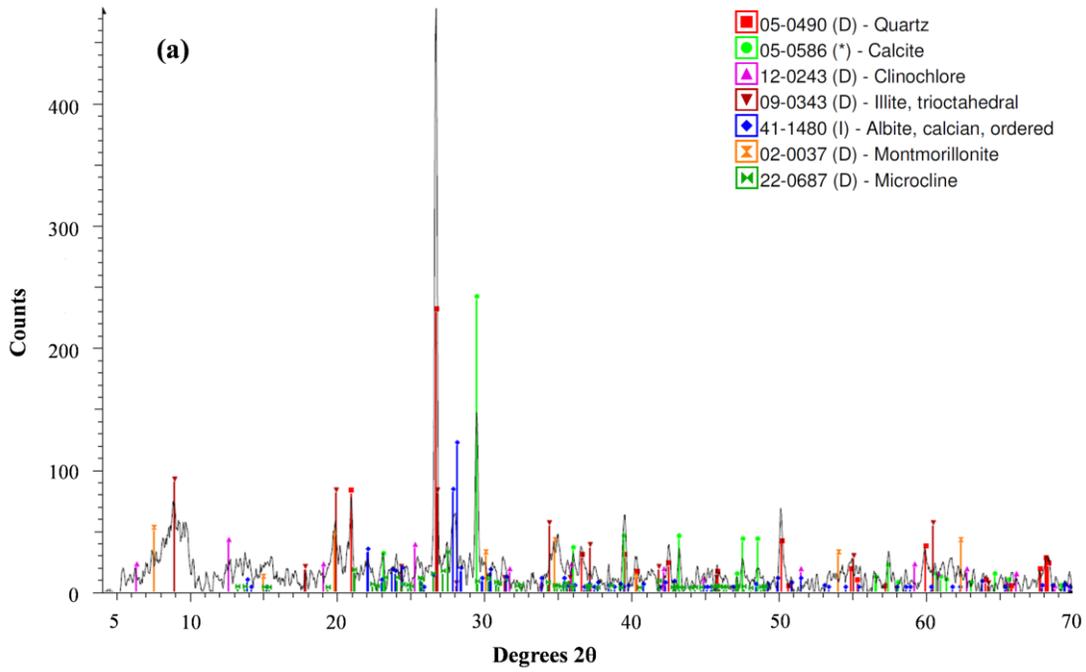
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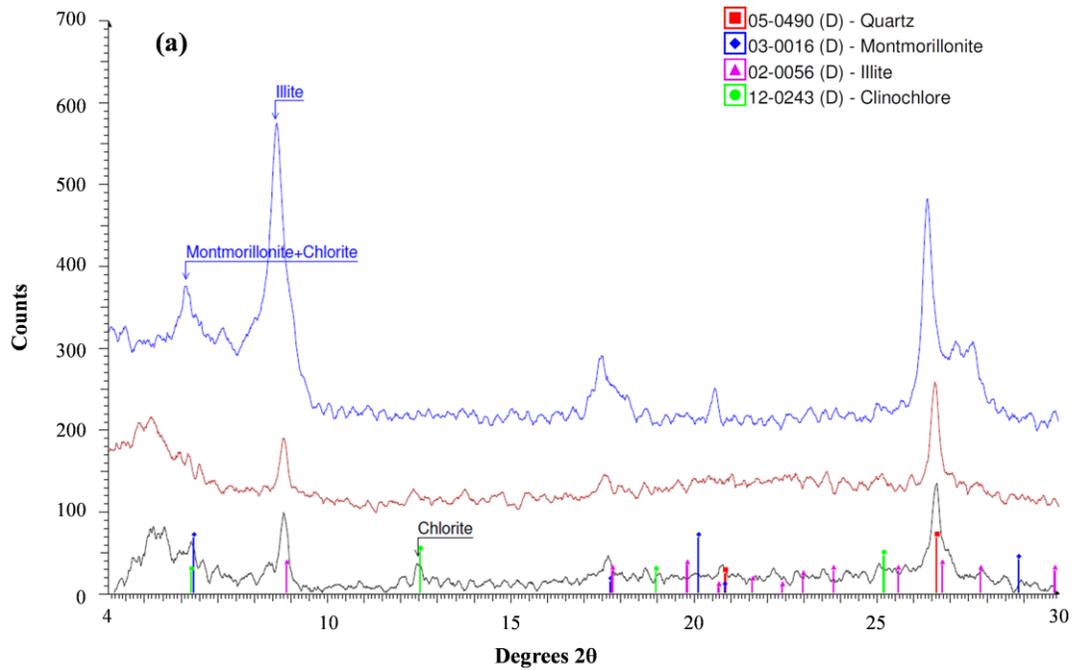
(b)

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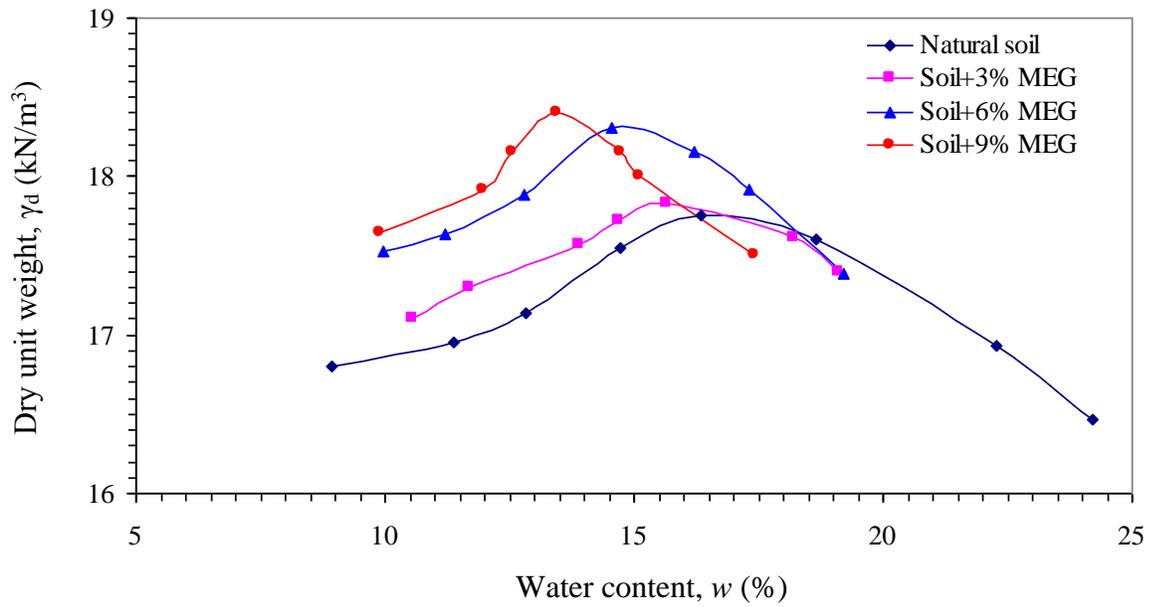
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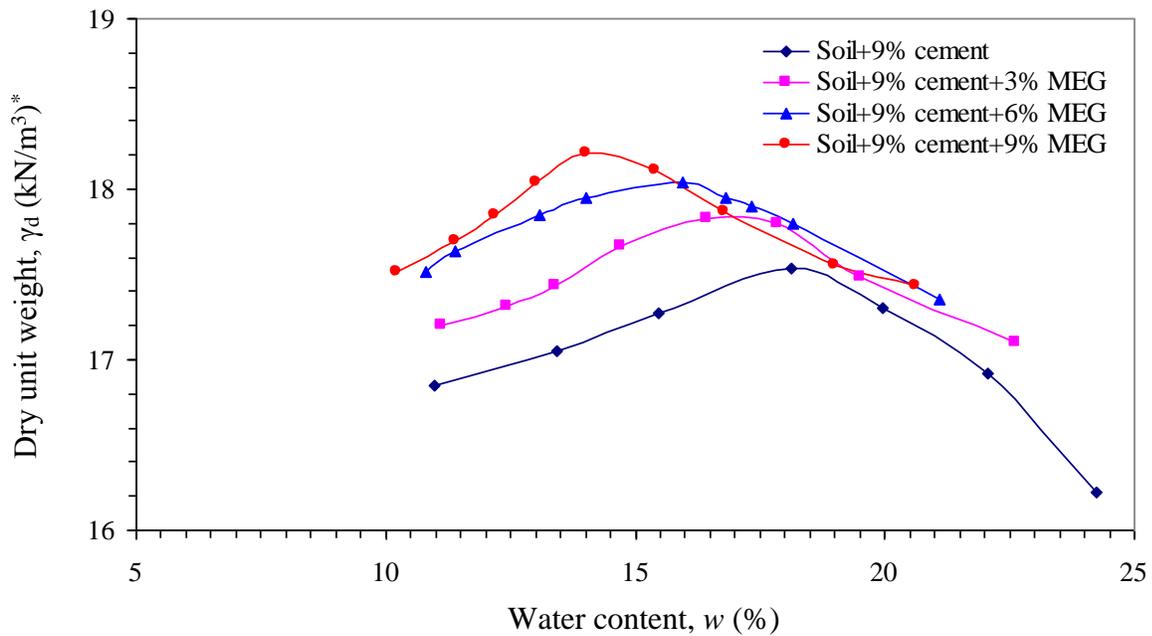
(b)

Fig.2. Compaction curves for (a)- natural soil and soil contaminated with different percentages of MEG (b)- soil cement with 9% cement and contaminated soil-cement with different percents of MEG.
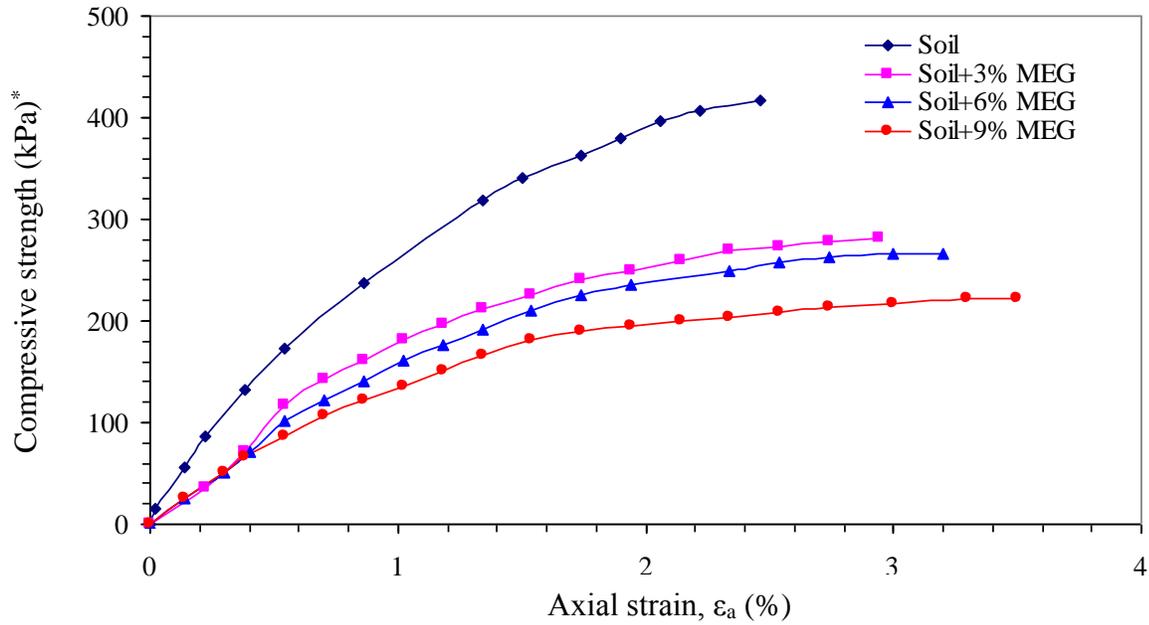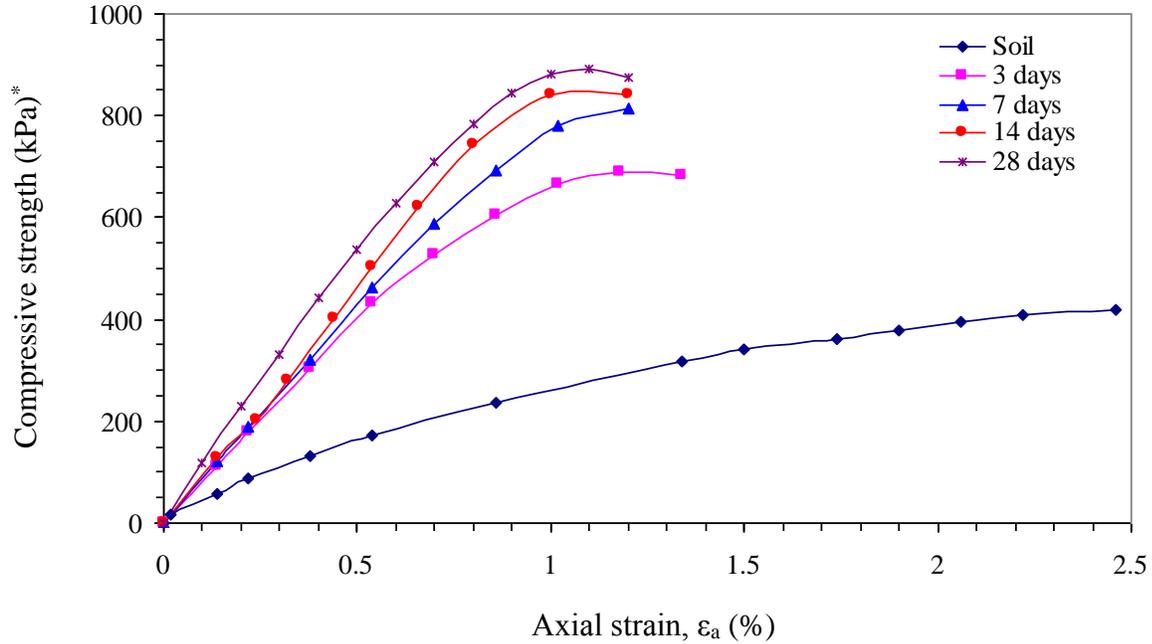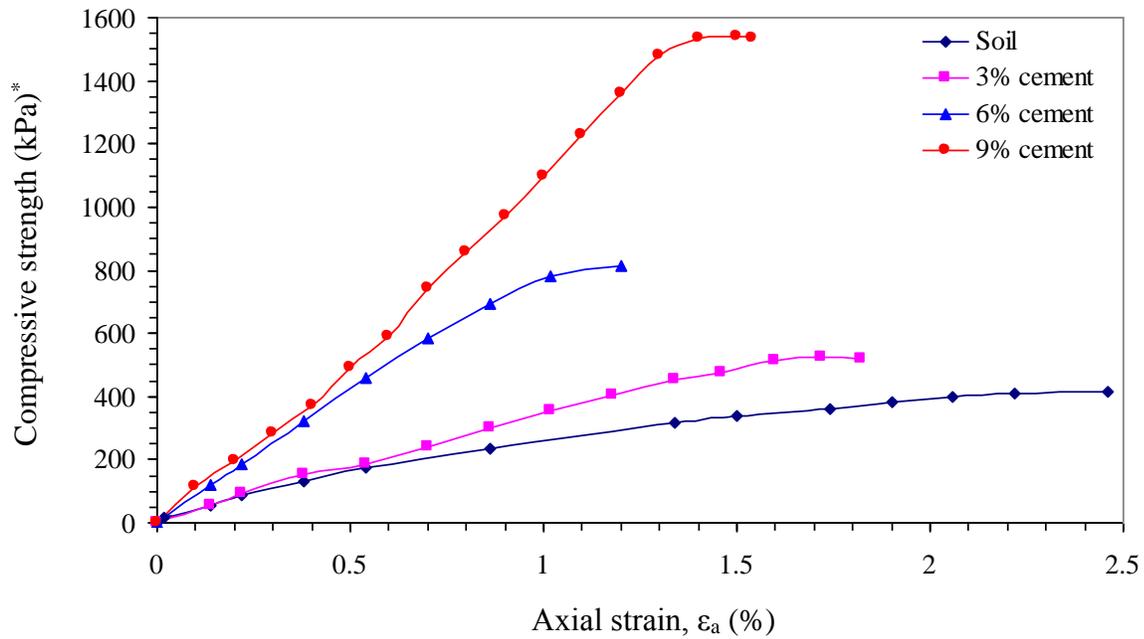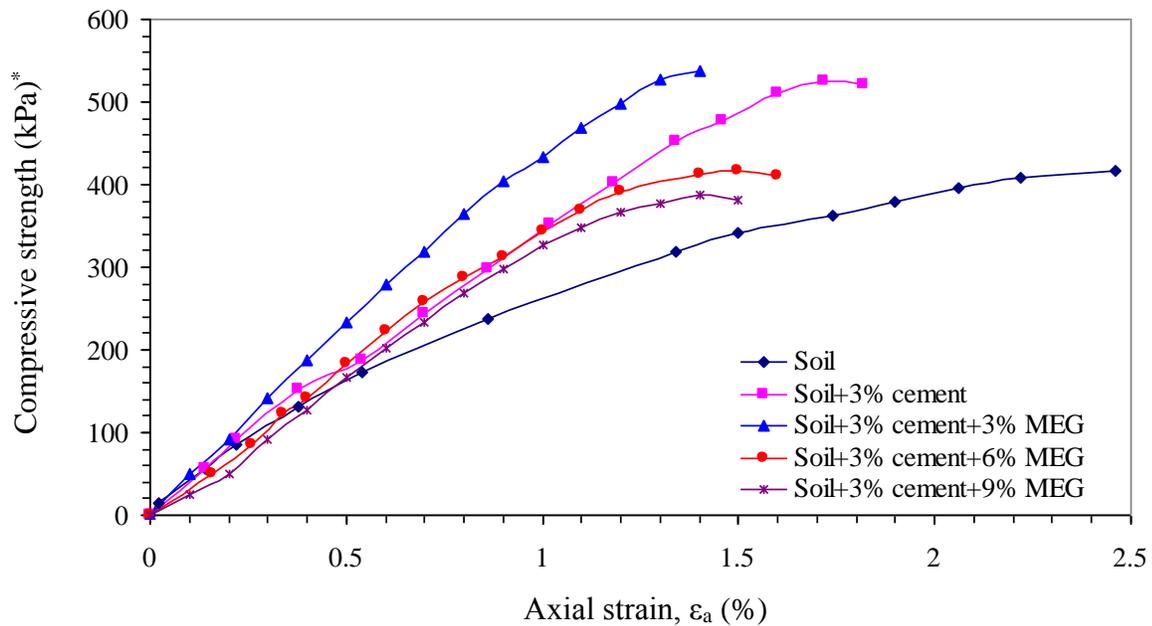
*- kN/m^3 = 6.368 pcf

Fig.3. Stress-strain curves for natural soil and soil contaminated with different percentage of MEG

*- kPa = $1.45*10^{-1}$ psi

Fig.4. Stress-strain curves for natural soil and mixture of soil with 6% cement at different curing times
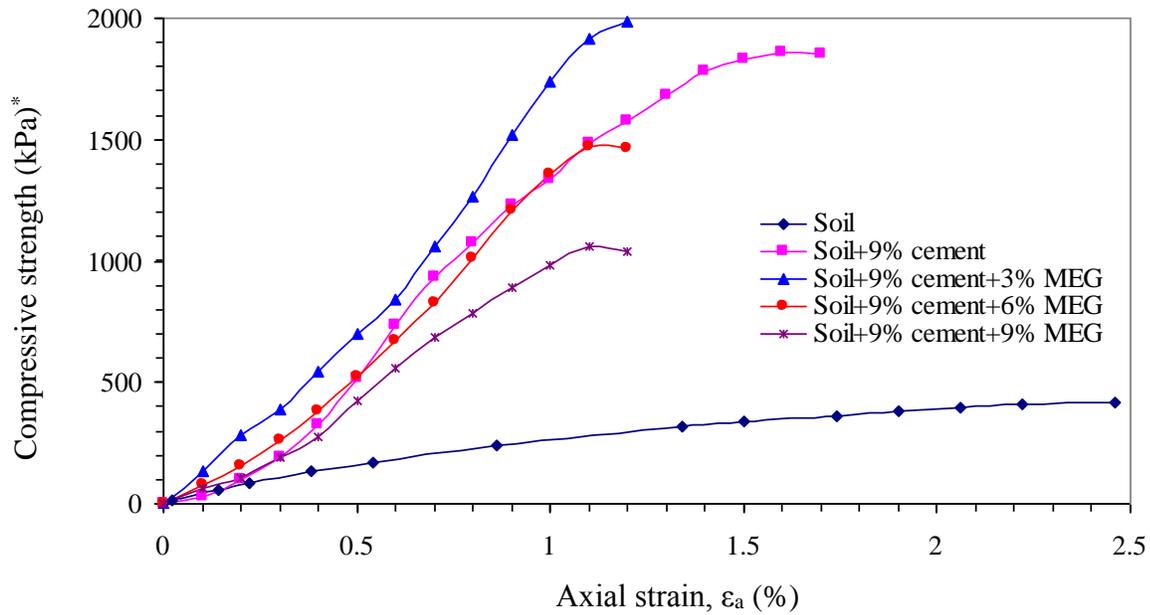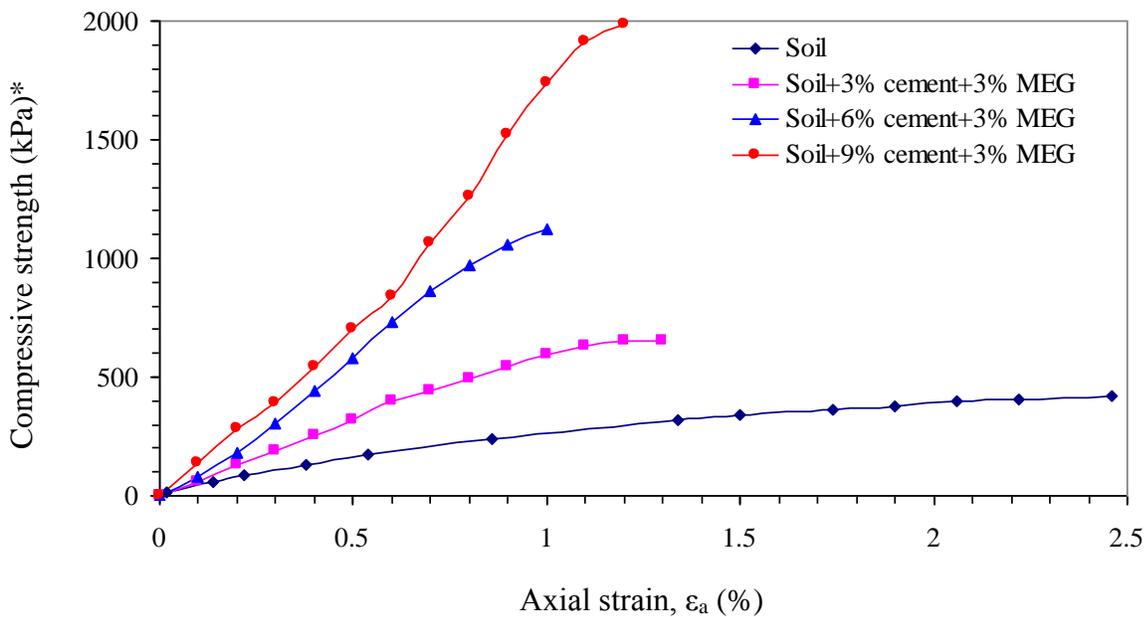
*- kPa = $1.45*10^{-1}$ psi

Fig.5. Stress-strain curves for natural soil and mixtures of soil with different percentages of cement at curing time of 7 days

*- kPa = $1.45*10^{-1}$ psi

Fig.6. Stress-strain curves for natural soil, soil with 3% cement and mixtures of soil-cement with different percentages of MEG

*- kPa = $1.45*10^{-1}$ psi

Fig.7. Stress-strain curves for natural soil, soil with 9% cement and mixture of soil cement with different percentages of MEG at curing time of 28 days
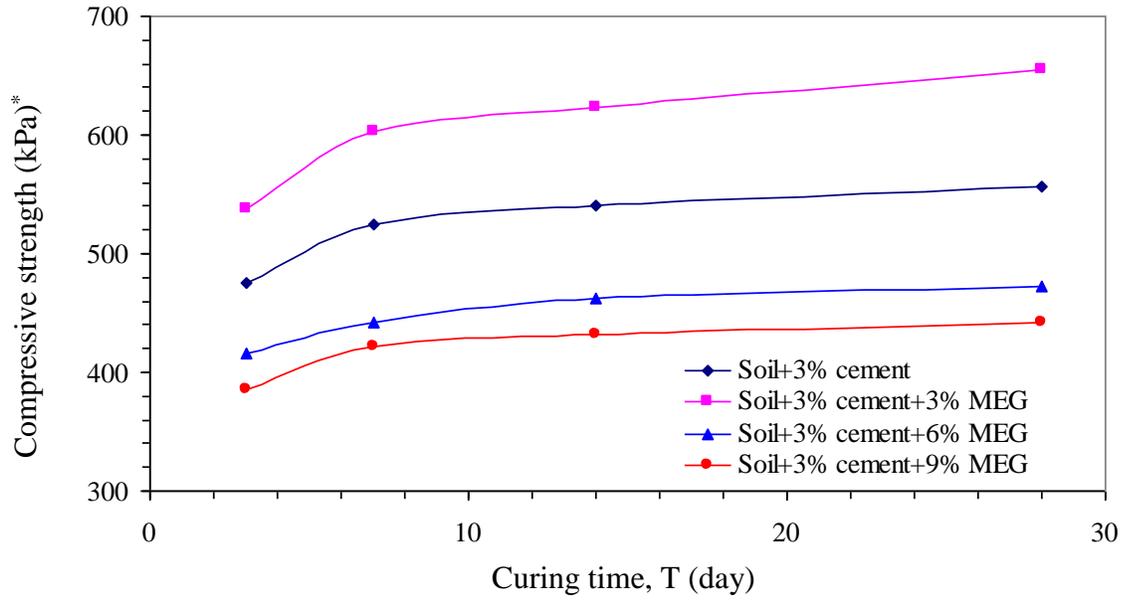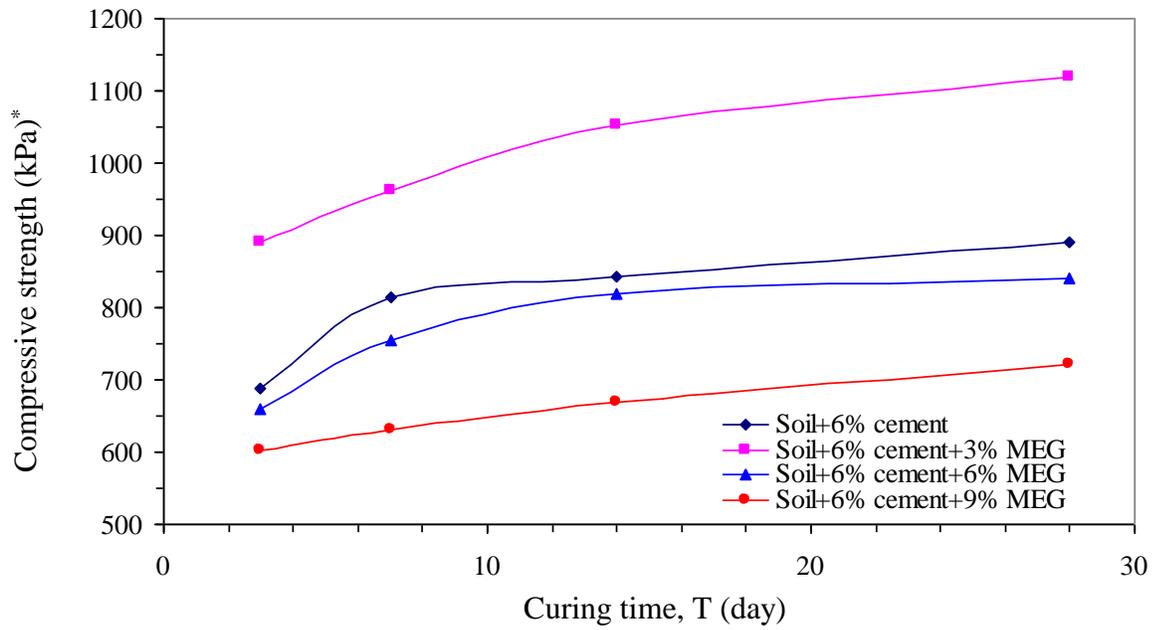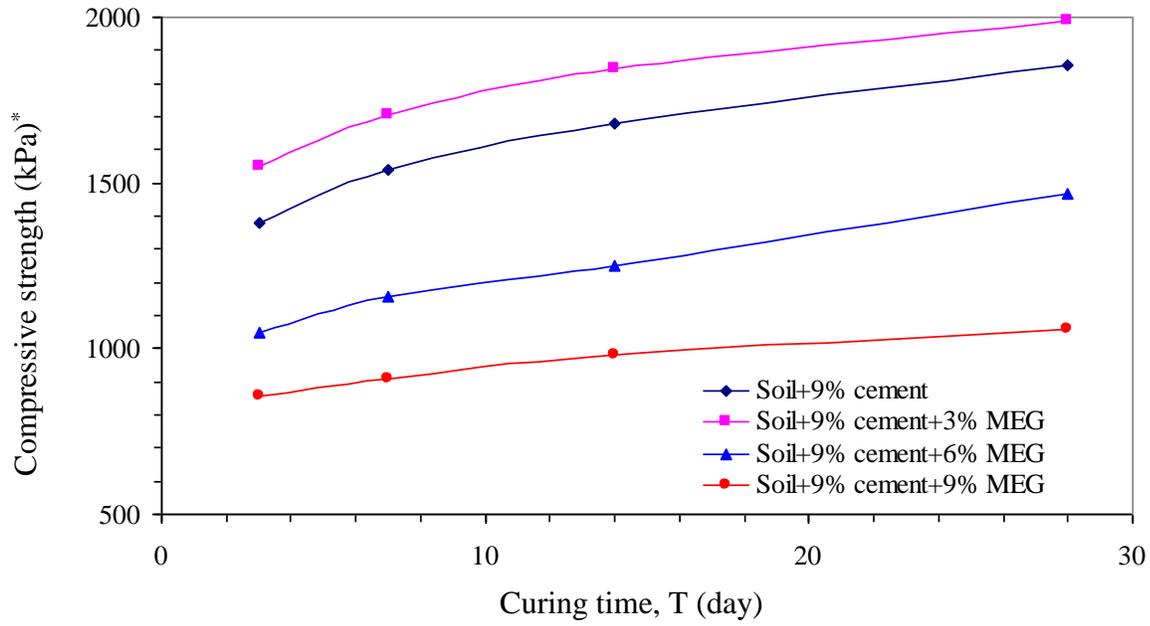
*- $kPa = 1.45*10^{-1}$ psi

Fig.8. Stress-strain curves for natural soil and mixture of soil with different percents of cement and 3% MEG at curing time of 28 days

*- $kPa = 1.45*10^{-1}$ psi

(a)

(b)

(c)

Fig.9. Strength – curing time curves **(a)** Soil with 3% cement and mixtures of soil-cement with different percents of MEG **(b)** Soil with 6% cement and mixtures of soil-cement with different percents of ethylene **(c)** Soil with 9% cement and mixtures of soil-cement with different percents of MEG

*- kPa = $1.45*10^{-1}$ psi