Case Study

Index properties, mineralogy composition and strength of clay soil with the presence of diesel

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Abstract

Diesel contamination in the soil may occur in different ways, and its interaction in the soil is uncertain and may have negative impacts. This paper presents the interaction between clay soil with moisture content of 30% and diesel content of 1%, 3% and 6% of dry mass. The soil is taken from Colombia to know the effect of diesel on the index properties (moisture content, specific gravity of solids, Atterberg limits), cation-exchange capacity, mineralogy composition and unconfined compression strength; moreover, the samples are tested at different temperatures considering if it is known the presence of diesel or not in the soil because the presence of diesel increases organic components, then if there is known the presence the temperature is $50 \pm 5^\circ\text{C}$ but $110 \pm 5^\circ\text{C}$. The diffractograms showed that diesel did not affect the mineralogical composition in the exposure period of 7 days, but in real cases the hydrocarbon may be for prolonged periods, months or even years. Independent of the test temperature, there was an increase in moisture content and decrease in specific gravity of solids as diesel content increased. The Atterberg limits had an uncertain behavior by the presence of diesel and change in the test temperature. The cation-exchange capacity was increased by the presence of diesel independent of the test temperature. The parameters of unconfined compression strength decreased as diesel content increased. The research concludes that diesel effects over geotechnical parameters of the soil generates negative impact, and projects that have soils with diesel need special attention, so it is important to keep doing research where diesel has more time of exposition in the soil.

Keywords Clays · Index properties · Diesel · Strength

1 Introduction

Nowadays the growth of world population has generated an increase in the consumption of petroleum and its derivatives, and these increase the probability of spill accidents occurring during the transport in highways or railway systems, leaks in the storage tanks or piping lines and clandestine shots or attacks against petroleum production infrastructure [14, 16, 24]. In addition, there are spills by not having maintenance of the supply systems and roads.

The general hypothesis about the consequences of diesel in the soil is that nothing happens on the structure and properties, and for that reason the geotechnical parameters

are not researched. To verify the possible changes, and if it is necessary to do special remediation treatments, the research should be done; this is the reason of the study, to check whether the diesel affects or not the soil. Nevertheless, the researchers have found that the hydrocarbon spills affect soil structure by the rupture of the aggregates, which increase the retention of water in the superficial layer and the potential hydric [3]. If these soils are used such as in highway materials or construction projects, their structural changes, mineralogical and index properties are crucial to guarantee stability and safety in the works.

Some authors have researched this topic, and they have evidenced changes in the microstructural, Atterberg limits,

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specific gravity of solids, particle size distribution and strength, but it depends on the grade and kind of hydrocarbon [1, 2, 4, 8, 14, 24].

For example, the unconfined compression strength of a soil with diesel is decreased, which is more susceptible to fail [13]. Now, if the soil has gas oil, the soil increases cohesion and liquid limit, but decreases the internal friction angle and plastic limit; moreover, it generates the formation of flocculated structures, and the shear stress does not change significantly with increasing the gas oil [10].

Other scientists mention that the internal friction angle, unconfined compression strength, specific gravity of solids, cohesion and Atterberg limits decrease in the presence of diesel, but pH increases [9, 11, 16, 19, 20]. However, there are some authors that report other behaviors; for example, Atterberg limits are increased in the presence of diesel [22], and the internal friction angle is increased in the presence of kerosene and gas oil [15]. All authors show up the importance to keep doing investigations, and for that reason this study seeks to determinate the changes and effects in the mineralogy composition and geotechnical properties of clay soil by the presence of diesel, and there is a special contribution to analyze the effect of the test temperature because if the diesel presence is unknown the temperature is 110 ± 5 °C but 50 ± 5 °C, it has not been researched.

2 Materials and methods

2.1 Materials and sample preparation methods

The study was carried out over high plasticity clay (CH) samples from Colombia that had 4.2% of organic matter, which did not have enough influence over the soil properties because the liquid limit after dried in the oven was not minor that 75% of that limit before the dried process, and for that reason the clay was considered not organic. The first step was to dry soil at air temperature (up to 40 °C) because higher temperatures affect chemical composition or properties of the soil. The second step was to crush the

dried soil and add water to have 30% moisture content, and this was selected as a plastic state that was easy to use with diesel. The third step was to add diesel in different percentages which were 1%, 3% and 6% by mass of dry soil, as shown in Fig. 1. The diesel had a density of 865.12 kg/m^3 , and kinematic viscosity at 40 °C between 1.9 and $5 \text{ mm}^2/\text{s}$. The samples were kept in a room with humidity and temperature control.

The interaction between soil and diesel was throughout 7 days, next it was realized different laboratories. In addition, the standards provide requirements about the test temperature, which is 110 ± 5 °C, but if there is presence of hydrocarbons it should be reduced to 50 ± 5 °C by the presence of organic compounds. It is important to notice that the sample control (without diesel) was tested only at 110 ± 5 °C because it did not have enough organic matter to classify such organic clay and reduce the temperature.

This study was carried out at both temperatures, but at 50 ± 5 °C were tested only samples with diesel. The tests were conducted to determine the moisture content, specific gravity of the solids, Atterberg limits, mineralogy composition, unconfined compression strength and cation-exchange capacity.

2.2 Laboratory test

The samples were preserved in hermetic bags and control conditions in a dark room (19 °C) to avoid loss of diesel by evaporation and to reach that all experiments units had the same environmental conditions. The process in the laboratory was based on experimental procedures of other researchers [2, 11, 18, 20, 24]. The samples were tested 7 days after their preparation, and were checked everyday the preservation conditions to avoid alterations by external factors, and therefore, the internal validation was guaranteed. The tests were developed with respect to standards INVIAS (Instituto Nacional de Vías) 2013 based on ASTM, and modified standards for soils with the presence of hydrocarbons, project developed by Universidad Pontificia Bolivariana Seccional Bucaramanga, Colciencias and Ecopetrol

Fig. 1 Samples preparation. **a** Dry soil, **b** crushed dried soil, **c** add water and diesel, **d** sample conservation in hermetic bags

S.A—Instituto Colombiano del Petróleo. Finally, the analysis of mineralogy with X-ray diffraction (XRD) method of dust was realized for samples with 0% and 6% diesel content for analyzing the critical conditions.

3 Results and discussion

3.1 Mineralogy composition

The control sample (0% diesel content) was analyzed with XRD, and the results show that it is dominated by quartz

(> 50%), the presence of kaolinite (5–15%) and traces of clays 14 Å (< 5%) that may have smectite, vermiculite or chlorite, but the test could not distinguish it, as shown in Fig. 2. It is important to notice that the samples need a special content like ethylene glycol and heating at 550 °C to distinguish the traces of clays 14 Å [21]. The results of the sample with 6% diesel content indicate that the dominant mineral is still quartz (> 50%), the presence of kaolinite (5–15%) and clays 14 Å are maintained, as shown in Fig. 3. However, the presence of diesel in the soil structure attenuated the clays 14 Å and kaolinite. In conclusion, the diesel

Fig. 2 X-ray diffraction for sample control

Fig. 3 X-ray diffraction for sample with 6% diesel

Fig. 4 Moisture content versus diesel content

did not affect the composition of soil like in the study of a tropical residual soil contaminated with gasoline [6].

3.2 Moisture content

Figure 4 shows the results at 110 ± 5 °C and 50 ± 5 °C. However, it is important to notice that the control sample was tested only at 110 ± 5 °C because it did not have enough organic matter to reduce the temperature. At 110 ± 5 °C, the moisture content has tendency to increase with the addition of diesel, it is represented in a very strong positive linear association of 96.3%, but at 50 ± 5 °C is shown a very strong positive linear association of 87.0%. Therefore, if there is more diesel in the soil structure, it has higher moisture content.

At 50 ± 5 °C decreases the moisture content with respect to temperature of 110 ± 5 °C because the rate of evaporation of the liquids soil is higher at 110 ± 5 °C. Nevertheless, at 50 ± 5 °C for diesel content of 3% the property increases in 4.58% with respect to diesel content of 1% because there are more liquid in the soil structure, and for the diesel content of 6% the property increases by 5.54% compared to the diesel content of 1% for the same reason.

There are not papers that report increase on the moisture content with the addition of diesel, and this property has a limited investigation. Moreover, Liu et al. [11] show the complexity to determinate this property because the hydrocarbon in solid state adhered to the solid soil particles, and the evaporation rate of hydrocarbon and water is different throughout the dried process; thus, the evaporation rate is not enough to remove all hydrocarbons of the soil; therefore, the equation of moisture content should be modified to take into account mass of diesel, mass of water and mass of dry soil.

3.3 Specific gravity of the solids

Figure 5 shows that the specific gravity of the solids is 2.69 for the control sample and 2.09 for the diesel content of

Fig. 5 Specific gravity of the solids

6% at 110 ± 5 °C, which represents a reduction of 22.3%. In both temperatures, the specific gravity of the solids decreases because the diesel is not totally evaporated off the soil structure, and some diesel adhered to soil structure of permanent way, which increases the volume of solid soil particles. At 50 ± 5 °C, the specific gravity goes of 2.53 to diesel content of 1% to 2.38 for the diesel content of 6%, which is a reduction of 5.93%. These results highlight that the specific gravity of the solids decreases with the addition of diesel, which is showed by different researchers [22]. On the other hand, to diesel content of 6% an unexpected change in the behavior of the property is evidenced, which is caused by the higher content of diesel that adhered to solid soil particles, and the higher temperature test generated a high evaporation rate of liquids; thus, the mass of the dry soil was minor.

In addition, this test is done with water, which might have carried out an increase in the specific gravity because clay particles are partiality hydrated; however, the diesel interacts with soil structure and does not allow the interaction with water added; therefore, the specific gravity decreases. The fact that the diesel adhered to solid soil particles might erode soil structure and reduce the strength which affects geotechnical properties and designs.

3.4 Atterberg limits

The consistency limits are characteristic to fine-grained soils and function of moisture content. Diesel substantially modified its values as shown in Table 1.

The liquid limit as control sample is 59.2%, and the diesel content of 6% is 65.0% at 110 ± 5 °C, which represents an experimental variation of 9.80%. At 50 ± 5 °C, the liquid limit in the diesel content of 1% is 55%, and in the diesel content of 6% is 62.3%, representing an experimental variation of 13.27%. The liquid limit is increased with diesel addition, and this behavior is explained by two reasons. The first is that diesel gives an additional cohesion to soil which needs more water to change the state, and the

Table 1 Results about liquid limit, plastic limit, shrinkage limit and plasticity index

	Diesel content						
	0%	1%		3%		6%	
	110±5 °C	110±5 °C	50±5 °C	110±5 °C	50±5 °C	110±5 °C	50±5 °C
Liquid limit (%)	59.2	59.9	55.0	64.8	58.6	65.0	62.3
Plastic limit (%)	29.7	28.6	30.0	30.0	29.5	31.1	30.9
Shrinkage limit (%)	23.9	23.1	19.8	22.4	20.0	22.3	26.0
Plasticity index (%)	29.5	31.3	25.0	34.8	29.1	33.9	31.4

second is that diesel does not decrease the diffuse double layer of the clays, which result similar with other authors [12, 22, 24]. On the other hand, the increase in liquid limit at 50±5 °C is smaller than at 110±5 °C because this temperature has higher evaporation rate; therefore, temperature is a key factor to calculate the magnitude of changes in soil properties.

The plastic limit is increased with diesel addition. For control sample, it is 29.7%, and for diesel content of 6% is 31.1% at 110±5 °C, which represents an experimental variation of 4.71%. For diesel content of 1%, it is 30.0%, and for diesel content of 6% is 30.9% at 50±5 °C, which represents an experimental variation of 3.00%. The increase in the plastic limits is explained because diesel adhered to the soil particles, which needs more water to change the consistency [12, 22, 24]. In addition, molding the ball and rolling it between the palms on the hands was complex and needed much time to get the plastic limit with the increase in diesel content because expelling diesel from the soil structure requires much time, and the soil with diesel tends to become harder near the limit.

The shrinkage limit is decreased with diesel addition at 110±5 °C. For sample control, it is 23.9%, and for diesel content of 6% is 22.3% at 110±5 °C, which represents an experimental variation of 6.69%. The decrease is attributed to the fact that diesel modified the surface properties of solid soil particles. For diesel content of 1%, it is 19.8%, and for diesel content of 6% is 26.0% at 50±5 °C, which represents an experimental variation of 31.3%; therefore, the shrinkage limit is increased. Nobody has reported an increase in the shrinkage limit. The test temperature is key to get correct values, and at 50±5 °C the evaporation rate was not enough to remove all the diesel in the structure of soil, and some diesel adhered to solid soil particles, for these reasons the property is increased.

The plasticity index for control sample is 29.5%, and for diesel content of 6% is 33.9% at 110±5 °C, which represents an experimental variation of 14.9%. For diesel content of 1% is 25.0%, and for diesel content of 6% is 31.4% at 50±5 °C, which represents an experimental variation of 25.6%. These results indicate that soil with diesel has more plasticity.

The changes in the liquid limit and plasticity index might modify soil classification defined in USCS (Unified Soil Classification System). All samples have a plasticity index that is very close to empirical boundary called the 'A' line; if diesel content was higher than 6%, the soil could change its classification of high-compressibility clay (CH) defined in USCS.

3.5 Cation-exchange capacity

The cation-exchange capacity CEC (mEq, 100 g) was calculated using correlations with liquid limit [23]. The experimental determination of CEC is complex and is done indirectly with procedures that are questioned because they modify the properties of the soil, and therefore, the correlations are good alternatives to use in this report.

$$\text{CEC} = 0.45 \text{ LL} - 5.00 \quad (\text{Farrar and Coleman 1967}) \quad (1)$$

$$\text{CEC} = 1.74 \text{ LL} - 38.3 \quad (\text{Smith et al. 1985}) \quad (2)$$

Farrar and Coleman's equation has a correlation coefficient of 0.90, and Smith et al [17] equation has a correlation coefficient of 0.85. Farrar and Coleman's equation was found empirically for British clay soils, and Smith et al [17] equation was found for Israel's clay, sandy clay loam, silty clay, and so on. Statically both methods found good relationships between liquid limit and CEC, but it was for certain clay minerals; therefore, it is better to use Farrar and Coleman's equation because samples were undisturbed clays that contained quartz, illite, kaolinite and montmorillonite minerals that are alike to the soil characteristics used in this investigation.

Figures 6 and 7 show that diesel increases the CEC because diesel adhered to the soil particles and generates an apparent flocculation, therefore the specific surface area is increased. The change in the specific surface area affects the diffuse double-layer thickness that is very sensitive to this property variation. Moreover, the equations are based on the liquid limit that increases with the addition of diesel.

Based on CEC results with Farrar and Coleman's equation, the classification of potential expansion in the soil is

Fig. 6 CEC at $110 \pm 5^\circ\text{C}$ Fig. 7 CEC at $50 \pm 5^\circ\text{C}$

very low independent of the test temperature. Now, based on CEC results with Smith et al [17] the classification of potential expansion is very high. The difference between both correlations is significant and modifies the interpretation of potential expansion because these equations were determined for some clay soil. The coefficient that multiplies the liquid limit in Smith et al [17] equation is 1.74, while Farrar and Coleman's equation is 0.45, which represents a great difference. Therefore, Farrar and Coleman's equation is more similar to the soil used, and thus the values are adopted and the potential expansion is low [7]. It is important to do laboratory tests to compare with theory results.

3.6 Unconfined compression strength

The dry density was 1.15 g/cm^3 as a control parameter, and for this purpose, the specimens were compacted in a mold of 91.13 cm^3 ; but, this process was not easy because the diesel was expelled in the compaction process. The samples after the failure in the compression process were tested to check moisture content that was in Sect. 3.2, so the control sample was tested at $110 \pm 5^\circ\text{C}$, and samples

Fig. 8 Unconfined compression strength

with diesel were tested at both temperatures. Figure 8 shows the mechanical behavior of the control sample and samples with diesel, which notices that strength and strain are reduced as diesel content increases. For diesel content of 1%, the strain is reduced by 38.6%, for diesel content of 3% the strain is reduced by 43.3%, and for diesel content of 6% the strain is reduced by 44.8% with respect to the control sample.

The failure of the samples was brittle. The strength is reduced from 357.1 to 199.4 kPa, which represents a reduction of 44.2%. Moreover, it is observed that the greatest loss of strength is presented for diesel content of 6%. This behavior is explained because the clay particles structure is destroyed by the diesel adhered to solid soil particles that have reorientation of water molecules and modify the adsorbed layers, which has relation with a higher cation-exchange capacity of the soil. This behavior was reported by different authors [5, 12, 16, 22], and they explain that water molecules interact with clay minerals to give a cohesive behavior and resist load; however, the diesel is not able to do it and reduces strength.

4 Conclusions

Diesel did not affect the mineralogical structure, considering that exposure period was short (7 days). The crystalline phases identified were three, the dominant mineral was quartz, and kaolinite and 14 Å clays were found in lower proportions with attenuations in the presence of diesel. The moisture content showed a tendency to increase without being proportional to diesel content at $110 \pm 5^\circ\text{C}$, and a tendency to decrease at $50 \pm 5^\circ\text{C}$. The specific gravity of the solids decreased. The limits of Atterberg were affected by diesel with an increase in liquid and plastic limits, but a decrease in shrinkage limits. The CEC increased, and

the classification of potential expansion was very low. The soil lost strength and reduced its ability to deform. When soil had diesel content of 1% and 3%, there was an indefinite behavior in the properties, and therefore, these percentages were a transition value for the soil behavior. Diesel adhered to solid soil particles, which increased the cohesion and generated apparent flocculation that might erode the soil structure. The test temperature affected the results, and its behavior was undefined and generated an uncertainty in the estimation of soil parameters. It is important to keep doing investigations with more time of exposition at diesel and more samples.

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Compliance with ethical standards

Conflict of interest The author declares that he/she has no conflict of interest.

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