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Effects of Gasoil Contamination on Geotechnical Properties of Kaolinite Soils

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Abstract

The contamination of soils and groundwater by toxic and/or hazardous organic pollutants is a widespread environmental problem. One group of these contaminants is petroleum products. Soil pollution caused by petrochemical activities, oil spills and leakage is not only an environmental issue but also a geotechnical issue. Physical and chemical reactions between soil and contaminant lead to change in soil properties and behaviour. In this paper, a set of laboratory tests including the direct shear test, uniaxial compression test, Atterberg limits and Scanning Electron Microscope (SEM) have been carried out on Kaolinite samples polluted with different percentages of gasoil. The direct shear test results demonstrate that increasing the pollutant percentage leads to an increase of cohesion and a decrease in internal friction angle of the soil. Also, increasing the amount of gasoil to a certain percentage results in a decrease in the uniaxial strength and the plasticity index of the soil.

Key words: Contaminated soil, Laboratory tests, Kaolinite, Geotechnical properties, gasoil.

تاثیر آلاینده گازوئیل بر پارامترهای مقاومتی خاک کائولینیت

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چکیده

آلودگی خاک و آب‌های زیرزمینی به مواد ارگانیک و سمی یک مشکل شایع محیط زیستی است. در این میان محصولات نفتی یکی از مهمترین آلاینده های محیط زیست محسوب می‌شود. آلودگی خاک از طریق فعالیتهای پتروشیمی و نشت مواد نفتی تنها یک مسئله زیست محیطی نمی باشد بلکه یک مسئله ژئوتکنیکی نیز محسوب می شود. در اثر فرآیندهای فیزیکی-شیمیایی که بین آلاینده و خاک رخ می‌دهد، رفتار و خصوصیات خاک تغییر می‌کند. این امر می‌تواند باعث تغییر ظرفیت باربری خاک گردد. در این مقاله، مجموعه‌ی کاملی از آزمایشات مکانیک خاک شامل برش مستقیم، تک محوری، حدود اتربرگ و همچنین مشاهده توسط میکروسکوپ الکتریکی پیمایشی بر روی نمونه‌های خاک کائولینیت آلوده به درصدهای مختلف گازوئیل انجام شده است. نتایج آزمایش برش مستقیم نشان داده است که افزایش درصد آلودگی منجر به افزایش چسبندگی و کاهش زاویه اصطکاک داخلی می شود. همچنین افزایش درصد گازوئیل تا مقدار مشخصی باعث کاهش یافتن مقاومت محدود نشده و شاخص خمیری خاک می گردد.

کلمات کلیدی: خاک آلوده، مطالعات آزمایشگاهی، کائولینیت، پارامترهای خاک، گازوئیل.

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1. Introduction

Petroleum soil contamination leads to changes in strength properties, permeability and compressibility of soil as the result of physical-chemical processes between soil and contaminants. Using contaminated soil, knowledge of geotechnical properties and behaviour of contaminated soil is needed [1]. Neglecting the effects of contamination on soil behaviour may cause problem that threat stability of the structure. It may lead to costly environmental issues which sometimes have no solutions. The extent of contamination depends on the chemical composition of the contaminant and the properties of the soil [2]. We can consider the subject of contaminated soils from two points of view: (1) the contaminant transport processes and (2) the strength and compressibility of the soil [3]. Although, the impact of pollution on physical and chemical properties of soil types is important, limited research has been done in this regard.

Sridharn and Rao found that the shear strength behaviour of contaminated soil is highly complex and depends on several factors, such as type of clay mineral, water content, nature of pore fluid, stress history, stress loading rate, temperature and soil texture. Thus, a separate study of contaminant effects on soil shear strength is difficult [4]. Moor and Mitchel stated that the physical-chemical interaction between electrolyte clay and pore fluid resulted in decrease in dielectric constant and a consequent increase in soil strength [5]. Lambe found that any phenomenon responsible for an increase in dual layer, may reduce shear strength due to increasing repulsion between particles [6]. Shin and Das studied bearing capacity of unsaturated oil-contaminated sand, and also examined the effect of different percentages and viscosity of contaminants on the internal friction angle. The results obtained from direct shear test showed reduction of friction angle with increasing contaminant content and, for a specified percentage of pollutants, friction angle decreased with increasing viscosity of contaminants [7]. Khamehchiyan and his colleagues found that the increase of pollutant resulted in an increase in internal friction angle for clay (CL) and decrease for sandy soil (SP and SM). The result of the compression test indicated that the contamination of soil by crude oil reduced the maximum dry density and created optimum moisture content. Also, increased oil content leads to a reduction in the Atterberg limits which is in contrast with Habib-ur-rahman's view [1, 8]. The conclusion of the experiments carried out on the oil-polluted dry sand by Vijay K. Puri showed that if water is replaced by oil for condensing sand, both the optimum moisture content and maximum dry density increase [9].

Alsandad and his colleagues studied geotechnical properties of Kuwait's oil-polluted sand with direct shear test apparatus in which sand was prepared with different percentages of density and was polluted with different percentages of heavy oil, light crude oil and gasoil. A five to seven degree decrease in level of the sand internal friction angle was observed. The maximum reduction in the internal friction angle was related to heavy crude oil. A decrease in internal friction angle is obvious from loose to dense sand [10]. Ur-rehman and his colleagues conducted a study on the geotechnical behaviour of petroleum- contaminated clay soils with high plastic properties and concluded that the maximum dry density of contaminated soil was much higher than that of non-contaminated soil. However, the optimum moisture content is less than for clean soil [11]. Singh and his colleagues studied clay soil consolidation parameters (CH and CL) for contaminated soil with various contents of engine oil, gasoil, gasoil and kerosene. Results showed that the settlement or compaction index for both types of polluted soil increased and consolidation coefficient decreased, except for kerosene [12]. Kermani conducted research on effectiveness of petroleum on shear strength parameters and compressibility of soil. The results indicated that, with a constant moisture content, there is a direct relationship between the internal friction angle and the percentage of pollutants. However, there is an inverse relationship between cohesion and the percentage of pollutants. While percentage of the emission is fixed, increasing the water leads to a decrease in the internal friction angle and an increase in cohesion [13]. Al-Hamaiedh and his colleagues studied impact of oil contamination on the geotechnical properties of soil and feasibility of cleaning up contaminated soil using electro-chemical methods [14].

Clay soils have low permeability, consequently transport and dispersion of pollutants in clay soils is much less than in coarse-grained soils. So it is suitable to use a clay for oil reservoir beds to prevent migration of contaminants and ground water contimination. As a result, if clay is more active, more swelling is caused by water penetration. Among the clay minerals, Kaolinite has the least amount of activity and, it is well suited to achieving these goals. Due to high electrochemical activity of clay minerals, they can be strongly influenced by surrounding environment. Thus, in the presence of different materials, they exhibit different behaviours. In this paper, Kaolinite soil has been selected as a case study and gasoil is used as the pollutant. The direct shear test, uniaxial test, Atterberg limits and Scanning Electron Microscopy (SEM) were performed. Atterberg limits and SEM were undertaken in order to control and interpret the other tests results.

2. Properties of soil samples and contaminants

In this study, artificial soil was used in order to increase homogeneity of the samples. Kaolinite clay was the production of Iran China Clay Industries Company. To determine the physical characteristics of the soil used in this study, a series of experiments was carried out according to existing standards (Table 1). It should be noted that, since clay is an adhesive material, oil was used instead of water to obtain the specific gravity of clay. X-ray Diffraction (XRD) analysis was used to determine the mineralogy of Kaolinite. The chemical and physical properties of Kaolinite are given in Tables 2 and 3. The gasoil used was the product of Iranian Oil Refining and Distribution company. The properties of the gasoil are given in Table 4.

Table 1. Tests to identify material properties.

Test	Standard
Hydrometer	ASTM D 422-63
Grading	ASTM D 421-87 , ASTM D 422-87
Determination of moisture	ASTM D 2216-90
Determination of specified gravity	ASTM D 854-83
Standard density	ASTM D 698-78
Atterberg limits	ASTM D 4318-87

Table 2. Chemical composition of the soil.

Elements	%
L.O.I	2.46
Na2O	0.007
MgO	0.40
Al2O3	26.33
SiO2	67.51
P2O5	0.09
SO3	0.09
K2O	0.44
CaO	1.89
TiO2	0.03
V2O5	<0.1
Cr2O3	<0.1
MnO	0.01
Fe2O3	0.49

Table 3. Physical properties of the soil.

property	value
Effective size	0.001mm
Uniformity coefficient	1
Aggregation factor	1
Maximum dry density	16.5
Optimum moisture content	16.5
Gs	2.6
Unified classified	CL
Plastic index	19

Table4. Properties of the gasoil.

Property	Value
Relative density at 15/6°c	8.2-8.6 $^{KN}/_{m^3}$
Ignition temperature	56°C
Self-ignition temperature	257°C
Boiling temperature	150 − 390°C

3. Preparation of samples and experiments

Soil samples were passed through a sieve No.4 to separate aggregates and, the samples were dried by oven at 105ºC for 24 hours. Then the samples were mixed with specified percentages of gasoil. To ensure complete absorption, the samples stored for 10 days at a temperature of 30ºC and then used for testing. All mixed samples kept under constant temperature and under the same conditions. To reduce the number of variables, tests were performed in a laboratory which has a limited temperature variation range.

3.1 Direct shear test

The direct shear test was performed in accordance with ASTM D3080-72 and shear force applied by rate of 1 mm/min. Dimensions of the box were 6 cm × 6 cm and the depth was 2.5 cm. Experiments were performed in an un-drained condition to maintain the concentration constant during test to prevent transpiration of contamination from samples. Considering the relative density of 65% for this test and maximum dry density of kaolinite equal to 1.65, the maximum dry density for specimens was 1.02 gr/cm^3. Samples were mixed with gasoil to the amounts of 2, 4, 6, 12, 16 and 20 percent by weight of the dry soil samples. Some samples were mixed with water in the amount of 12 and 16 percent by weight of the dry soil samples for comparison.

3.2 Uniaxial test

The dimensions of the samples used in this experiment were 3.8 cm diameter and 7.9 cm height and the test was performed in accordance with ASTM-D2166-85 standard. The relative density of the test was 65%. The percentages of gasoil used in uniaxial test were the same as direct shear tests. The test performed in strain control condition. Calculating unconfined compressive strength, modified area is as follow:

$$A' = \frac{A}{1-\varepsilon} \quad (1)$$

Where: A' = modified area of the sample, A = primary area of the sample and ε= axial strain.

3.3 Scanning Electron Microscope (SEM)

An improved understanding and interpretation could be found by using Scanning Electron Microscope (SEM). This type of microscope can produce images with high magnification (10 to 100,000 times) and has more clarity than other conventional microscopes. Four kaolinite samples were taken images: i) clean Kaolinite, ii) contained 12% water, iii) contained 12% gasoil and iv) contained of 12% water and 12% gasoil.

3.4 Atterberg Limits tests

Atterberg limits tests were conducted for specified samples which were in uniaxial and direct shear tests. They were performed based on ASTM 4318-87 standard. The Atterberg limit is expressed by plastic and liquid limits and a plasticity index. Liquid limit expresses the minimum percentage of water in which soil particles flow under their weight and plastic limit introduces the minimum percentage of water, in which soil is moulded without breaking. Although these limits are easily obtained and their qualitative correlations with soil composition and physical properties have been approved, interpretation about the relationship between values and factors is very complex [1, 15]. Atterberg Limits test results are useful for controlling other test results.

4. Test results

The test results were considered for evaluating strength characteristics of the gasoil-contaminated soil. In these experiments, the main variable is the percentage of gasoil and the important issue is the impact of this factor on the soil properties.

4.1 Direct shear test result

The direct shear test is aimed to achieve soil strength parameters, such as internal friction angle and cohesion. To analyze the results of samples contaminated with gasoil, similar direct shear tests performed with water to compare the results of two experiments.

4.1.1 Results of direct shear test on contaminated samples

Diagrams of shear stress versus horizontal displacement, and vertical displacement versus horizontal displacement for all samples at normal stress of 150 KPa are plotted in Figures 1 and 2, respectively. As the figures depict, there is just a trivial difference among maximum sustainable shear stress magnitudes for samples with different percentages of gasoil. Increasing the gasoil contents to 12%, more stress magnitudes are observed, to the same value of horizontal displacement. In other words, the soil becomes harder than the one with the lower gasoil content. As Fig. 2 shows, by increasing the gasoil contents to 12%, vertical displacements of the samples first decreased and then increased. The increase of gasoil contents does not have any important effect on internal friction angle of Kaolinite. By raising the gasoil content to 20%, the reduction of internal friction angle was only 1 degree, but it had a significant effect on the cohesion value (Fig. 3 and Fig. 4).

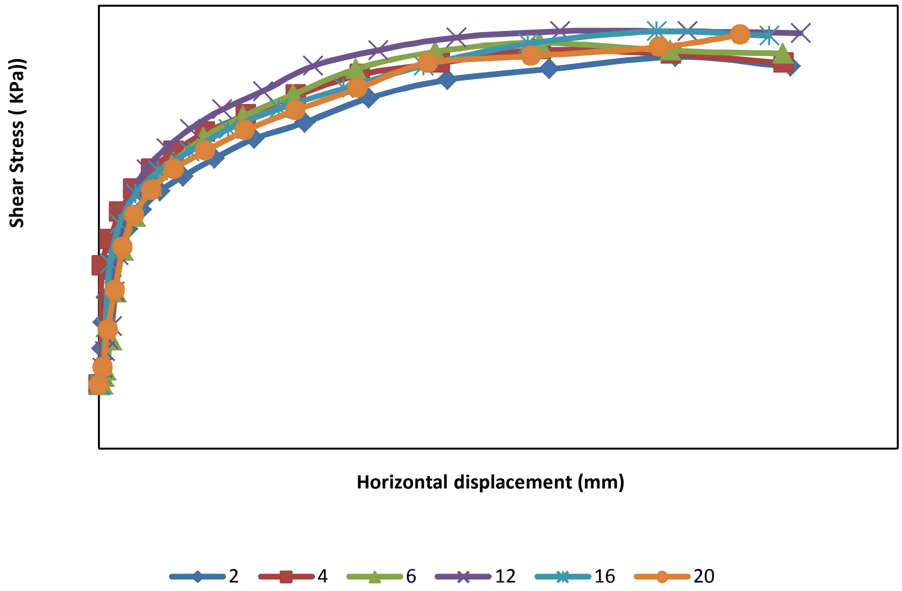

Figure 1. Influence of gasoil content on the direct shear test.

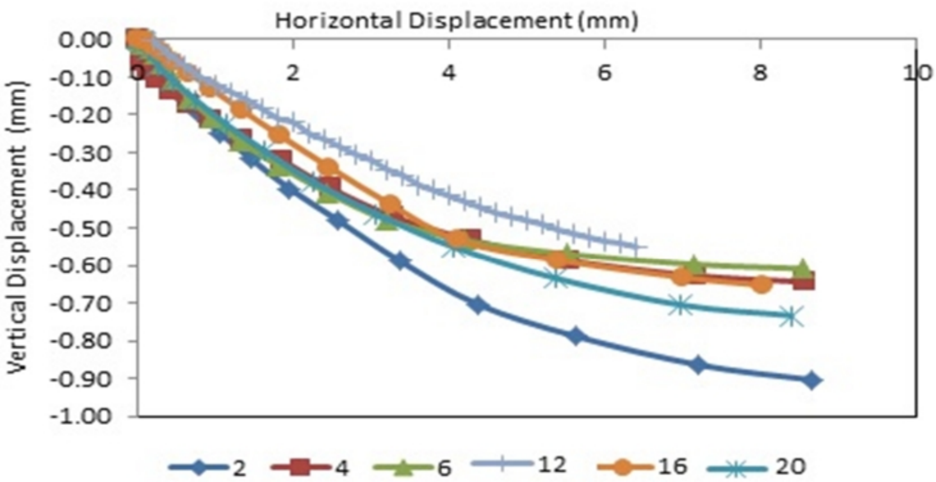

Figure 2. Influence of gasoil content on the direct shear test.

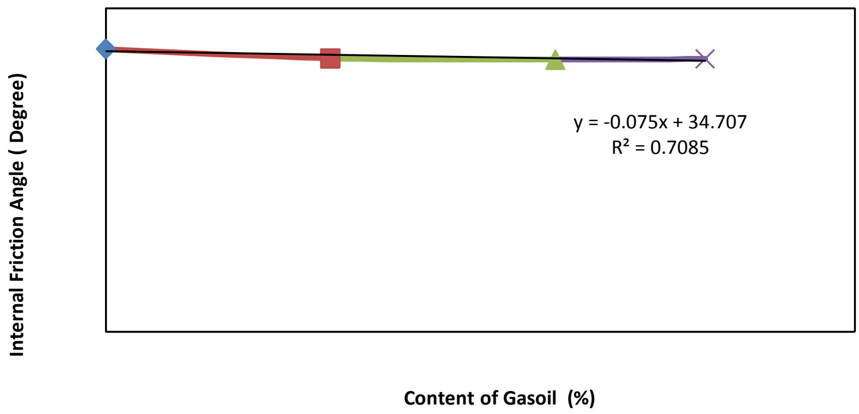

Figure 3. Influence of gasoil content on the internal friction angle.

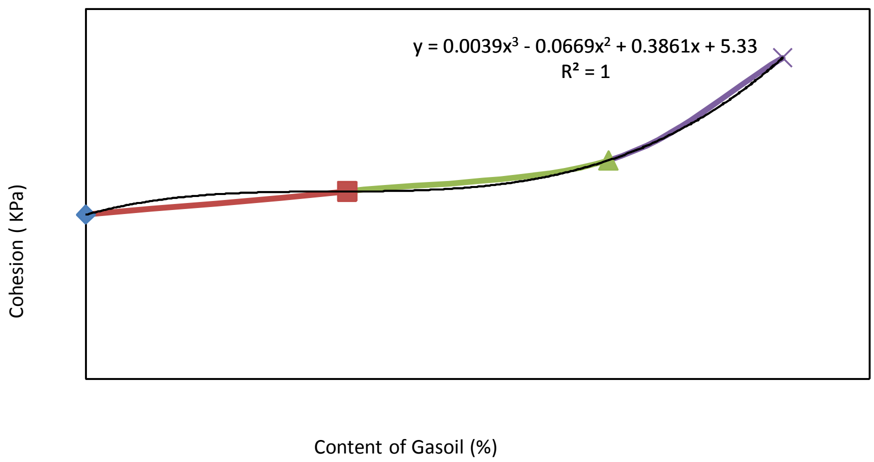

Figure 4. Influence of gasoil content on cohesion.

According to Lambe, if dielectric constant and PH of the pore fluid increase, shear strength of soil will decrease [6]. The gasoil dielectric constant is low and it is considered as an insulator material. Rao and Sridharan believe that, due to the physical-chemical interaction that occurs between fluid and clay, the dielectric constant of fluid decreases [4] and it leads to an increase in shear strength [6].

In general, cohesion is the result of three different components including (i) adhesion due to compression, (ii) electromagnetic and electrostatic gravitation and (iii) suction [16]. Since the density of all samples are the same, density factor plays no role in the results. Gasoil is regarded as a hydrocarbon and a non-polar liquid, so it is impossible to make a connection between clay molecules and gasoil. The only likely link is the Van der Waals bond which is much weaker than a polar bond and does not cause any important cohesion. Therefore, suction is expected to be the main cause of cohesion in these samples. According to Zhao's investigations, organic materials such as petroleum hydrocarbons decrease repulsion among the clay particles. This can cause the particles to come closer and to increase adhesion among the particles [17].

Results of the investigations by Habibur Rehman and colleagues, and Khamehchiyan and colleagues and Kermani show that enhancement of oil contents increases internal friction angle. Formation of separated mass and altering the structure from clay to granular, Kermani believes these are the reasons for this phenomenon [1, 11, 13]. The SEM results in this paper show that gasoil will increase the amount of masses in the soil and, because of gasoil contamination, the soil structure alters from a sparse to coagulation mode and so, because of a reduction in the contact area among the particles, the internal friction angle reduces.

4.1.2 Results of direct shear tests on wet samples

Analyzing the results of direct shear tests on samples contaminated by gasoil, similar experiments were performed using water. Better interpretation can be achieved by comparing results of the two tests (Figures 5 and 6). Both gasoil and water reduced the internal friction angle but because of the polar bond between clay soil and water, clay can absorb water better than gasoil. Accordingly, the reduction in the internal friction angle of clay due to water is higher than to gasoil. Samples which are mixed with water can lead both electrostatic attraction and suction to cohesion. As a result, increasing the water contents of the samples also increases cohesion from 5 KPa to 20 KPa. According to Al-Shayea, by increasing water content up to a certain value in soil samples, both cohesion increment factors are effective and, with increasing the moisture content, cohesion decreases. The results of altering cohesion by increasing both water and gasoil are the same but, since gasoil is a non-polar liquid, electrostatic attraction does not lead to increased cohesion. Hence, gasoil contamination shows less adhesion than water in kaolinite [18].

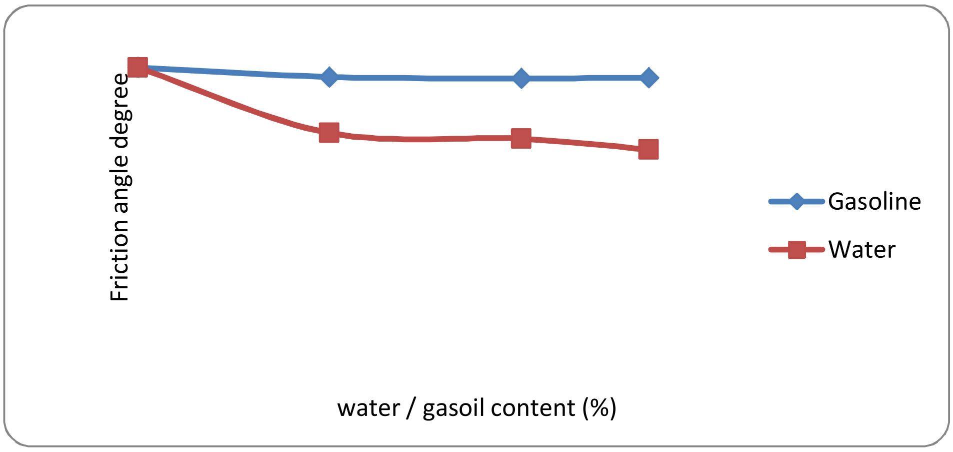

Figure 5. Influence of gasoil and water content percentage on the internal friction angle.

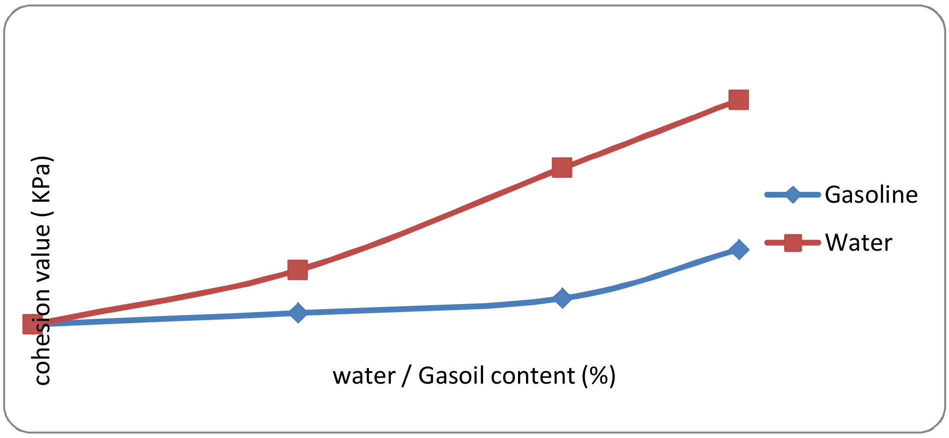

Figure 6. Influence of gasoil and water content on cohesion.

4.2 Uniaxial test

At the beginning of loading in uniaxial test, some specimens sustained the load without deformation. This happens because of uneven surface of specimen. For modifying the results, the amounts of load which were sustained without deformation were detracted from the total bearing load. Based on the results (Fig. 7) it is observed that, for certain strains on the graph, the corresponding stress value increases with increasing the gasoil content to 12%, and then decreases. Mohr's circle radius in this experiment is equal to half of the unconfined compression strength which indicates soil cohesion. The trends show an increment in cohesion by increasing the gasoil contents to 12%. This trend endorses the assumption that adhesion is created because of suction. By increasing the pore fluid to a certain percentage, suction increases but, with further increasing of pore fluid and approaching the soil moisture to saturation, suction is reduced and, thus, adhesion is also reduced.

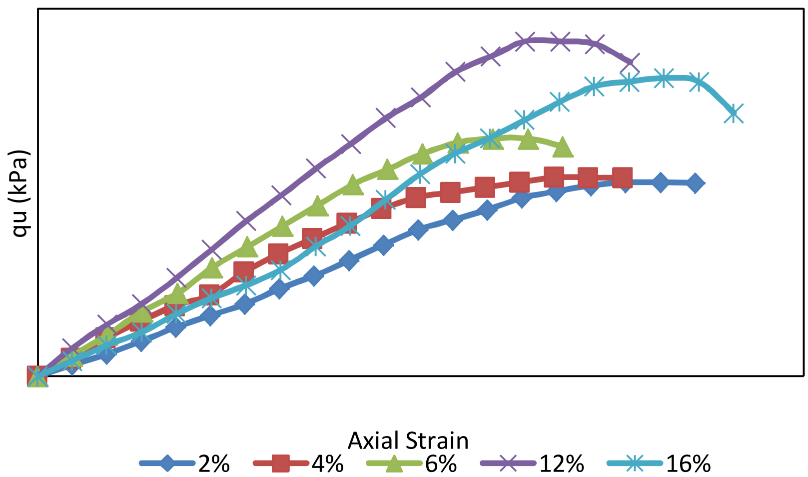

Figure 7. Influence of gasoil content on uniaxial compressive strength.

4.3 Soil texture

As shown in Figure 9, existence of water among the clay layers and plates causes more soil masses and also creates a unified structure. It is expected that cohesion of the wet sample would be greater than that of the dry sample. Diffused distribution of masses increases the contact area among the particles, which leads to increased friction among the particles. Diffused distribution of masses in wet samples was more than in dry ones. Adhesion and electrical attraction among the particles of soil and water in wet samples are the main factors in creating the coagulation of mass particles. As Figures 8, 9 and 11 illustrate, gasoil coagulated and this increased the number of masses. Comparing the following figures, more accumulation in mass is shown in Figure 10 in comparison with Figures 9 and 11. Therefore, it is concluded that gasoil intensifies the effect of water in coagulation and the number of mass particles.

4.4 Atterberg limits test

Whenever plastic properties of clays get higher, the higher cohesion is resulted. According to the skempton relation (1957), uniaxial strength of normal consolidation clay has a direct relationship with the plasticity index [19].

$$\frac{S_u}{P'} = 0.11+0.0037\ PI \qquad (2)$$

Where: S_u is unconfined compressive strength, P′ is effective vertical overburden pressure and PI is the plastic index.

Test results show that through increasing the gasoil content to 12%, both the uniaxial compressive strength and plastic index increase; additional gasoil content leads to decreasing both of them.

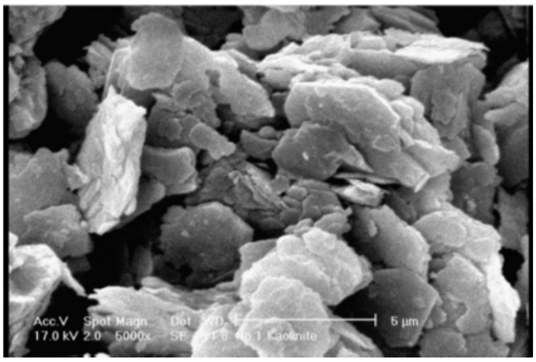

Figure 8. SEM image of clean Kaolinite.

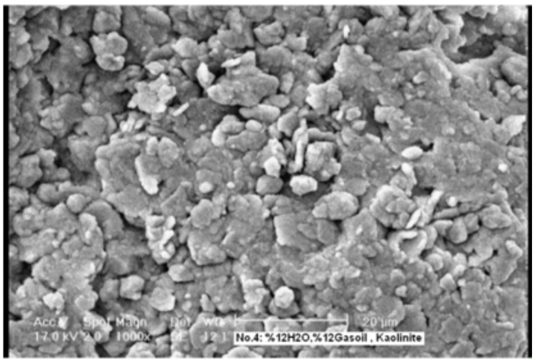

Figure 10 SEM image of Kaolinite with 12% water and 12% gasoil contents.

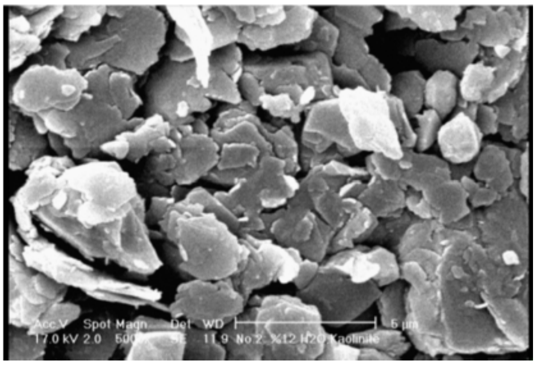

Figure 9. SEM image of Kaolinite with a 12% water content.

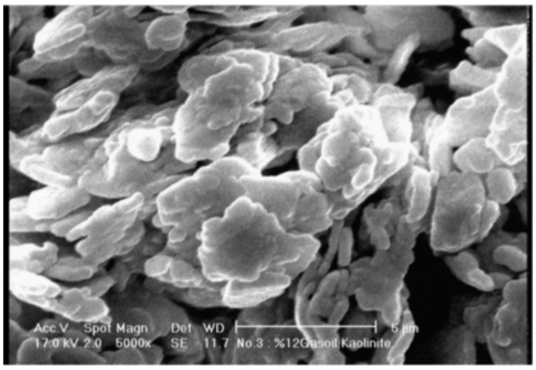

Figure 11. SEM image of Kaolinite with 12% gasoil content.

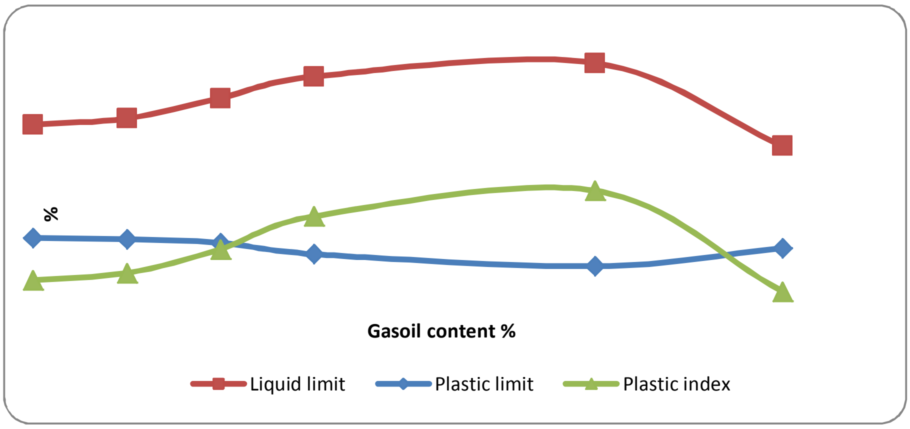

Figure 12. Influence of gasoil content on Atterberg limits.

5. Conclusion

The results of direct shear tests carried out in this paper resulted in an increase in soil cohesion and a decrease in internal friction angle. The presence of gasoil contaminant in the samples has a stronger effect on adhesion than on the friction angle; by adding gasoil up to 20% of the dry soil weight sample, adhesion rises from 5 KPa to 12.36 KPa, while internal friction angle is only reduced by one degree.

By implementing the direct shear test on three moist soil samples, it was found that the wetter the soil, the more adhesion and the less internal friction angle. The direct shear test results of gasoil-contaminated soil are similar to those of wet soil samples. However, since water is a polar liquid and gasoline is non-polar, the effects of water on adhesion enhancement and the reduction of internal friction angle are greater than with gasoil.

With an increase in gasoil to 12 percent, the uniaxial compressive strength increases and then decreases. This trend reflects the hard response of kaolinite soil to increasing the gasoil to 12 percent. These results are consistent with the results of the direct shear test. This trend demonstrates that the soil adhesion increases with increasing gasoil content.

By increasing the contaminant to 12 percent, the liquid limit decreases and plastic limit increases. This means that soil plasticity increases by adding gasoline up to 12 percent. This result is compatible with the results of both direct shear test and uniaxial test. The results of Atterberg Limits and SEM confirmed the other test results also.

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