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Engineering Geological Properties of Oil-Contaminated Granitic and Metasedimentary Soils

(Sifat Geologi Kejuruteraan Tanih Granit dan Metasedimen Tercemar Minyak)

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ABSTRACT

Hydrocarbon is a light-non aqueous phase liquid or known as LNAPL. It poses environmental hazard if accidentally spilled out into the soil and water systems as a result of its insoluble nature in water. LNAPL component infiltrates into soil through pore spaces and afloat at the top of groundwater level. Some of this hydrocarbon would trap and clog within the voids, difficult to remove and costly to clean. The occurence of hydrocarbon in the soil definitely degraded the behaviour of soils in terms of engineering properties. This study aimed to investigate the engineering properties of oil-contaminated soil for two different residual soils originally developed from in-situ weathering of granitic and metasedimentary rocks. The physical characterisations of the soil were determined including particle size distribution, specific gravity test and x-ray diffraction (XRD). The engineering parameters for the contaminated and uncontaminated soils were Atterberg limits, compaction and soil shear strength (UU tests). The amounts of hydrocarbon added to soil were varied at 0%, 4%, 8%, 12% and 16% of dried weigth of soil samples. The results from the particle size distribution analysis showed that residual soil from granitic rock comprises of 38% sand, 33% silt and 4% clay while metasedimentary soil consists of 4% sand, 43% silt dan 29% clay. The mean values of specific gravity for the granitic and metasedimentary soils were 2.56 and 2.61, respectively. The types of minerals present in granitic soil sample were quartz, kaolinite and gibbsite while metasedimentary soil consists of quartz and kaolinite. The Atterberg limits value decreased as a result of increasing amount of added hydrocarbon into the soil. A similar behaviouir was observed with the values of maximum dry density and optimum water content with increasing hydrocarbon content. The overall unconsolidated undrained shear strength, C_u showed a decreasing trend with the increase in hydrocarbon content.

Keywords: Contaminated soil; engineering parameter; hydrocarbon; LNAPL

ABSTRAK

Hidrokarbon adalah bahan cecair ringan tidak larut atau dikenali sebagai LNAPL. Ia menyumbang kepada hazad persekitaran jika tertumpah secara tidak sengaja ke dalam sistem tanah dan air kesan daripada sifatnya yang tidak larut air. Komponen LNAPL meresap ke dalam tanah melalui ruang rongga dan terapung di permukaan paras air tanah. Sebahagian hidrokarbon mungkin terperangkap dan tersumbat di dalam rongga, sukar untuk dikeluarkan dan memerlukan kos bagi membersihkannya. Kehadiran hidrokarbon di dalam tanah pasti menyusutkan sifat tanah daripada segi cirian kejuruteraan. Kajian ini bertujuan untuk menyiasat sifat-sifat kejuruteraan tanah tercemar minyak bagi dua jenis tanah baki yang asalnya terbentuk secara luluhawa in-situ batuan granit dan batuan metasedimen. Pencirian tanah yang ditentukan termasuk taburan saiz partikel, graviti spesifik dan pembelauan sinar-x (XRD). Parameter-paramter kejuruteraan bagi tanah tercemar dan tidak tercemar adalah had-had Atterberg, pemadatan dan kekuatan ricih (ujian UU). Jumlah hidrokarbon yang ditambah ke atas tanah bebrbeza-beza pada 0%, 4%, 8%, 12% dan 16% bagi berta kering sampel-sampel tanah. Hasil daripada analisi taburan saiz partikel menunjukkan tanah baki daripada batuan granit terdiri daripada 38% pasir, 33% lodak dan 4% lempung manakala tanah metasedimen pulam terdiri daripada 4% pasir, 43% lodak dan 29% lempung. Nilai-nilai purata graviti spesifik bagi tanah granit dan metasedimen masing-masing adalah 2.56 dan 2.61. Jenis mineral yang hadir bagi tanah granit adalah kuarza, kaolinit dan gibsit manakala tanah metsedimen terdiri daripada kuarza dan kaolinit. Nilai-nilai Atterberg menyusut akibat peningkatan jumlah hidrokarbon yang ditambah kepada tanah. Perlakuan yang sama diperhatikan bagi nilai-nilai ketumpatan kering maksimum dan kandungan air optimum dengan peningkatan kandungan hidrokarbon. Kekuatan ricih keseluruhan tidak terkukuh dan tidak bersalir, C_u menunjukkan corak penyusutan dengan peningkatan kandungan hidrokarbon.

Kata kunci: Hidrokarbon; LNAPL; parameter kejuruteraan; tanah tercemar

INTRODUCTION

Oil spill usually occurs during transportation and poses a major environmental hazard. It is difficult and costly to remove. There are several potential sources of oil leakage to surrounding ecosystem through damaged pipeline, tanker accidents, discharges from coastal facilities, offshore petroleum production and natural seepage (Habib-ur-Rehman et al. 2007). Improper management of disused engine oil and illegal dumping of other hydrocarbon components are common practice in many developed countries.

The spillage of hydrocarbon liquid moves downward under gravity partially saturating the soil in its path toward groundwater level (Pamukcu & Hijazi 1992). For LNAPL components, they float and spread horizontally within the capillary zone. A further saturation of soil by hydrocarbon is expected to change the engineering behaviour of soil. The fabric and mineralogy is among factors that control the mechanical properties besides stress history and initial density (Blight et al. 1997). The presence of various kinds of clay minerals which are chemically active can interact differently with pore fluid. The change in engineering behaviour can be related to the change of its fabric (Gauffreau 1988; Pamucku et al. 1990; Tuncan & Pamucku 1992). Generally, hydrocarbon is more viscous than water therefore it relatively moves slower within the groundwater body. Some hydrocarbons might be trapped and clogged, reducing pore volume and led to a reduction in hydraulic conductivity of contaminated soils (Khamehchiyan et al. 2007).

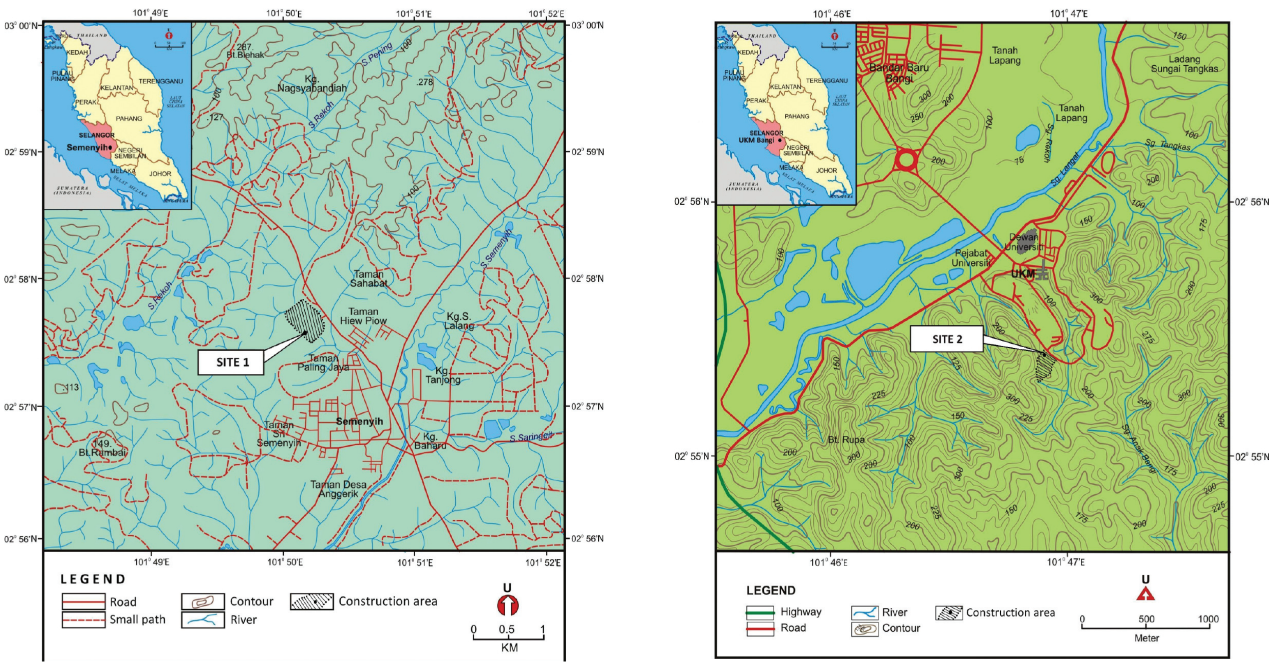
Much researches have been carried out to investigate the efffects of hydrocarbon on the engineering characteristics of oil-contaminated soil. Acar and Olvieri (1989) studied the influences of pore fluid on the fabric and hydraulic conductivity of compacted clay. They concluded that the change in hydraulic conductivity associated with the change in fabric when the molding pore fluid and permeation pore fluid are water. As a result of soil contamination, various liquids interact with chemically active soil of clay particles, altering their behaviour (Habib-ur-Rehman et al. 2007). Alsanad and Eid (1995) performed a a series of laboratory tests in order to determine the influence of oil contamination and aging effect on geotechnical properties of Kuwaiti sand. The amounts of oil added to the sand were varied and the parameters of shear strength, compressibility, permeability and compaction were determined. Aiban (1998) examined the effects of temperature on contaminated soil strength, porosity and compaction with samples collected from east Saudi Arabia. The compressibility and deformation of oil-contaminated sand increased as the temperature was increased above room temperature. The shear strength was found to be independant of testing temperature when samples compacted to their maximum dry densities. Evgin and Das (1992) performed a series of triaxial tests on contaminated and uncontaminated clean sands. The results showed that the oil saturated samples drastically reduced the friction angle for loose and dense samples. On the other hand, it apparently increased the volumetric strain. This findings also suggested that settlement of footing would increase as a result of oil contamination. Shin and Das (2001) studied the load capacity for oil partially saturated sand at oil content ranged between 0% and 6%. The results indicated that the load capacity dropped with the increase of oil content. Khamehchiyan et al. (2007) investigated the effect of crude oil on geotechnical properties of sandy-soil and clay. The results showed that the Atterberg limits decreased with the increase in oil percentage. The increase of oil content in the soil samples also caused the decrease of maximum dry density, optimum water content, porosity and shear strength.

This study aimed to investigate the effects of hydrocarbon on the engineering properties of residual soils developed from granitic and metasedimentary rocks. These earth materials are readily available and have a wide distribution in Peninsular Malaysia. Most of residual soils have been widely used in engineering practices such as embankment, foundation, liners and base material for roads. In terms of site remediation, geotechnical knowledge is essential in order to understand their behaviour and to design proper approches for removal and cleaning oil-contaminated soil schemes. Therefore it is vital to establish their response in terms of engineering behaviour and comparison was made between contaminated and uncontaminated soils.

METHODS

SAMPLE PREPARATION AND SOIL CHARACTERISATION

The soil samples used in this study were collected from two sites representing residual soils developed from *in-situ* weathering of granitic rock and sedimentary rock. The granitic soil samples were taken from Semenyih area (Figure 1(a)). The site was cleared and located close to the Jalan Semenyih. Meanwhile the latter type of soil was collected at construction site for the new Faculty of Science and Technology building at Universiti Kebangsaan Malaysia Campus, Bangi Selangor (Figure 1(b)). A hand-auger was used to obtain disturbed samples at depth 10 cm below the ground surface and kept in plastic bag. Approximately 30 kg of samples were collected for each type of soil and were air dried under room temperature for a few days. The samples were divided into 5 portions, weighing 5 kg each. The physical characterization of both soils were carried out such as particle size distribution, specific gravity and X-ray diffraction (XRD). Engine oil was used in this study to represent one of the hydrocarbon components of LNAPL. Each portion of soil sample was mixed thoroughly with engine oil at different percentages of 0%, 4%, 8%, 12%, and 16% to the dry weight of soil. The samples were kept in airtight container for 2 weeks to attain a homogeneous mixture. The samples then were used to determine the engineering properties of the soils. The tests carried out on the soil samples are accordance to BS1377 (1990).



(a) (b)

FIGURE 1. The locations of the sampling sites for the residual soils (a) UKM Bangi campus and (b) Semenyih area

ENGINEERING PROPERITIES OF SOILS

Atterberg limits Atterberg limits for fine material of soils have been used extensively in geotechnical engineering for identification, description and classification of soils and as a basis for the preliminary assessment of their mechanical properties (Khamehchiyan et al. 2007). The tests are used to establish empirical information of the soil reaction to water. It can be used to assess the mechanical behaviour of soils in natural and remolded states.

Therefore the contamination of hydrocarbon in soils might modify the soil engineering behaviour. The Atterberg limit aims to determine the minimum water contents at which soil begins to deform as a plastic or liquid (Lee & Baraza 1999). The liquid limit was determined using the Cassagrande method where the paste of soil was put in a cup and subjected to shallow drops. The water content for plastic limit was determined by rolling the soil thread until it started to crumble at about 3 mm long. The plasticity index, I_p is defined the difference between liquid limit and plastic limit. The Atterberg limits are usually presented on a plasticity chart and plotting the data between the plasticity index and the liquid limit. This chart is used to classify the soil based on different behaviours.

COMPACTION TEST

Compaction tests were performed based on a Proctor Standard compaction method (2.5 kg rammer) in order to achieve the relationship between moisture content and dry density of the soil samples. Soil samples were compacted in steel mould in three equal layers using the rammer, each layer being given 27 blows evenly distributed over the mould area. The dry maximum density and optimum moisture content were derived from the compaction curve. A similar procedure was repeated for oil-contaminated soil samples at different hydrocarbon contents.

TRIAXIAL TEST

The shear strength of the soils was studied using the unconsolidated undrained (UU) conventional triaxial tests. The samples were prepared from the compaction tests. The samples were 36 mm in diameter and 76 mm high were extruded from the compaction mould. Three different confining pressures of 140, 280 and 420 kPa were applied to the samples. Three samples were prepared for each percentage of hydrocarbon addition. The rate of strain was 2% per min which is equivalent to a starin of 1.5 mm per min. The shearing of each sample was continued until the sample had failed or until 20% of strain was achieved.

RESULTS AND DISCUSSIONS

SOIL CHARACTERIZATION

Particle size analysis showed that the granitic soil samples consisted of 64% sand, 34% silt and 2% clay while metasedimentary soil samples consisted of 34% gravel, 37% sand, 27% silt and 2% clay. It is clearly seen that the granitic soils are higher in sand percentage if compared with the metasedimentary soils. The proportions of gravel and sand in metasedimentary soils are close while granitic soils showed the highest percentage of sand. Both soil samples showed small amount of clay proportion. The particle size distribution of both soil samples is shown in Figure 2. Based on the texture classification, granitic and metasedimentary soils could be classified as sandy loam and silty clay loam, respectively.

The results from the XRD analysis on the granitic soils indicated the presence of quartz, kaolinite and gibbsite. The metasedimentary soils consisted predominantly of quartz and kaolinite. Quartz present in both soils are resistant to chemical weathering. Kaolinite minerals are the result of chemical weathering of feldspar minerals. Gibbsite minerals are directly formed from primary minerals or alteration from kaolinite. This is caused by the unstable nature of kaolinite in wet conditions. Specific gravity values for granitic and metasedimentary soils were 2.56 and 2.6, respectively.

ATTERBERG LIMITS

The results from the liquid limit and plastic limit tests for the granitic and metasedimentary soils are shown in Figure 3(a) and Figure 3(b). The results of this study were also compared with the data obtained from the basaltic soils by Noorsheila Sofhia (2009) in order to understand at the influence of hydrocarbon on different soils. The addition of hydrocarbon into the studied soils clearly affected the engineering properties of the contaminated soils. The increase in the hydrocarbon contents in soils caused the reduction of the water content at the liquid limit and plastic limit. A similar picture was also seen by Khamehchiyan et al. (2007) based on their study on sandy soils. The presence of hydrocarbon which is non-polarised liquid has caused the reduction in thichkness of water film around the clay minerals. Hyrocarbon relatively makes first contact with clay minerals instead of water. Since water is a binding agent between clay minerals and its presence around the clay mineral provides the plasticity characteristics. This would not happen if clays are surrounded by hydrocarbon. In addition, the trend of reduction of the water content at Atterberg limits with increasing hydrocarbon contents is best represented by a straight line as shown in Figure 3.

For the granitic soils the water content at the plastic and liquid limit were always below the metasedimentary soils. The metasedimentary soils seemed very close to the pattern showed by the basaltic soils studied by Noorsheila Sofhia (2009). The high value of liquid limit for the metasedimentary soils indicated that they have a higher water absorption capability if compared to the granitic soils.

The plastic index plots at different content of hydrocarbon for the granitic and metasedimentary soils are shown in Figure 4(a). The plasticity index values for the granitic and metasedimentary soils ranged between 18% and 20% and 18% and 21% of water content, respectively. The increase in hydrocarbon addition on both types of soils has not changed the placticity index values since the variable was calculated from the difference between liquid and plastic limits. The data points of the Atterberg limits from the granitic and metasedimentary soils were also plotted on the plasticity chart (Figure 4(b)). It is clearly seen that the increase in hydrocarbon content has moved the behaviour of soils to the left of the plasticity chart, reducing the water contents at liquid limits for the granitic and metasedimentary soils. The granitic soils samples fall within the CL region, suggesting that they behave as in inorganic soils of low to moderate plasticity. The metasedimentary soils are confined within the MH field indicating inorganic silts with high compressibility.

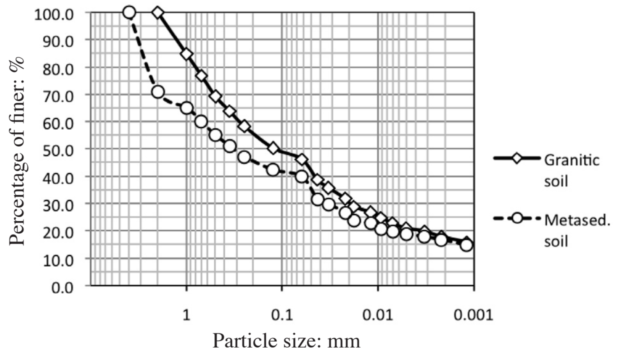
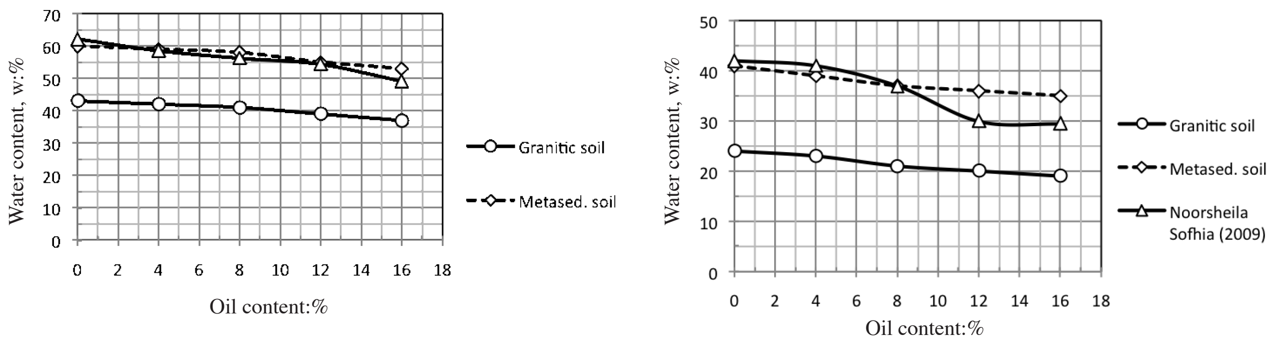
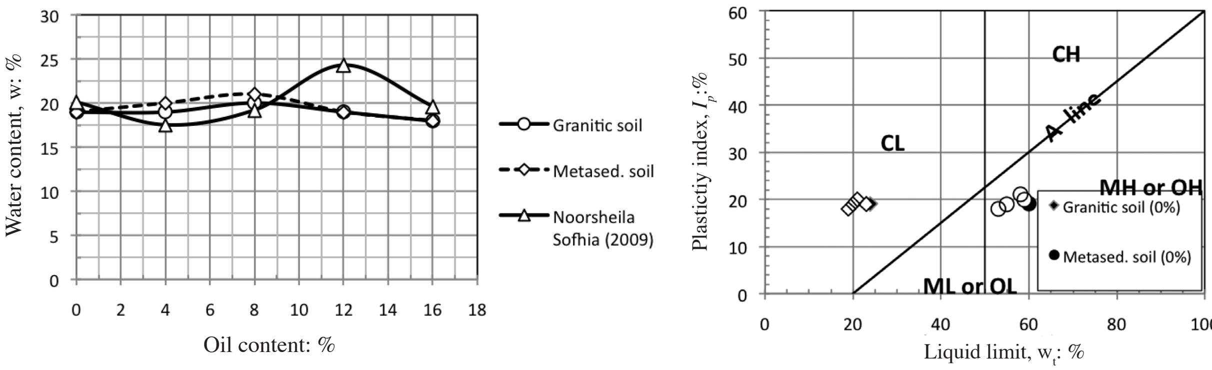


FIGURE 2. The particle size distribution curves of both types of soils



(a) (b)

FIGURE 3. Results of the Atterberg limits tests on graniti and metasedimentary soils (a) liquid limit (b) plastic limit



(a) (b)

FIGURE 4. (a) The trends of plasticity index (*w* %) and (b) data points on the plasticity chart, taken from Unified Soil Classification System. *CH*: inorganic clays of high plasticity; *CL*; inorganic clays of low to medium plasticity

COMPACTION TEST

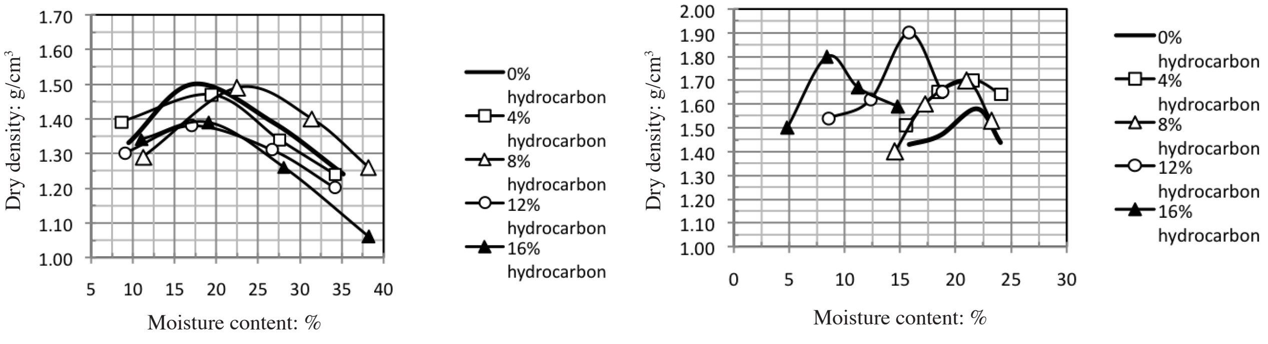
The results suggested that there were no significant changes to the water volume. Jumikis (1968) stated that compaction is a way to increase dry density of the soil by increasing the loose density and decreasing the permeability. Figures 5(a) and 5(b) shows the dry density value, $\rho_{dry\,max}$ for both samples. The maximum dry density, $\rho_{dry\,max}$ for 0% granite sample was 1.50 g/cm^3 while the optimum water percentage value w_{opt} is 17.16%. For the 4% oil-contaminated soil, $\rho_{dry\,max}$ was 1.47 g/cm^3 while the w_{opt} value was 19.39%. The 8% oil-contaminated soil, the value for $\rho_{dry\,max}$ was 1.49 g/cm^3 and its w_{opt} value at 22.46%. The value of $\rho_{dry\,max}$ for 12% oil-contaminated soil was 1.57 g/cm^3 while its w_{opt} value was 9.01%. As for the 16% oil-contaminated soil, the ρ_{drymax} value was 1.54 g/cm^3 and its w_{opt} value was 11.01%.

For metasedimentary soil, the increase in oil percentage had caused a decrease in the optimum water percentage, w_{opt} and increase in the maximum dry density value, $\rho_{dry\,max}$. The w_{opt} values for these soil samples range from 8.4% to 21.9% while its $\rho_{dry\,max}$ ranged between 1.58 g/cm^3 and 2.0 g/cm^3. Granitic samples showed w_{opt} because its particles can be easily separated by water due to its bigger sandy grain size and hence producing the lubricant to the soil. As for the metasediment soil sample, its optimum water content is low because it is a firm soil and could hardly be compacted.

SOIL SHEAR STRENGTH

Shear strength value, C_u was gained based on Mohr circle plotted based on triaxial test results (Figure 6). The trend showed that the increase in oil content has reduced the soil shear strength. This implies that the sample will be easily slipped or sheared with higher oil content when the shear strain applied. Figures 7 (a), (b) and (c) show the shear stress curves along the axis direction, σ_1 against the axial straining percentage, ε% for different amount of oil content in metasedimentary sample. Results showed that sample without oil, (0% oil) had a highest maximum stress when strain was applied under certain amount of applied confining pressure. This is followed by sample with 4%, 8%, 12% and 16% of oil. The decrease in shear stress was due to its increase in oil viscoscity and hence a decrease in grain's friction angle in the soil sample.

The total stress curves against strain at different confining pressure applied measured along the axial, σ_1 in the percentage of axial strain for granitic sample are in Figure 8 (a), (b) and (c). The figures show different shear stress associated with different percentage of oil



(a) (b)

FIGURE 5. Compaction curve for (a) granite soil and (b) for metasedimentary soil

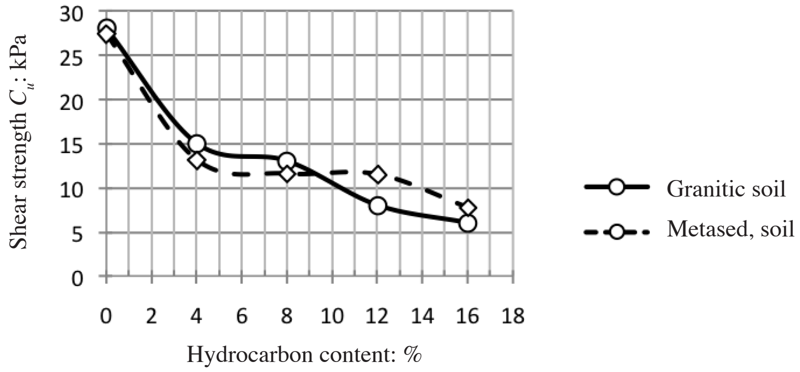
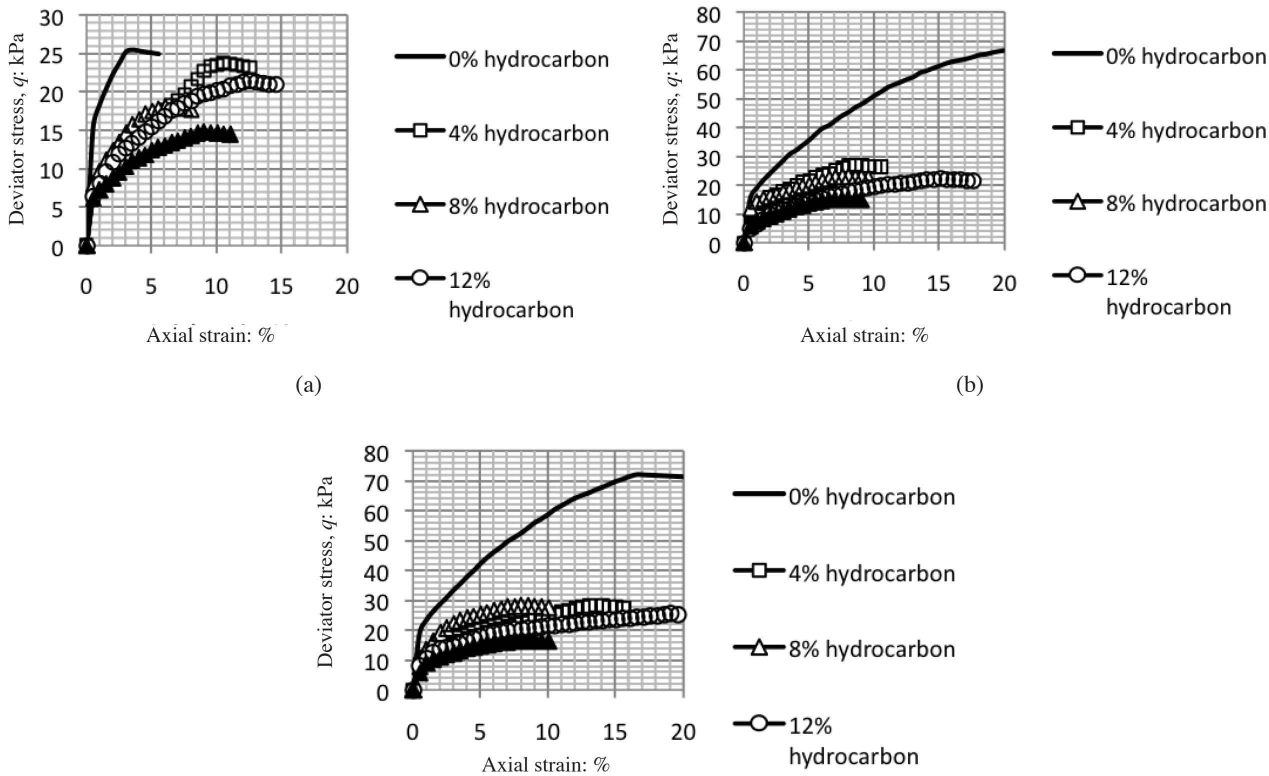


FIGURE 6. Shear strength values, C_u for granitic and metasedimentary soils



(c)

FIGURE 7. The relationship between shear stress and strain for metasedimentary soil with different applied confining pressures of (a) 140 kPa, (b) 280 kPa, and (c) 420 kPa

content in the granitic and metasedimentary soil. Sample without contamination showed the highest maximum strength followed by sample with 4%, 8%, 12% and 16% oil. The exponential curves clearly indicate the affect of oil content in reducing the shear strength of oil during the test. The presence of oil in the sample reduced the friction angle of the soil particles and hence the shear stress applied to it. The range of shear stress applied for the samples with 4% to 16% oil content were between 5 kPa and 30 kPa. The presence of oil in the samples reduces between 50% and 60% of the maximum uncontaminated metasedimentary soil shear stress values and 60% to 70% of the uncontaminated granitic soil shear stress value. This difference was probably due to the difference in soil particle sizes or the mineral content of both types of soils. The particle size difference will affect the homogeneity of the soil samples and hence the degree of frictions between the grain size.

CONCLUSION

Particle size analysis showed that granite sampel consist of 38% sand, 33% silt and 4% clay. The high sand content soil can be suitably named as sandy loam. Metasedimentary

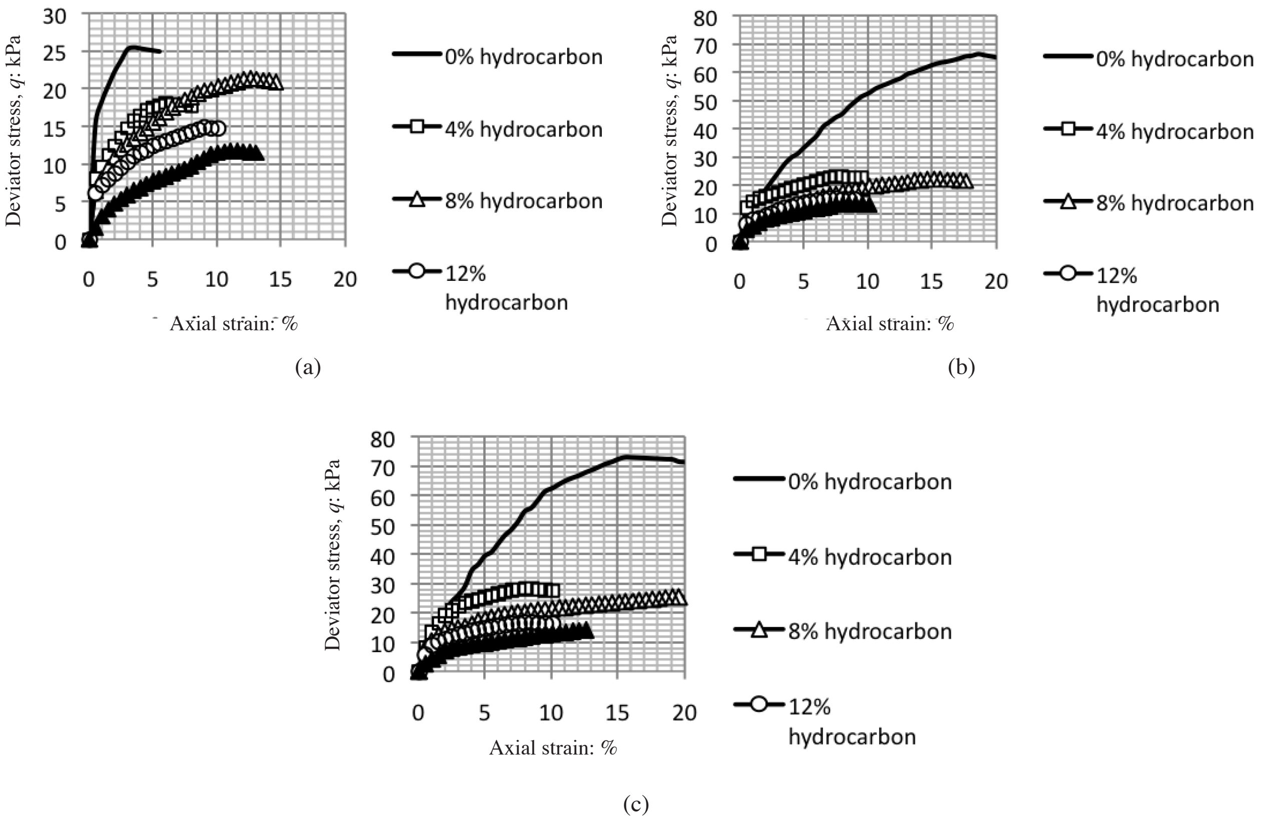


FIGURE 8. The relationship between deviatoricr stress and strain for granite soil with different applied confining pressures of (a) 140 kPa, (b) 280 kPa, and (c) 420 kPa

sample consist of 4% sand, 43% silt and 29% clay. The high clay content soil can be classified as silty clay loam. Atterberg limits decreased with increase oil content in both samples during the test. A decrease in maximum dry density, $\rho_{dry\ max}$ with increasing of oil contents for all samples were also observed in the compaction tests. The increase in oil content also decreased the water content needed to reach the maximum dry density, $\rho_{dry\ max.}$ The unconfined undrained triaxial test applied on each sample showed a decrease of C_u value with an increase in oil content.

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