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# EXPERIMENTAL MEASUREMENT OF UNDRAINED SHEAR STRENGTH OF FINE GRAINED SOIL-CRUDE OIL MIXTURES USING DIFFERENT TECHNIQUES

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## Abstract

A series of undrained shear strength tests was performed on fine-grained soil mixed with varying amounts of crude oil ranging between 0 to 14% using four different techniques including unconsolidated undrained triaxial test (UUTX), unconfined compression test (UCT), fall cone test (FCT), and laboratory vane shear test (LVT). The goal was to investigate the effect of crude oil on the undrained shear strength of fine-grained soil and to assess the measurement techniques for the purpose of establishing correlations between the undrained shear strength measured by different techniques. Results show that the soil plasticity increases with the crude oil up to 5% then slightly decreases for higher crude oil content. The maximum reported increment in the soil plasticity is 190% at 5% crude oil content, then decreases for higher crude oil content. Results show a decrease in undrained shear strength because of crude oil additive. The slope of reduction in undrained shear strength decreases for crude oil content more than 2%. For the four measurement techniques, the results show that the behaviour of undrained shear strength is the same for the tested soil specimens, but the magnitude is different. It is observed that the FCT underestimates the undrained shear strength by approximately 20% in comparison to that measured by UUTX. The closest results of undrained shear strength to the Triaxial test are the unconfined compression test. Quantitatively, it is found that UCT underestimates the undrained shear strength by only 5% in comparison to that measured by UUTX. Correlation factors were developed for the four techniques so that they are useful for practicians to convert the undrained shear strength among different techniques.

Keywords: Crude oil, Fine grained soil, Undrained shear strength.

## 1. Introduction

In oil-producing countries such as Iraq, there is a possibility to a certain level that the surface and subsurface soils nearby oil refineries, extraction wells, transportation lines and oil storage tanks are getting contaminated with crude oil or one of its derivatives. Oil contamination can be occurred intentionally during wars or not intentionally because of natural disasters, accidents, and drilling. These activities may cause leakage in transportation tankers, above and underground oil storage tanks and the transmission pipes resulted in releasing oil into the surrounding soil and causing soil contamination. Soil contamination above a certain level is considered a serious concern to geotechnical engineers. It basically cannot be overlooked because it may cause to adversely alter the soil geotechnical properties [1].

In Kuwait, Al-Sanad [2] reported that storage tanks and well heads were destroyed during the gulf war between 1990 and 1991. In United States of America, Patel [3] stated that even though a good storage tanks maintenance, leakage from the storage tanks could be occurred and polluted the under footing and surrounding soils. Prasanna and Manoharan [4] reported that approximately 10% of daily world produced oil is entering the environment and the ground as contaminants. These examples and reports infer that the soils get contaminated and research studies should be performed to investigating the problem and seeking for mitigation. The effects of crude oil or one of its derivatives on geotechnical properties such as soil physical and index properties, mechanical properties, and hydraulic properties have been covered in literatures for both coarse-grained soils and fine-grained soils, however, the undrained condition of fine-grained soils have not been comprehensively studied leaving a gap of knowledge to be filled.

In geotechnical problems, either total stress analysis or effective stress analysis is usually applied depending on loading and drainage conditions. For coarse-grained soils, effective stress analysis is used under static load because the sands are free draining so that the excess pore water pressure dissipates quickly [5]. On the other hand, for fine-grained soils, total stress analysis should be used for short term condition (i.e., during and immediately after construction) because fine-grained soils do not have sufficient time for the excess pore water pressure to dissipate. However, for long term condition, effective stress analysis should be applied because there is sufficient time for the excess pore water pressure to dissipate under static load. Because crude oil or one of its derivatives may affect the soil fabric, the decision of using the effective stress analysis or total stress analysis should be changed accordingly under the same loading condition. It is to be expected that the crude oil or its derivatives affect the shear strength parameters used for both the total stress analysis and effective stress analysis. For instance, in sand, there is an agreement among researchers that the presence of crude oil or its derivatives as a pore fluid reduces the soil effective angle of internal friction ($\emptyset'$).

It was reported that the amount of reduction is a function of oil viscosity, soil texture, soil gradation, and degree of contamination [1, 6-13]. For fine-grained soils, there is an agreement among some researchers that the presence of crude oil or its derivatives lead to increase the effective angle of internal friction ($\emptyset'$) and reduce the soil effective cohesion ($c'$) [14-17]. However, Shah et al. [18]; Safehian et al. [19]; Salimnezhad et al. [20] found that both angle of internal friction and effective cohesion reduced as the crude oil increased. Interestingly both groups agreed that the shear strength of fine-grained soils decreased as the contaminated content increased [17, 21-27].

Only few research has been studied the effect of crude oil on undrained shear strength ($S_u$), a parameter used for total stress analysis (short term condition) of clayey soils [28]. It was found that the undrained shear strength ($S_u$) of the soil was considerably reduced with the oil content and the reduction depended on the degree of contamination because added oil could lubricate the surfaces of clay particles, and consequently it caused to reduce the undrained shear strength ($S_u$). This possible reason needs further research to be verified. Not only the lack of research on undrained shear strength of oil contaminated fine-grained soil, but also the inherent variability of the undrained shear strength ($S_u$) [29] have encouraged to conduct further research on this topic.

The objectives of the current research are to investigate the effect of crude oil on soil plasticity, as it considers a simple and easy way to preliminary predict soil strength via correlations [30], and on the undrained shear strength ($S_u$) of clayey soil. It is also to provide comparison between the undrained shear strength ($S_u$) measured by different techniques.

Moreover, it is to establish correlations between the undrained shear strength measured by different techniques to help geotechnical designer to select appropriate undrained shear strength values regardless the measurement technique used to obtain these values. To achieve these objectives, an efficient laboratory-testing program was conducted on the clayey soil and clayey soil-crude oil mixtures to measure the undrained shear strength ($S_u$) of soils using unconsolidated undrained triaxial test (UUTX), unconfined compression test (UCT), fall cone test (FCT), and laboratory vane shear test (LVT).

## 2. Materials Characterization

The soil used in this study was obtained from Erbil city- Iraq. It was collected from a depth of about 1m below the ground surface. Physical soil properties were measured according to ASTM standards and results were presented in Table 1. According to the Unified Soil Classification System, the soil was classified as a low plasticity clayey soil (CL) as shown in Table 1.

**Table 1. Soil properties used in the study.**

| **Soil properties** | | **Standard Specifications** | **Value** |
|---|---|---|---|
| Specific gravity, Gs | | ASTM D-854 | 2.7 |
| Atterberg Limits | Liquid limit, LL (%) | ASTM D-4318 | 37 |
| | Plastic limit, PL (%) | ASTM D-4318 | 22 |
| | Plasticity index, PI (%) | | 15 |
| Unified soil classification system (USCS) | | | CL |
| Compaction characteristics | Maximum dry density (g/cm$^3$) | ASTM D-698 | 1.985 |
| | Optimum water content (%) | | 13.9 |

Crude oil was brought from Khurmala oil field in Erbil province and used as an additive mixed with the clayey soil. The laboratory tests were performed to measure the properties of crude oil and the results were shown in Table 2.

**Table 2. Crude oil properties.**

| Sample | Flash Point $^0C$ | Density @ $25^oC(g/cm^3)$ | $^0$API* | Viscosity (Cp) |
|---|---|---|---|---|
| Kar Refinery | 53 | 0.849 | 23.261 | 18.2 |

*API: American Petroleum Institute

The mixing procedure of soil with the crude oil was done by mixing an oven dry soil with specified percentages of crude oil. The specified percentages of crude oil used in the current study were 0, 2, 5, 8, 11, and 14% by weight of dry soil sample. The mixing process was done by adding the crude oil to the sample and thoroughly mixed by hand, then the mixture was placed in a sealed plastic bags and stored for 30 days for allowing aging, homogeneity, and possible reactions between crude oil and soil to be occurred Khamehchiyan et al. [14].

## 3. Methodology

### 3.1. Consistency limits test

The clayey soil was sieved on No.40 (0.42 mm) for performing the consistency limits tests. The consistency limits tests were performed for both clayey soil and clayey soil-crude oil mixtures according to ASTM D4318 [31]. Crude oil was mixed with clayey soil samples in percentages of 0%, 2%, 5%, 8%, 11% and 14% by dry weight following the procedure explained above. The liquid limit (LL) and plastic limit (PL) tests were conducted in accordance with the ASTM D4318 standards [31] and plasticity index (PI) was calculated from the expression of PI = LL - PL.

### 3.2. Compaction test

Standard Proctor compaction test (ASTM D698) [32] was carried out on both clayey soil and on clayey soil-crude oil mixtures samples. The soil samples were first mixed with varies crude oil percentages of 0, 2, 5, 8, 11, 14% following the procedure explained previously. For each crude oil content, five samples were prepared at different water contents to obtain the optimum moisture content and maximum dry density associated with each crude oil content. Figure 1 shows graphically the shapes of compaction curves and how they change with varying crude oil percentage. The results of the compaction test presented in Fig. 1 show that as crude oil increases, compaction characteristics of soil represented by optimum moisture content (OMC) and maximum dry density decrease. Quantitatively, results show that the maximum dry density decreases from 1.948 $g/cm^3$ for uncontaminated soil to 1.859 $g/cm^3$ for soil contaminated with 14% crude oil. The associated optimum water content was also decreased from 13.9% for uncontaminated soil to 5.1 for 14% crude oil content. It is observed from the results that the presence of oil reduces the amount of water needed to reach maximum dry density. This result is confirmed by the findings reported by [14; 22; 33; 34]. The recent study reported by [33] using the concept of flocculation / dispersing to explain the compaction behaviour due to contamination. At various level of oil contamination, the flocculation of contaminated soils was different, resulted in different compaction behaviour. When water was added to contaminated soils, clay particles in the soil were dispersed. Contaminated soils with more oil content required less water to reach the optimum value because soil pores had already included oil. As oil content increases, lower water content is required for deflocculating the contaminated soil and reaching the maximum dry density.

A study by [34] using the different concept which is the coating and diffuse double layer to explain the reduction in maximum dry density and optimum moisture content with increasing oil content. They stated that crude oil is a hydrophobic and when it is mixed with the soil, it coats the particles of clay and disallows free water from interacting with them. Therefore, as crude oil content increased, less water was needed to reach the optimum moisture content. It was found that using the same compaction effort for uncontaminated and contaminated soil samples, the maximum dry density of soils decreased as the oil content increased. This is because crude oil entering to pore fluid caused to increase the thickness of the diffuse double layer, resulted in the soil particles were gotten less packed and consequently, the maximum dry density decreased.

The obtained compaction curves results presented in Fig. 1 were adopted for preparing all the soil specimens used for undrained shear strength measurements. In fact, all the specimens used for undrained shear strength measurements were prepared at the maximum dry unit weight and associated crude oil-water content as explained in detail in the following section.

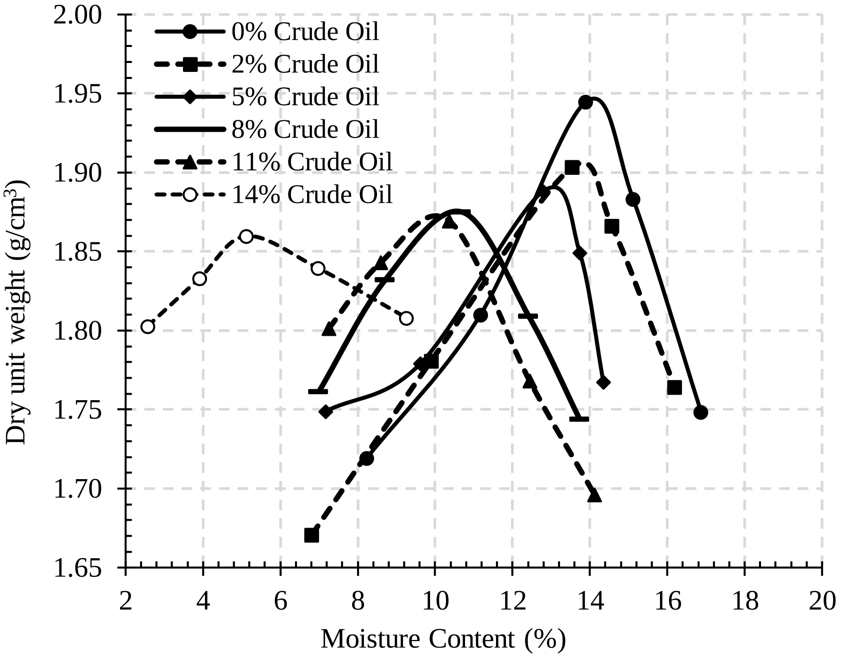

**Fig. 1. Compaction curves of clayey soil-crude oil mixtures.**

## 3.3. Undrained shear strength tests

### 3.3.1. Triaxial test

Unconsolidated Undrained Triaxial tests (UUTX) were conducted using the UTM-0108.SMPR Triaxial Testing Machine manufactured by UTEST Company. For each soil sample, firstly, specified percentages of crude oil including 0, 2, 5, 8, 11, 14% were added to oven-dried clayey soil samples. The mixtures were thoroughly mixed following a procedure explained previously. Water was added to the mixture at the optimum moisture content associated with each crude oil content as presented in Fig. 1. The mixtures were placed into sealed plastic bags for 24 hours [35]. Following ASTM D2850 [35] procedure, a cylindrical mold having a diameter of 5.0 cm and height of 10 cm was assembled on triaxial base and the soil was compacted dynamically in 10 equal layers using tamping method. Before saturation process started, a 10 kPa effective stress had been applied and maintained during saturation process.

A total of eighteen specimens were tested under UUTX testing condition. Three specimens of each crude oil percentage were tested at different effective confining stress of 50, 100, 200 kPa. After saturation, the specimens were sheared under UU triaxial tests.

### 3.3.2. Unconfined compression test

Unconfined compression tests (UCT) were conducted using the automated Geocomp LoadTrac II Test System Uniaxial Testing Machine manufactured by Geocomp Company. The clayey soil and clayey soil-crude oil mixtures were prepared using the same procedure as the Triaxial tests, but the testing procedure is different. After the completion of compaction process, the specimen was placed on the testing machine base and a small amount of uniaxial load was applied. The specimens were sheared under uniaxial loading condition. In this testing condition, the specimen experiences no confining stress in which it considers a special case of undrained condition. In current study, tested specimens were sheared under a strain rate of 1.27 mm/min [36].

### 3.3.3. Fall cone test

The clayey soil was sieved on No.40 (0.42 mm) for performing the liquid limit tests using the fall cone equipment according to British Standard (BS 1377) [37]. The results were adopted to empirically estimating the undrained shear strength of soils using Eq. (1) [38]

$$s_u = k\frac{m}{d^2} \tag{1}$$

where $m$ is the cone mass (g), $d$ is the cone penetration depth (mm), and $k$ is a constant that is a function of the cone angle (for a cone angle of 30°, $k$=0.85).

The soil samples of clayey soil and clayey soil-crude oil mixtures were prepared with different crude oil contents of 0, 2, 5, 8, 11, and 14% following the procedure explained previously. Then, the mixture was mixed with water at the optimum moisture content. The mixtures were placed in sealed plastic bags for homogeneity.

The ELE fall cone device with a 30° cone and 0.785 N weight was used. The dimensions of the sample cup were a diameter of 55 mm, and a height of 40 mm. Prepared sample was placed into fall cone cup using a spatula and compacted to the maximum dry unit weight. The surface of the cup was levelled using side of a straight edge to obtain a smooth surface. Finally, the sample was put on the device base and ensuring that the cone tip is barely touching the surface of the tested sample. At the end of five second penetrating time, the penetration distance was measured. At least three trials were performed to check the repeatability of the tested samples.

### 3.3.4. Laboratory vane shear test

The tests were conducted using Laboratory vane shear Apparatus (LVT) manufactured by Wykeham France. The LVT device has blades with the dimensions of 12.5 mm in diameter, 25 mm in height and 0.01 mm in thickness. The soil samples of clayey soil and clayey soil-crude oil mixtures were prepared with different crude oil contents of 0, 2, 5, 8, 11, and 14% using the same procedure as for the fall cone test, but the testing procedure is different. After the completion of specimen preparation, the specimen was put on the base of the vane device with blades were barely touching the soil sample surface. A constant testing rate of blades rotation was used. The experiments were performed three times for repeatability. The undrained shear strength was calculated using Eqs. (2) and (3) presented in ASTM D2573 [39] given below.

$$s_u = \frac{T}{K} \tag{2}$$

$$K = \frac{\pi D^2 H}{2}\left[1 + \frac{D}{3H}\right] \tag{3}$$

where $T$ is a Torque, $K$ is a vane coefficient, $D$ is the width of blades, and $H$ is the height of blades.

## 4. Results and Discussions

### 4.1. Effect of crude oil on Atterberg limits

The Atterberg limits of clayey soil and clayey soil-crude oil mixture are graphically presented in Fig. 2. The figure shows clearly that the liquid limit (LL) increases as the crude oil percentage increases up to 5% then it decreases slightly for higher crude oil percentage. Then it approximately levels off at crude oil of higher than 8%. Quantitatively, at 5 % crude oil, the reported LL is 58%. This value is approximately 1.57 times the LL of uncontaminated soil. The plastic limit (PL) also increases with the crude oil content. It is also reported that the PL increases by 1.3 for crude oil of 2%. For higher crude oil content (5 and 8%), the PL increases only slightly, followed by a significant increase for crude oil of 11% afterword, the trend levels off. The plasticity index (PI) of the clayey soil-crude oil mixtures increases with the crude oil up to 5%. The maximum reported PI value is 29% at 5% crude oil content. This value is approximately 1.9 times the PI of uncontaminated soil. For higher crude oil content, the PI decreases and it approximately levels off at crude oil higher that 11%. It is noticed that the results of the LL and PI follow the pattern observed by [17; 40]. In literature, different theories were adopted to explain the response of the Atterberg limits to oil contaminants. For instance, a study by [17;41] adopted a theory of viscous nature of pore fluid. They stated that a thin oil layer shared with adjacent clay particle served as a viscos interface which helped the clay retain its structures under its own weight and cause to increase LL. However, for high oil content, a thicker layer would be formed and exceeded a critical value. Consequently, clay particle would slip on each other and cause to reduce the LL. Other research studies, on the other hand, stated that the increase in LL is due to extra cohesion provided because of contaminants [42].

For plastic limit, diffuse double layer theory was adopted to explain the response of the PL to the oil content. It is common knowledge that water molecular is dipolar and it is attracted to the cations in double layer and negatively charged clayey particle surface, consequently, hydrogen bond will be formed. Water in clay can be double layer water, water held by attraction force to the clay particle, absorbed water, water held strongly by clay particles and governs the plastic properties of clay [43]. The process of adding crude oil to the clayey soils would cause to cover clay particles and does not permit water molecules to reach the double-layer water, resulted in more water is needed for the soil to obtain plastic properties [15]. These results agree with the finding of [15, 33, 34, 41, 42, 44] but it is in contrast with the findings of [14; 22; 23], who cited that the Atterberg limits decreased with increasing oil content in low plastic soils.

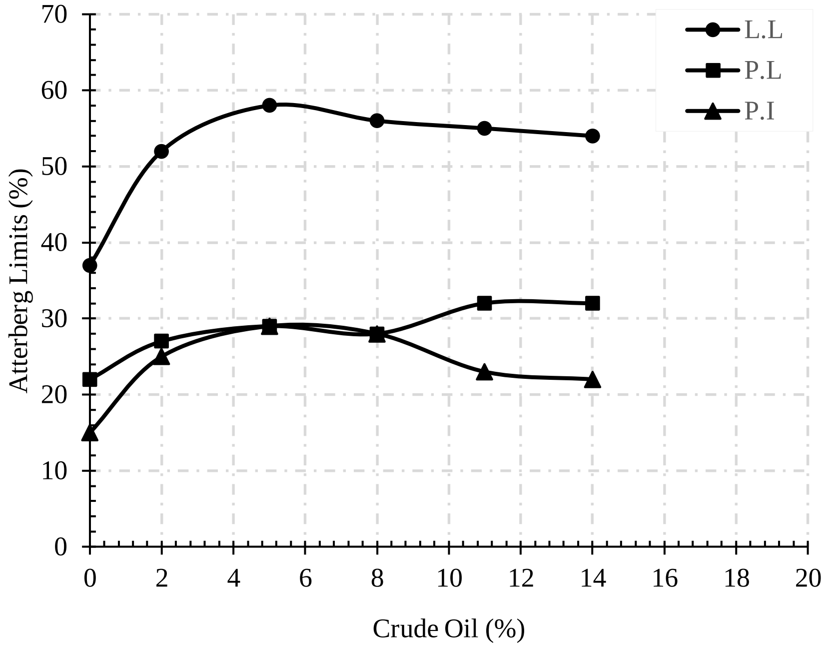

**Fig. 2. Atterberg limits of clayey soil-crude oil mixtures.**

It is noted that the crude oil affects the geotechnical classification of clayey soil as shown in Fig. 3. Figs. 3(a) and (b) show the plasticity charts with the incorporation of the Unified Soil Classification System (USCS) and American Association of State Highway and Transportation Officials (AASHTO), respectively. Mixing crude oil with soil caused micro-structural transformation of the soil from clay particle to more like a silty soil at higher crude oil content [42]. The clayey soil uses in this study is classified as CL based on USCS. The classification alters from CL to CH for the 2, 5, and 8% crude oil content and it changes to ML for higher crude oil content (i.e. 11, and 14%). Alternative and more common soil classification type used particularly in road design and construction works is the AASHTO classification system. The suitability of the materials could be assessed using such soil classification system. For instance, it is found that soil classification changed to A-7-6 for the 2, 5, and 8% crude oil content and it changes from A-6 and A-2-6 to A-7-5 and A-2-7 for higher crude oil content (i.e. 11, and 14%) and the group index (GI) of the mixture is higher than that of clayey soil. This finding shows that the clayey soil-crude oil mixtures become less suitable as a base or sub-base material than the clayey soil.

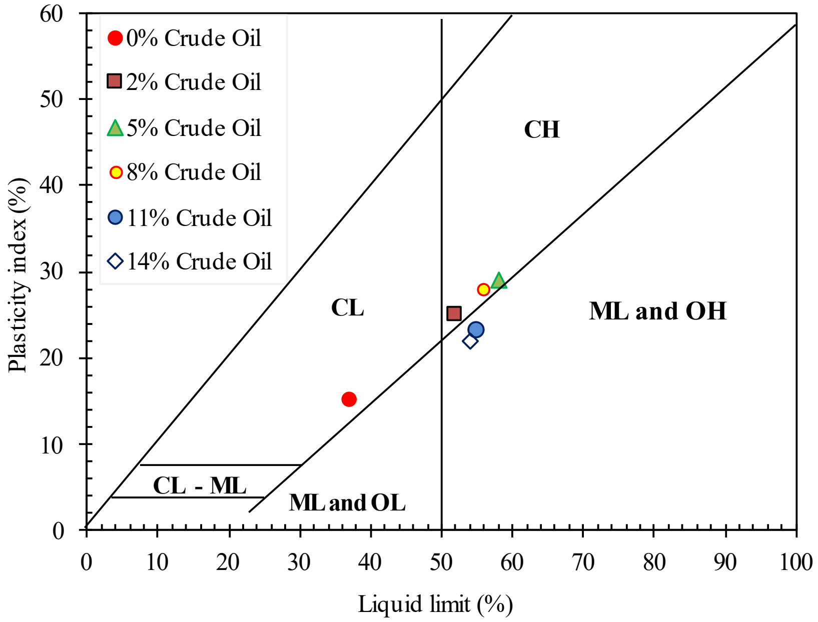

**Fig. 3 (a). Soil classification of clayey soil-crude oil mixtures using USCS.**

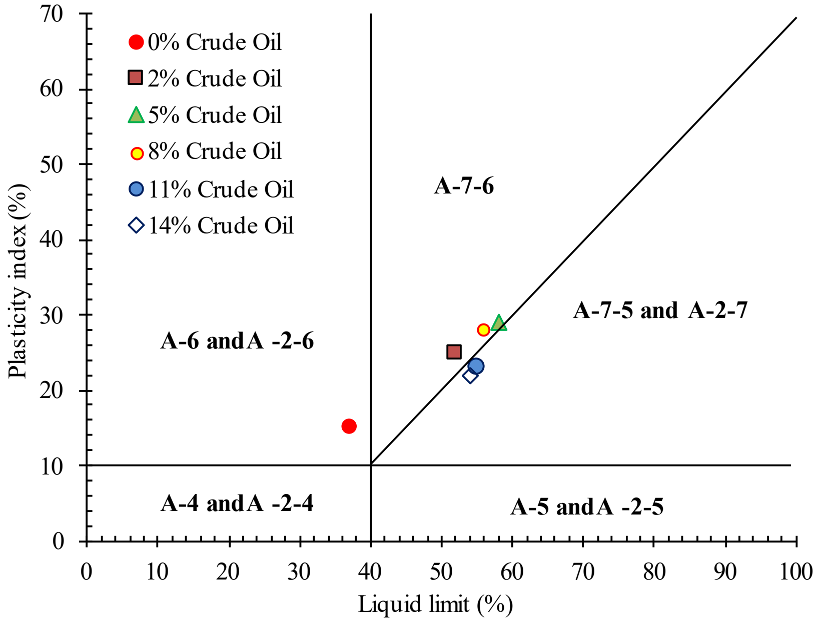

**Fig. 3 (b). Soil classification of clayey soil-crude oil mixtures using ASHTTO.**

## 4.2. Effect of crude oil on undrained shear strength

### 4.2.1. Unconsolidated undrained triaxial test

The unconsolidated undrained Triaxial tests (UUTX) of both clayey soil and clayey soil-crude oil mixtures were performed and the results were presented in Figs. 4 and 5. The stress-strain curves presented in Fig. 4 show that the values of the deviator stresses are unaffected by the confining stress for both clayey soils and clayey soil-crude oil mixture specimens implying that the friction angle is zero and the soil strength only contributes from the cohesion part. It is clearly shown that the soil specimens with 0% crude oil content achieve a higher value of deviator stress in comparison with the clayey soil-crude oil mixture specimens. It is also observed from the figure that a strain hardening-softening behaviour for low confining stress and low crude oil content forming a peak at axial strain ranging between 6-8%. For higher confining stress and higher crude oil content, the peaks disappear and a strain hardening behaviour is observed. Moreover, it is observed that the deviator stress at failure and the associated axial strains decrease as the oil increases.

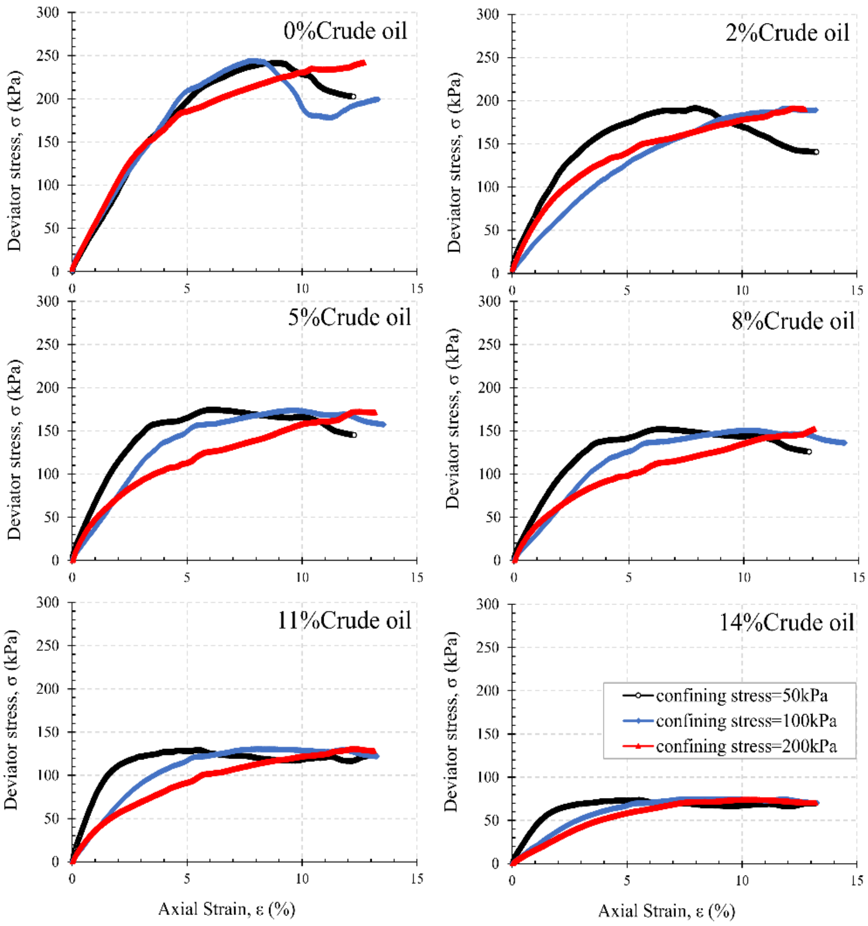

**Fig. 4. Stress-strain curves of clayey soil-crude oil mixtures measured by UUTX.**

The undrained shear strength from triaxial test ($S_{u(TX)}$) was extracted from Mohr circles assuming that the friction angle($\emptyset' = 0$), a condition where the soil assumed to be fully saturated [45]. The results of undrained shear strength at different confining stress and different crude oil content are presented in Fig. 5. The effect of crude oil on the undrained shear strength of clayey soil is clearly shown in Fig. 5. It is noted that the undrained shear strength calculated from Mohr circles is reduced by about 20.7% for 2% crude oil in comparison with the 0% crude oil content. For higher crude oil content, a less reduction amount in the $S_{u(TX)}$ is reported. For a maximum crude oil content (14%) used in this study, it is reported that a 60.3% reduction in $S_{u(TX)}$ in comparison with the 0% crude oil content. These results confirm the finding reported in literature by Karkush and Jihad [44] and Salimnezhad et al. [20]. This can be explained by a combination of two mechanisms. The first one is the physicochemical interaction between oil-water and clay particles caused by change of pore fluid dielectric constant. The electrical double layer is formed when mineral grains interact with the pore fluid, resulted in decrease in soil undrained shear strength. The second mechanism is due to pore fluid-mineral interactions changes which cause to a reduction in frictional properties at particle contacts. This effect can be estimated in terms of pore fluid viscosity. An increase in pore fluid viscosity due to crude oil contamination changes the properties of mineral-to-pore fluid contacts and cause a reduction in soil undrained shear strength [46]. Another possible reason is that the presence of crude oil will partially or fully coat soil particles and consequently, the interparticle slippage increases and subsequently, the undrained shear strength will decrease [47]. Similar findings were reported by Ur-Rehman et al. [42].

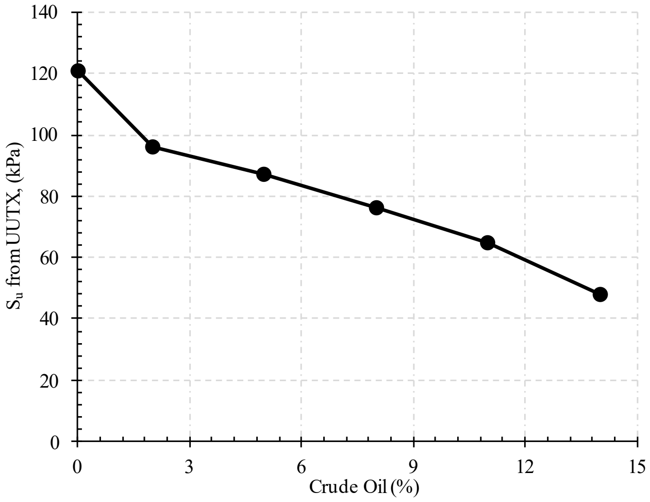

**Fig. 5. Undrained shear strength (Su) with crude oil using UUTX.**

### 4.2.2. Unconfined compression test

Unconfined compression tests (UCT) were carried out on clayey soil and clayey soil-crude oil mixtures to assess the effect of contamination on the stress-strain characteristics of clayey soil and on the undrained shear strength ($S_{u(UCT)}$). During shearing, an axial strain of 1.27 mm/min was applied to the specimen until failure [36]. The maximum axial stress value was an unconfined compressive strength and half of the value was reported as the undrained shear strength ($S_{u(UCT)}$). Figure 6 shows the stress-strain curves of both clayey soil and clayey soil-crude oil mixtures. The strain-hardening/softening behaviour is observed for tests. Peak values are generally exhibited at low axial strain of about 2.5-4.5 %. Stress-strain features are a function of the level of oil content. With exceptional to 2% crude oil content, distinct peak strength at lower strain is observed for higher oil content resulted in higher initial elastic modulus or stiffness. It is also observed that for the highest crude oil content used, a drastic reduction is observed after peak failure, indicating that the specimens lost its residual strength (brittle failure). Some of the results agree with literature [14]. However, some of the findings vary from those on literatures. This variation could be due to the fact that fine grained soils consist of different compounds and different types of minerals such that the degrees of interactions with oils will be, consequently, different [17].

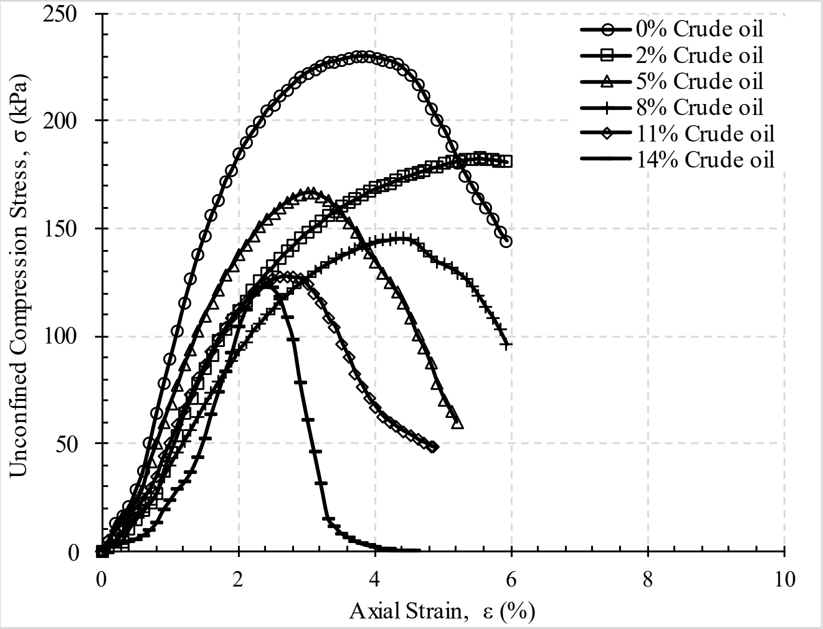

**Fig. 6. Stress-strain curves of clayey soil-crude oil mixtures measured by UCT.**

The undrained shear strength ($S_{u(UCT)}$)) was plotted against the crude oil content as shown in Fig. 7. Clearly shown that the soil specimens mixing with 0% crude oil achieves a higher value of $S_{u(UCT)}$) in comparison with the clayey soil-crude oil mixture specimens. It is also observed that the $S_{u(UCT)}$)) decreases slightly with the crude oil content. Quantitatively, it is found that the $S_{u(UCT)}$ values decreases from 115 to 91 kPa for 2% crude oil which is equivalent to a reduction percentage of around 20%. As the crude oil increases the reduction in the $S_{u(UCT)}$ values increases but with a less reduction percentage. For instance, at the maximum crude oil used in this study, the $S_{u(UCT)}$ decreases from 115 to 46kPa, which is equivalent to a reduction percentage in the $S_{u(UCT)}$ values of 60%. The decreases in the $S_{u(UCT)}$ could be due to lubrication action which causes weak bonding within the soil matrix caused to reduce the soil cohesion. Similar findings were observed in Oluremi et al. [40] results.

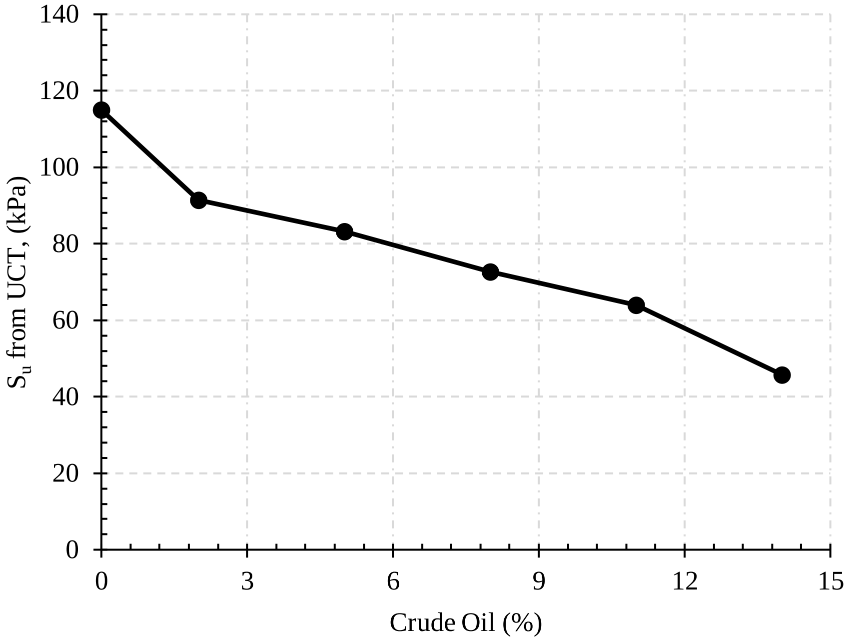

**Fig. 7. Undrained shear strength (Su) with crude oil using UCT.**

### 4.2.3. Fall cone test

Hansbo's [38] empirical equation (Eq. (1)) was adopted to evaluate the undrained shear strength of the fall cone test ($S_{u(FCT)}$) for both clayey soil and clayey soil-crude oil mixtures. Figure 8 displays the relationship between the $S_{u(FCT)}$ and crude oil content. The results show that the ($S_{u(FCT)}$) are generally decreased as the crude oil increases. Figure 9 shows that the value of ($S_{u(FCT)}$) is 98 for clayey soil mixed with 0% oil and it decreases from 77 to 40 kPa for the minimum and maximum crude oil content used in this study, respectively. The reduction percentage was quantitative relative to the 0% crude oil content, and it was found to be 21 and 59% for the minimum and maximum oil content used, respectively. Furthermore, it was observed that as the oil increases the reduction in the $S_{u(UCT)}$ values increases but with a less reduction percentage.

### 4.2.4. Laboratory vane shear test

Laboratory Vane Shear tests (LVT) were performed on clayey soil and clayey soil-crude oil mixtures. The undrained shear strength ($S_{u(LVT)}$) was calculated using the Eq. (2) presented previously and the results were shown in Fig. 8. The relationship between the $S_{u(LVT)}$ and crude oil content illustrated in Fig. 8 shows that the $S_{u(LVT)}$ of the clayey soil-crude oil mixtures generally decreases as the crude oil increases. Quantitively, it was reported that the $S_{u(LVT)}$ of clayey soil with 0% crude oil content is 104 kPa, and the $S_{u(LVT)}$ of the minimum and maximum crude oil content used in this study are 84 and 43 kPa, respectively. The reduction percentages relative to the 0% crude oil content were 19.2 and 58.6 % for the minimum and maximum crude oil content respectively.

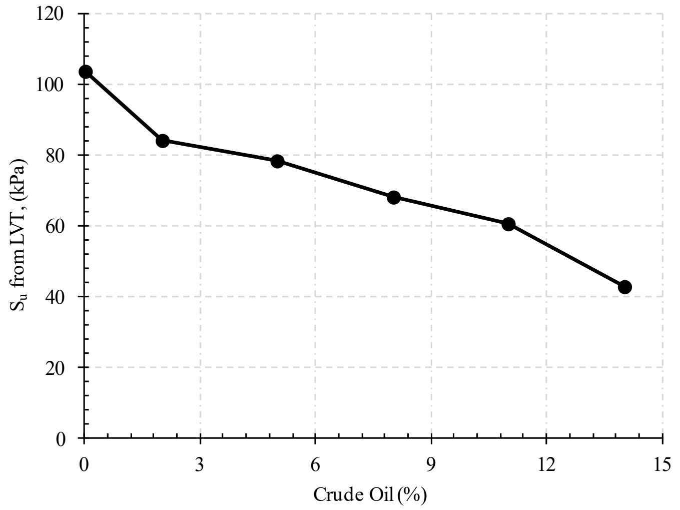

**Fig. 8. Undrained shear strength (Su) with crude oil using LVT.**

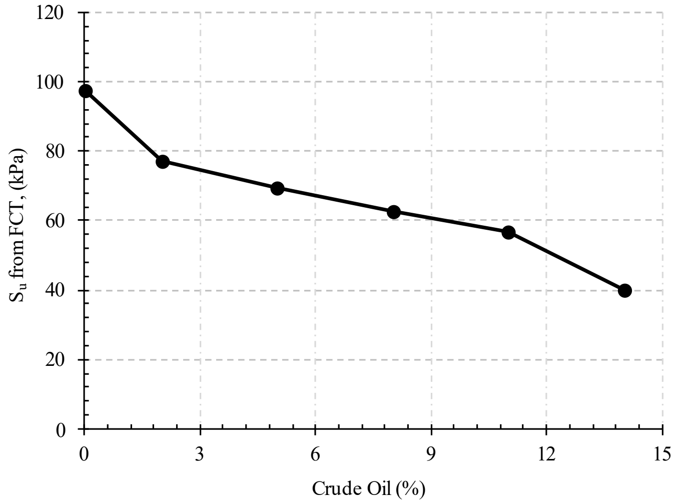

**Fig. 9. Undrained shear strength (Su) with crude oil using FCT.**

## 4.3. Undrained shear strength measured by different techniques

The results obtained by four different techniques: UUTX, UCT, FCT, and LVT were plotted against the crude oil content for clayey soil and clayey soil-crude oil mixtures as shown in Fig. 10. The undrained shear strength ($S_u$) measured by different techniques exhibits the same trend behaviour. Generally, it is observed that the $S_u$ decreases as the crude oil increases, but the magnitudes of reduction are different among the measurement techniques at a given crude oil content. The UUTX can be considered a more accurate test in comparison to other testing techniques because of stressing the soil specimen in lateral direction to simulating the field condition [47]. The unconfined compression test is an alternative test for measuring the undrained shear strength of soils. It is also assumed that the tested specimen is nearly saturated, but it is free of confining. The laboratory vane shear test is also used to measure the undrained shear strength via empirical equation(s). it is mainly used for nearly saturated soft soils. Shear strength is the resistance to the rotated blades. The last techniques which is the fall cone test, developed for measuring consistency limits, is used frequently to estimate undrained shear strength using empirical equation. In these testing techniques, the shear strength is function of cone penetration depth. Because not all geotechnical laboratories can be affordable of triaxial testing device, due to its expense, a much cheaper device can be alternatively used for measuring the undrained shear strength used for total stress analysis in preliminary design of geotechnical problem.

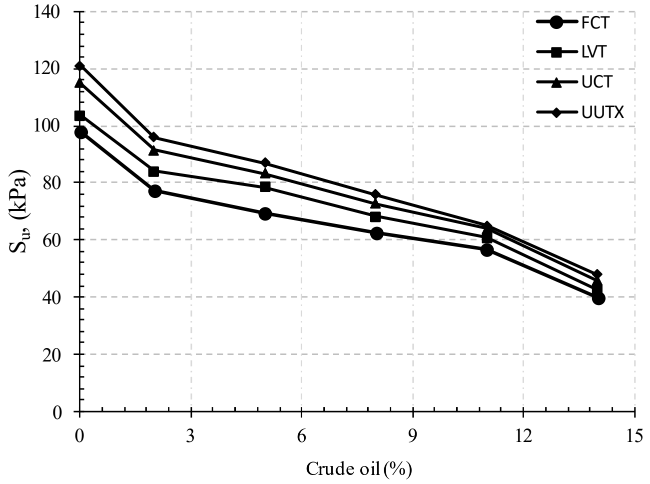

**Fig. 10. Undrained shear strength with crude oil using different techniques.**

For comparison, the results obtained by UUTX is assumed to be the control and the results of $S_u$ measured by other techniques compare with it as shown in Table 3. The ratio of the undrained shear strength measured by UCT to that measured by UUTX is 0.95, indicating that the unconfined compression technique underestimates the value of undrained shear strength. Table 3 and Fig. 11 show that the variation in the ratio is insignificant with crude oil content so that it can be ignored. Using the exponential function to fit the data of $S_u$ for both UUTX and UCT with a correlation factor of approximately 0.96 shows that the $S_u$ from UCT is underestimated the value by 5% as presented in equation (Eq. (4)). This finding is confirmed by the previous work done by [48] on a natural soft clay soil. They found that the $S_u$ measured by UCS is underestimated by 0.86% in comparison with that measured by UUTX.

$$S_{u(UCT)} = 0.95\ S_{u(TX)} \tag{4}$$

Similarly, the ratio of the undrained shear strength measured by FCT to that measured by UUTX was 0.81 for 2% crude oil content as shown in Table 3. The reduction percentage decreases only slightly for higher crude oil content. The results of $S_u$ measured by the two techniques were drawn and the data points were fitted using an exponential curve with a correlation factor of approximately 0.96 as shown in Fig. 12. Results show that the FCT technique underestimates the $S_u$ value by 20% according to equation (Eq. (5)). An approximately the same $S_u$ ratio of the $S_{u(FCT)}$ to $S_{u(TX)}$ was reported by [48]on a natural soft clay soil.

$$S_{u(FCT)} = 0.80\ S_{u(TX)} \tag{5}$$

The ratio of the undrained shear strength measured by LVT to that measured by UUTX was 0.86 for 2% crude oil content as shown in Table 3. This percentage decreases slightly for higher crude oil content. The data points measured by the two techniques were curve fitted using an exponential curve with a correlation factor of 0.95 as shown in Fig. 13 to establish a correlation between the two techniques. Results show that the LVT underestimates the $S_u$ value by 13% according to the correlation equation (Eq. (6)). The findings of [48] also agree with the current relation between $S_{u(LVT)}$ to $S_{u(TX)}$, but the previous work result is underestimated by approximately 15%.

$$S_{u(LVT)} = 0.87\ S_{u(TX)} \tag{6}$$

It should be highlighted that even though the UUTX is more accurate than other testing techniques because it takes into account the confining stress and the rate of shearing, a reasonable correlation has been driven among the $S_u$ measured by different techniques.

**Table 3. Undrained shear strength with crude oil using different techniques.**

| Crude oil (%) | Ratios of Undrained shear strength, $S_u$ to UUTX | | | |
|---|---|---|---|---|
| | UUTX | UCT | FCT | LVT |
| 0 | 1 | 0.95 | 0.81 | 0.86 |
| 2 | 1 | 0.95 | 0.80 | 0.88 |
| 5 | 1 | 0.95 | 0.79 | 0.91 |
| 8 | 1 | 0.96 | 0.83 | 0.89 |
| 11 | 1 | 0.98 | 0.88 | 0.94 |
| 14 | 1 | 0.96 | 0.83 | 0.90 |

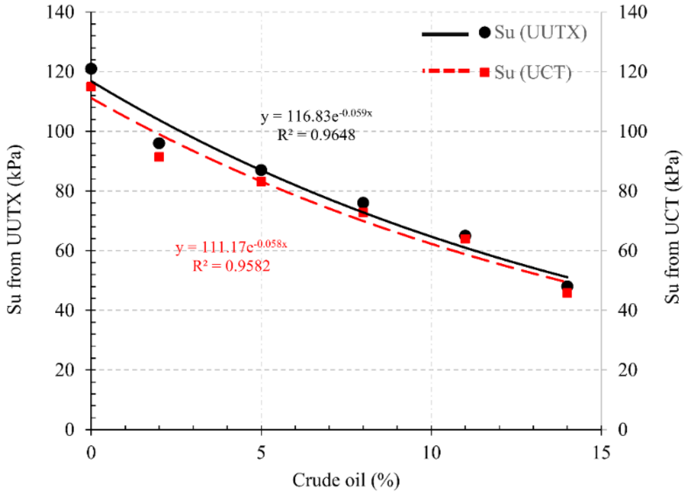

**Fig. 11. Undrained shear strength from UUTX and UCT.**

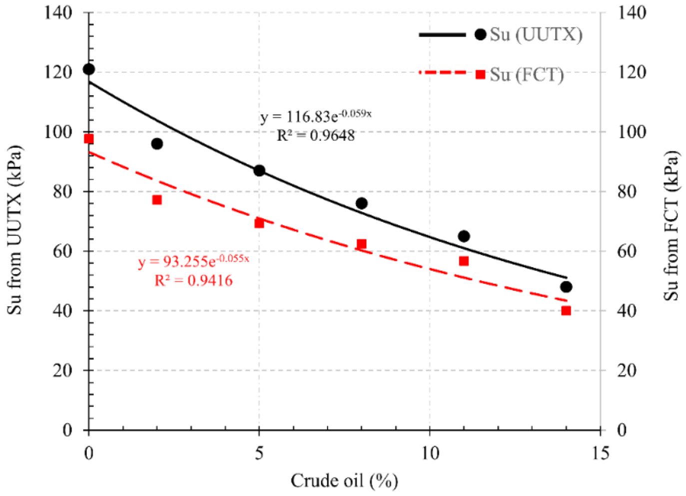

**Fig. 12. Undrained shear strength from UUTX and FCT.**

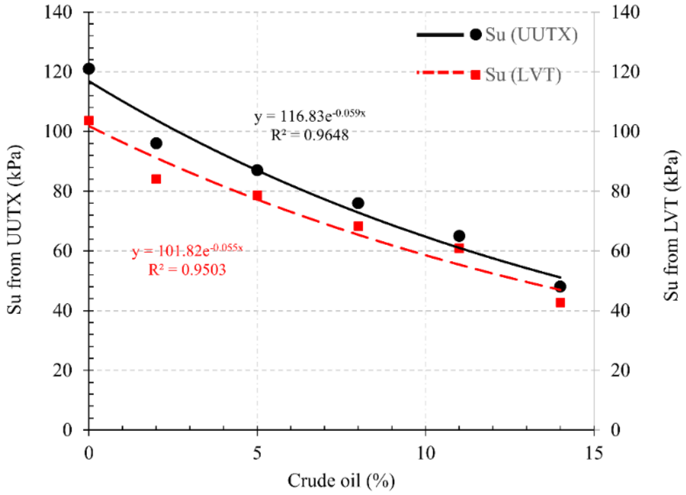

**Fig. 13. Undrained shear strength from UUTX and LVT.**

## 5. Conclusions

An intensive laboratory experiments was performed on clayey soil and clayey soil-crude oil mixtures specimens to study mainly the influence of crude oil on undrained shear strength of clayey soil using four different techniques including Unconsolidated Undrained Triaxial Tests, Unconfined Compression Test, Fall Cone Test, and Lab Vane Shear Test. It is also to find correlation factors between the undrained shear strength measured by four different techniques. From the results obtained in this study, a list of conclusions can be driven:

- It is found that the soil plasticity increases then decreases with crude oil content. The maximum reported increment in the soil plasticity is 9% at 5% crude oil content, then decreases for higher crude oil content.
- Results show a dependency of undrained shear strength on crude oil content. The undrained shear strength generally decreases with the increase in oil, but for oil content higher than 2%, the undrained shear strength reduces with less slope.
- Quantitatively, it is observed that the maximum reduction in the undrained shear strength associated with the 14% crude oil content was approximately 60% relative to the uncontaminated tested soil specimens. Interestingly, the reduction percent are approximately the same for all testing techniques adopted in this study.
- Four measurement techniques were used for undrained shear strength measurements. The results show that the behaviour of undrained shear strength is the same, but the magnitude is different.
- It is observed that the FCT underestimates the undrained shear strength by approximately one-fifth in comparison to that measured by triaxial test.
- The closest results of undrained shear strength to the Triaxial test are the unconfined compression technique where the later underestimates the undrained shear strength by only 5% relative the undrained shear strength measured by UUTX.
- Correlation factors were developed for the four techniques so that they are useful for practicians to convert the undrained shear strength among different techniques.

### Nomenclatures

| | |
|---|---|
| $c'$ | Effective cohesion, (kPa) |
| $S_u$ | Undrained shear strength, (kPa) |

***Greek Symbols***

| | |
|---|---|
| $\varnothing'$ | Effective angle of internal friction, deg. |

**Abbreviations**

| | |
|---|---|
| FCT | Fall cone test |
| LVT | Laboratory vane shear test |
| API | American Petroleum Institute |
| UCT | Unconfined compression test |
| UUTX | Unconsolidated undrained triaxial test |

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