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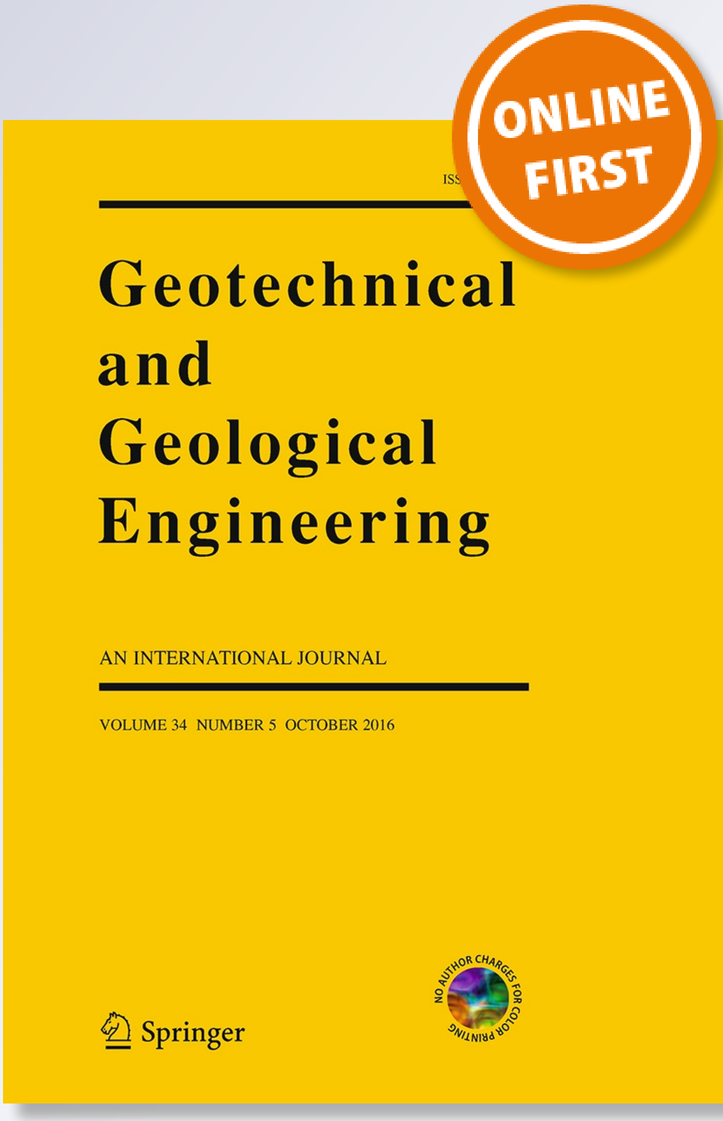

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ORIGINAL PAPER

The Effect of Diesel Fuel Pollution on the Efficiency of Soil Stabilization Method

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Abstract Chemical soil stabilization method can be applied as a remediation technique for contaminated soils. Since stabilization method can improve the soil geotechnical properties, the effect of contamination should be investigated on soil strength improvement with this method. This paper studies the effect of different additives such as lime, cement, rice husk ash and RRP-235 Special on the geotechnical properties of a diesel fuel contaminated kaolinite. A series of unconfined compressive strength and direct shear tests were performed on the contaminated kaolinite stabilized with additives in the amounts of 1, 3 and 5% by soil dry weight. Results showed that an increase in diesel fuel as contaminant up to 10% by dry weight of the soil had adverse effects on lime and rice husk ash stabilized soil strength and cohesion, while it increased the strength and cohesion of cement stabilized soil. The friction angle of all the lime, cement and rice husk ash stabilized samples was decreased with increasing the contaminant. An increase in RRP-235 Special had no impact on the soil strength properties.

Keywords Soil stabilization · Diesel fuel · Lime · Cement · Rice husk ash · RRP-235 Special

1 Introduction

The introduction of oil derivatives into soils not only changes their physical and mechanical properties (Kermani and Ebadi 2012; Khamehchiyan et al. 2007; Khosravi et al. 2013; Nasehi et al. 2016; Singh et al. 2008), but also imposes environmental risks. The soil stabilization method can be used in petroleum contaminated lands in order to decrease hydrocarbon concentrations in soils and leachates through volatilization, degradation and encapsulation (Schifano et al. 2007). Therefore, the contaminant movement and further ground water pollution may be prevented. Also soil mechanical properties can be improved through soil stabilization process.

For implementation of the projects in petroleum contaminated lands, the use of contaminated soil is encouraged in terms of economic aspects instead of utilizing soil removal and replacement. However geotechnical properties of the contaminated soil may not meet the project specifications. Given that soil stabilization method can improve soil mechanical properties and also remediate the contamination, applying this method on these kinds of soils is considerable in terms of economic aspects. Therefore, an evaluation of the effect of this method on

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mechanical properties of contaminated soils is of great importance.

Soil stabilization method is performed by means of physical, chemical, biological or electrical stabilization techniques. Chemical soil stabilization is usually performed by adding additives to the soil. Different types of these materials are generally divided into traditional (e.g. cement, lime, etc.) and non-traditional groups consisting of acidic stabilizers like RRP-235 Special (Reynolds Road Packer) and waste materials as rice husk ash which has gained lots of attention in recent years. In order to begin the soil stabilization process, some of these materials depending on their ingredients may require chemical compounds from soil minerals.

Few studies have been carried out to understand the effect of soil stabilization method on contaminated soils with organic fluids (especially petroleum hydrocarbons). Although mechanical properties of contaminated soils can be improved by adding binders (Shah et al. 2003; Tuncan et al. 2000), it is reported that some organic fluids may prevent the interaction between soil and the binder (Estabragh et al. 2015). However, evaluation of the efficiency of different additives with different ingredients will help us to better understand the effect of stabilization on the hydrocarbon contaminated soils.

Lime is one the conventional soil binders which is usually used in fine-grained soils to improve soil mechanical properties by cation exchange, flocculation/agglomeration and pozzolanic reactions. Reduced diffuse double-layer thickness by cation exchange changes the soil texture and results in a reduction in soil plasticity and swelling potential (Bhasin et al. 1978; Prusinski and Bhattacharja 1999). Long term pozzolanic reactions which produce hydrated cementitious products are considered as the main reason for developing strength in soil matrix (Diamond and Kinter 1966; Sherwood 1993). Cement is another practical binder which is widely used in soil stabilization. Hardening mechanism of cement is mostly based on hydration of tricalcium silicate. Strength improvement is the principal target of stabilizing soils with cement which is mainly gained by an increase in cohesion (Bell 1995). Improvement in soil mechanical properties such as decrease in plasticity index, increase in soil compressive and shear strength and bearing capacity with addition of cement in fine grained soils were reported (Anagnostopoulos 2015; Eskisar 2015; Mahamedi and Khemissa 2015; Khemissa and Mahamedi 2014; Pakbaz and Alipour 2012). The potential use of rice husk ash in soil stabilization method which results in lower construction costs has made it as an alternative to traditional binders. The ash produced from controlled burning of rice husk which is an agricultural waste mostly consists of amorphous silica. Application of this material solely or combined in soils improves the soil index properties (Alhassan 2008; Basha et al. 2005). Stabilizing contaminated lands with rice husk ash not only reduces the risks of remaining this material in the environment but also decreases the contamination migration and can improve soil geotechnical properties. RRP-235 Special is a liquid, water-soluble ion exchanger which acts as a catalyst in the soil. The ion exchanging mechanism of RRP impregnates the soil particles. As a result, soil may attain a much higher unit weight and strength.

There is lack of adequate data to fully understand the effect of oil and oil-derivatives contamination on the stabilization process. This study was carried out aimed to evaluate the effect of contamination on soil stabilization method efficiency by performing laboratory tests on the stabilized diesel fuel contaminated kaolinite. The tests were primarily performed on contaminated samples to study the effect of contamination on the soil mechanical properties. Then the clean and contaminated samples were stabilized and tested to evaluate the efficiency of the stabilization method on the samples. Since too many variable factors were included in this study, the subsidiary factors were maintained constant before performing the tests. Soil type was one of these factors which was selected from fine-grained clayey soils. Study of clay minerals is more important, since they have electrochemically active surfaces and thus more complex reactions occur between soil particles, contaminant and stabilizer. Since clay soils have a wide range of mineralogical composition, only one type of clay minerals, kaolinite, was used in the study. Unconfined compressive strength and direct shear tests were performed on the uncontaminated, contaminated and stabilized soils to determine the strength, cohesion and friction angle of the samples.

2 Materials

2.1 Soil and Diesel Fuel

Kaolinite used in this study is classified as clay of low plasticity (CL) according to unified soil classification system (ASTM D2487). The grain size distribution of

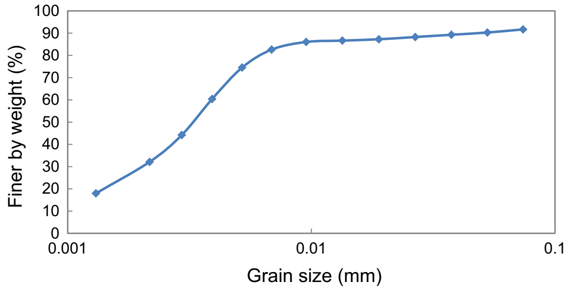

Fig. 1 Grain size distribution curve of the kaolinite

the kaolinite obtained from a hydrometer (ASTM D422) is shown in Fig. 1. Soil index properties were determined by performing specific gravity, consistency limits and standard proctor compaction tests on the clean kaolinite specimens according to ASTM D845, ASTM D4318 and ASTM D698, respectively. Results are given in Table 1. Chemical properties of pure kaolinite are summarized in Table 2. The diesel fuel properties used in this study are summarized in Table 3.

2.2 Binders

Four stabilizers consisting of lime, cement, rice husk ash and RRP-235 Special were used to stabilize the kaolinite. The main ingredient of RRP-235 Special is Sulphonic acid with the general formula RSO_3H, where R is an organic alkyl group.

The lime used in this study is commercially available hydrated lime with specific gravity of 2.28. The lime chemical properties are given in Table 4.

The cement used in this study is type II Portland cement (ASTM C150) with specific gravity of 3.07. Chemical properties are given in Table 4.

The rice husk ash was produced from burning rice husks in a furnace for 2 h. The temperature in the furnace was maintained at about 600 °C. Then, the ash was grinded in a ball mill grinder for 60 min. The results of chemical analysis are tabulated in Table 4. The specific gravity of the obtained ash is 2.15.

3 Specimen Preparation and Tests

3.1 Contaminated Samples

In order to make the results as comparable as possible, dry unit weight and moisture content were assumed almost the same in all the samples. In order to find these parameters, the compaction tests were performed on clean and contaminated kaolinite according to ASTM D698. According to Fig. 2, all the samples can be fabricated at the maximum dry unit weight for contaminated soil with diesel fuel in the amount of 20% by soil dry weight which is 13.5 kN/m^3. By selecting this point, the water contents of the samples changes from 6 to 14% by soil dry weight. Therefore, the average value of 10% was chosen as base water content. With this assumption, dry unit weights from 12.8 to 13.8 kN/m^3 are obtained from the figure. Therefore, the average value of 13.3 kN/m^3 was chosen as the base dry unit weight.

To prepare the contaminated soil, soil was passed through sieve no. 4 and oven dried for 24 h at 100 °C before mixing with diesel fuel. Diesel fuel in the amounts of 5, 10 and 20% by soil dry weight was manually mixed with soil for each specimen in closed plastic bags till the required homogeneity was obtained. Then the plastic bags were kept for 24 h at

Table 1 Geotechnical properties of the kaolinite

PL (%)	LL (%)	PI (%)	Specific gravity, G_s	USCS classification	$\gamma_{d_{max}}$ (kN/m^3)	W_{opt} (%)
25.7	44	18.3	2.60	CL	14.9	24

Table 2 Chemical analysis of the kaolinite

Compound	SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	Na_2O	K_2O	TiO_2	L.O.I.
Value (%)	63	24	1.2	0.55	0.55	0.4	0.3	0.04	9.96

Table 3 The diesel fuel properties

Unit weight at 25 °C (kN/m^3)	Ignition temperature (°C)	Self-ignition temperature (°C)	Boiling point (°C)
7.8–8.2	56	257	150–390

Table 4 Chemical composition of lime, cement and rice husk ash

Compounds	Lime (%)	Cement (%)	Rice husk ash (%)
CaO	73	64.07	0.96
SiO_2	0.45	21.25	89.56
Fe_2O_3	0.07	3.19	0.24
MgO	0.92	1.2	0.39
Al_2O_3	0.08	4.95	0.05
CO_2	0.81	0	0
SO_3	0	2.04	0.13
K_2O	0	0.63	1.53
NaO_3	0	0.38	0
Na_2O	0	0	0.09
P_2O_5	0	0	0.46
TiO_2	0	0	0.02
L.O.I.	24.67	2.29	6.57

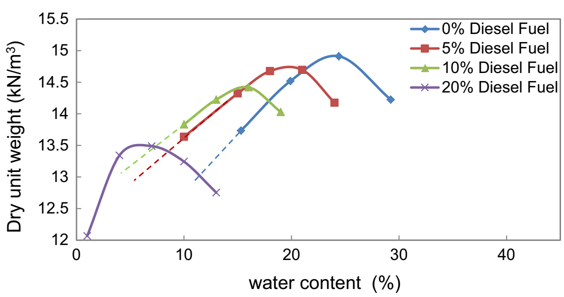

Fig. 2 Compaction curves for clean and contaminated samples

room temperature to achieve balance. Each bag was weighed after the balancing period in order to evaluate diesel fuel evaporation which was negligible. The diesel fuel contents were chosen from previous studies (Khamehchiyan et al. 2007; Khosravi et al. 2013). Then the specified water content was sprayed on the contaminated soils. After combining the mixture manually again, the contaminated soil was ready to prepare samples for each test.

3.2 Stabilized Samples

To make the samples as comparable as possible, all the stabilized samples were made with the same dry unit weight and water content as unstabilized samples. To prepare lime stabilized samples, lime in the amounts of 1, 3 and 5% by soil dry weight was added to the sieved and oven dried kaolinite and manually dry mixed for 1 min. Then the calculated amount of water was added to the mixture with a fine spray and mixed again for 5 more minutes (ASTM D3551). The mixing process was performed in closed plastic bags to prevent water evaporation. The similar procedure was performed in order to treat soils with cement and rice husk ash. To prepare RRP stabilized samples, at first water and RRP were thoroughly mixed and then added to the soil. Additive contents were chosen the same for comparison purposes. In the case of contaminated soil stabilization, at first the clean kaolinite was contaminated through procedure described in Sect. 3.1, then the contaminated soil was stabilized by adding additives and water similar to the procedure described above.

3.3 Unconfined Compressive Strength and Direct Shear Tests

Unconfined compressive strength (UCS) tests were performed using strain controlled application of the axial load with strain rate of 1 mm/min according to ASTM D2166. The prepared soil samples were compacted in four layers inside cylindrical molds (38 mm × 80 mm) to achieve the desired unit weight. Then the samples were ejected from the molds with a hydraulic extruder. Stabilized samples were wrapped with plastic films and stored for 7 days at 25 °C in waterproof containers under conditions which prevented moisture loss from the samples (ASTM D5102).

Direct shear tests were performed according to ASTM D3080 with controlled strain rate of 1 mm/min in order to study the effect of stabilization method on shear strength parameters of contaminated soils. In order to make the results as comparable as possible, the binders and water contents in stabilized direct shear samples were considered similar to unconfined compressive strength samples. The compaction of prepared soil was conducted in one layer in the shear box (60 mm × 60 mm × 25 mm). The samples were manually extruded from the mold to cure before testing. The curing conditions were similar to the one described for UCS samples.

4 Results and Discussion

4.1 Unconfined Compressive Strength Tests

4.1.1 Lime Stabilization

Unconfined compressive strength tests were performed on the clean, contaminated and lime stabilized soils. According to Fig. 3, in unstabilized samples (S + 0% L + 10% W + DF), an increase in diesel fuel up to 5% resulted in a higher strength. The slight increase in strength can be explained by the flocculated structure which is made by diesel fuel addition (Nasehi et al. 2016). It also indicates that adding lime improved the UCS of all the contaminated samples. Also the UCS of the stabilized contaminated samples decreased with increasing contamination content. The decrease in contaminated samples strength is more significant in higher lime contents which gets up to 16% with 20% diesel fuel in samples stabilized with 5% lime. This indicates that diesel fuel had an adverse effect on excess strength gained by pozzolanic reactions which can be due to the coating of soil particles with diesel fuel that inhibited the dissociation of alumino-silicates from soil particles. Unconfined compressive strength tests were also performed on lime stabilized samples made with different water contents to study the effect of water on the contaminated lime stabilized samples strength. Samples with pore fluid more than 30% couldn't be constructed due to presence of high pore fluid content. Results, shown in Fig. 4, indicate that the UCS of the lime stabilized samples is decreased with water addition. To evaluate the changes made in soil strength by pore fluid replacement, unconfined compressive tests results of contaminated samples made with water content of 10% and diesel fuel contents of 0, 5, 10 and 20% by soil dry weight and clean samples made with water contents of 10, 15, 20 and 30% by soil dry weight are depicted in Fig. 5. According to Fig. 5, samples containing diesel fuel reached higher strength values than the samples containing only water at the same pore fluid content. This can be explained by the changes in diffuse double-layer which is resulted from the pore fluid alteration. Given that the association of the clay particle with its double-layer controls the interaction with other particles (Lancellotta 2008), changing the pore fluid from water to diesel fuel, since diesel fuel is a nonpolar fluid and has a lower dielectric constant than water, results in an increase in soil shear strength (Olgun and Yildiz 2010; Rao 1985; Sridharan and Rao 1973, 1979). Since lime primarily modifies the soils by changing their diffuse double-layer thickness (Bell 1996), decrease in diffuse double-layer thickness with diesel fuel addition assisted the soil flocculation/agglomeration in presence of lime. Furthermore, soil shear strength is strongly dependent on pore fluid viscosity (Ratnaweera and meegoda 2006). Due to higher viscosity of diesel fuel, it is capable if resisting higher shear strengths than water.

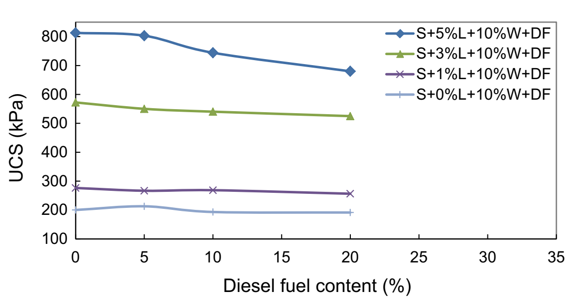

Fig. 3 Influence of different lime and diesel fuel contents on unconfined compressive strength of kaolinite (*S* soil, *L* lime, *w* water and *DF* diesel fuel)

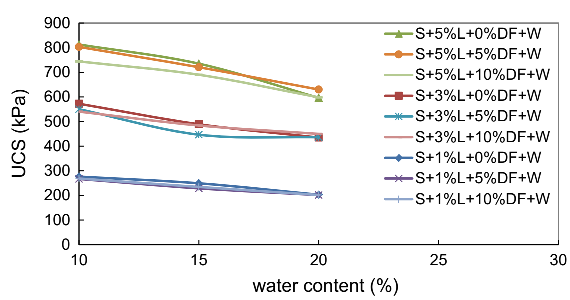

Fig. 4 Influence of different lime, diesel fuel and water contents on unconfined compressive strength of kaolinite (*S* soil, *L* lime, *W* water and *DF* diesel fuel)

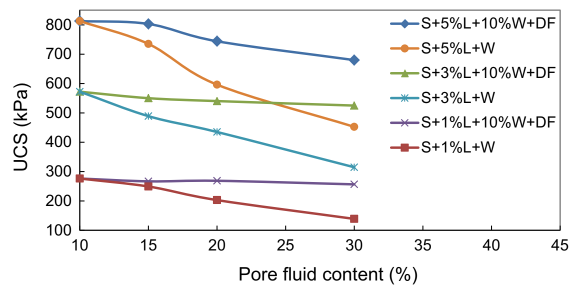

Fig. 5 Influence of different pore fluids on unconfined compressive strength of lime stabilized kaolinite (*S* soil, *L* lime, *w* water and *DF* diesel fuel)

This is in agreement with the variation of stabilized soil strength in the presence of diesel fuel instead of water presented in this study (Fig. 5).

4.1.2 Cement Stabilization

Unconfined compressive strength tests were performed on the cement stabilized soils to study the effect of a different binder with different ingredients on the contaminated samples strength. To make the results as comparable as possible, all the cement stabilized contaminated samples were prepared with the same amount of water (10% by soil dry weight) used in lime stabilized samples. Also different percentages of water were used instead of diesel fuel to compare the results. According to Fig. 6, cement addition increased the UCS of the contaminated samples. The overall gained strengths with addition of cement are higher than the samples stabilized with lime. According to Figs. 6 and 7, Stabilized samples containing diesel fuel reached higher strength values in comparison with samples made with water as the pore fluid at the same content. Also it is interesting to find that increasing diesel fuel up to 10%, not only had not adversely impacted the UCS of stabilized samples but also slightly increased the soil strength. Unlike lime, cement needs no other material from soil particles to produce cementitious compounds to start the soil stabilization. For this reason, diesel fuel addition up to 10% had no adverse effect on the excessive strength developed by cement. Pollard et al. (1991) reported that nonpolar organics do not hinder strength development in cementitious or pozzolanic systems. Tremblay et al. (2002) reported that oils and hydrocarbons, which are insoluble in water, delay the cement hydration but do not affect the final strength. Since the particles in fine-grained soils are much smaller than cement grains, by adding the cement, these soils are broken into small fragments coated with cement (Bell 2004). Contamination helps this process with changing the soil fabric from dispersed to a relatively flocculated fabric which increased the stabilization efficiency resulting in relatively higher strengths. The UCS of all the stabilized contaminated samples decreased with increasing diesel fuel up to 20% by approaching the soil saturation limit.

4.1.3 Rice Husk Ash Stabilization

The effect of rice husk ash was studied on the soil strength as an economical alternative to lime and cement. According to Fig. 8, the UCS of stabilized samples decreased with increasing the diesel fuel content. From low strength values gained by rice husk ash addition, it can be concluded that because of the calcium source deficiency, chemical reactions were unlikely happened in soil matrix during the given time. Slight increase in soil strength may be resulted from

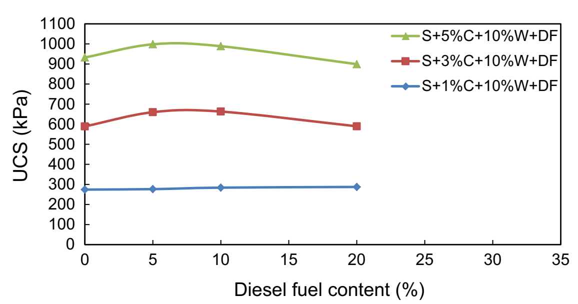

Fig. 6 Influence of different cement and diesel fuel contents on unconfined compressive strength of kaolinite (*S* soil, *C* cement, *w* water and *DF* diesel fuel)

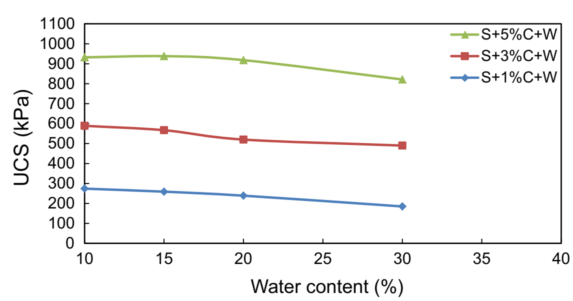

Fig. 7 Influence of different cement and water contents on unconfined compressive strength of kaolinite (*S* soil, *C* cement and *w* water)

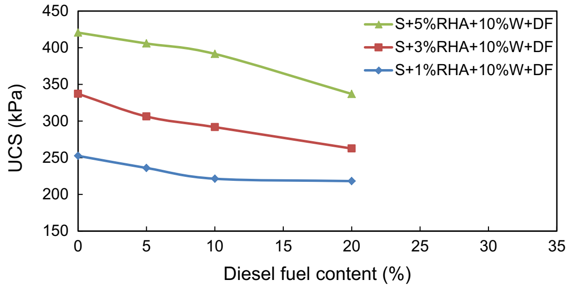

Fig. 8 Influence of different rice husk ash and diesel fuel contents on unconfined compressive strength of kaolinite (*S* soil, *RHA* rice husk ash, *W* water and *DF* diesel fuel)

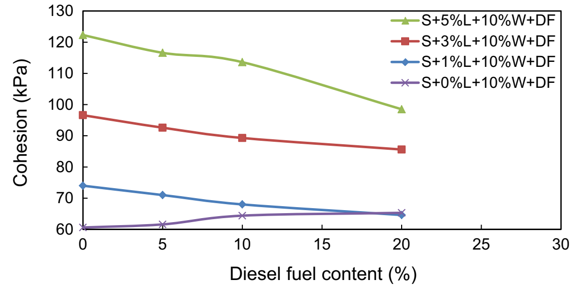

Fig. 9 Influence of different lime and diesel fuel contents on the cohesion of kaolinite (*S* soil, *L* lime, *W* water and *DF* diesel fuel)

reduced soil void ratio and the excessive structural strength gained by adding rice husk ash.

4.1.4 RRP Stabilization

Unconfined compressive strength tests were performed on RRP stabilized samples with the same dry unit weight and water content. Since the strength variations with increasing the RRP were negligible for the selected soil type and test conditions, no further tests were performed on this stabilizer.

4.2 Direct Shear Tests

4.2.1 Lime Stabilization

Direct shear tests were performed on the clean, contaminated and stabilized kaolinite in order to discover the effect of Diesel fuel on the cohesion, friction angle and shear strength of samples. Tests were performed in three different vertical stresses of 49.03, 98.06 and 147.09 kPa for each sample. According to Fig. 9, the cohesion of the unstabilized samples increased with increasing the diesel fuel content. The increase in cohesion can be due to the increased van der waals forces by diesel fuel addition. The alterations made in soils friction angle with lime and diesel fuel are shown in Fig. 10. The friction angle of the unstabilized samples decreased with increasing diesel fuel content which can be explained by the surface lubrication caused by diesel fuel. Figures 9 and 10 also indicate that the cohesion and friction angle of stabilized samples increased with increasing the lime content but the diesel fuel addition decreased the excessive cohesion and friction angle gained by the lime addition. The increase in cohesion and friction

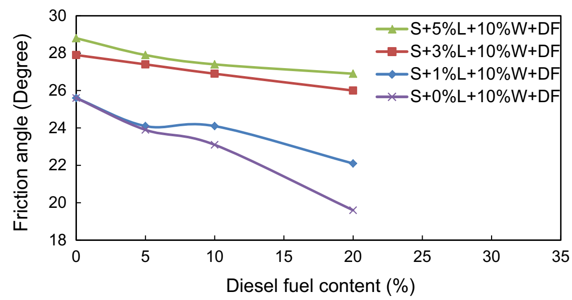

Fig. 10 Influence of different lime and diesel fuel contents on friction angle of kaolinite (*S* soil, *L* lime, *W* water and *DF* diesel fuel)

angle by lime addition is provided by the cementitious pozzolanic compounds formed in the given curing time. The decrease in cohesion and friction angle by diesel fuel addition indicates the destructive effect of the contamination on efficiency of pozzolanic compounds. The calculated shear strengths of the samples by the Mohr–Coulomb failure criterion are shown in Figs. 11 and 12. According to Figs. 11 and 12, although the diesel fuel addition had not significantly

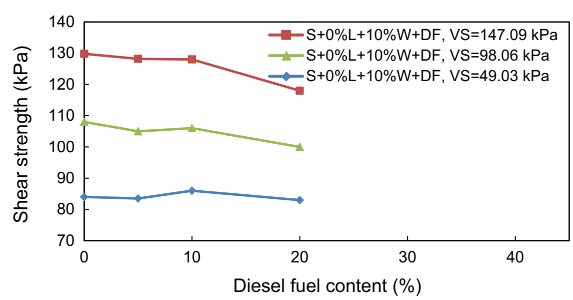

Fig. 11 Influence of different diesel fuel contents on shear strength of kaolinite samples with different vertical stresses (*S* soil, *L* lime, *W* water, *DF* diesel fuel and *VS* vertical stress)

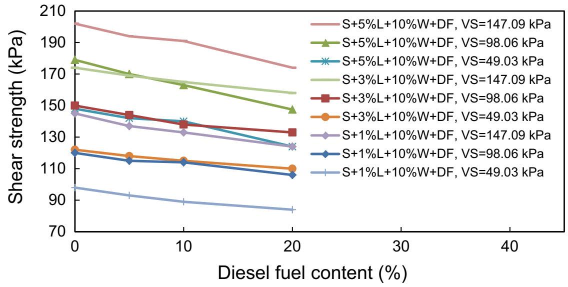

Fig. 12 Influence of different lime and diesel fuel contents on shear strength of kaolinite samples with different vertical stresses (*S* aoil, *L* lime, *W* water, *DF* diesel fuel and *VS* vertical stress)

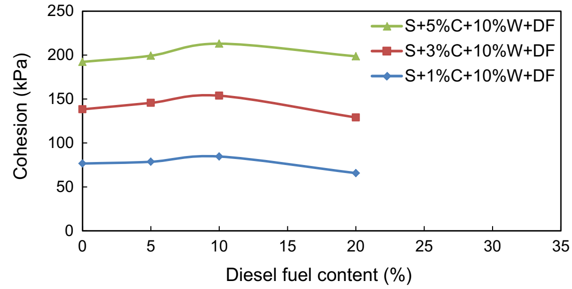

Fig. 13 Influence of different cement and diesel fuel contents on the cohesion of kaolinite (*S* soil, *C* cement, *W* water and *DF* diesel fuel)

changed the kaolinite strength, in presence of lime, diesel fuel decreased the shear strength of stabilized samples with different lime contents. The results are in agreement with the unconfined compressive strength test results.

4.2.2 *Cement Stabilization*

Figure 13 shows the effect of cement addition on the cohesion of the diesel fuel contaminated samples. Adding cement increased the cohesion of the kaolinite samples to relatively higher values than lime stabilized samples. The increase in cohesion is mostly gained by the hydration of the C_2S and C_3S available in cement. Also increasing the diesel fuel up to 10% increased the cohesion of the cement stabilized samples. However, unlike lime addition, the friction angle of the samples decreased with increasing cement content (Fig. 14). This reduction in friction angle can be explained by the high cohesion contents gained by cement addition which made the samples to act more like a soft rock. Also, diesel fuel addition decreased the friction angle of the samples which is caused by the lubrication effect of diesel fuel on the sheared surfaces. According to Fig. 15, the calculated amounts of shear strength show that increasing the diesel fuel up to 10% increased the cement stabilized samples shear strength, which is in agreement with the unconfined compressive strength test results. Increasing the diesel fuel up to 20% decreased the cohesion, friction angle and therefore the shear strength of the stabilized samples which is caused by the high content of pore fluid present in the soil.

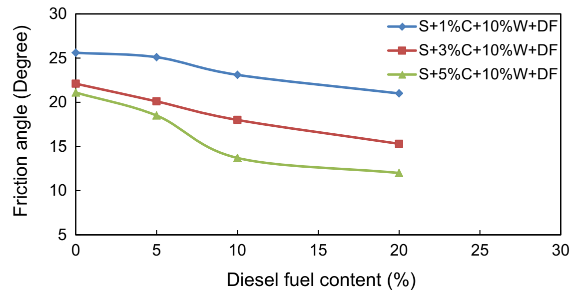

Fig. 14 Influence of different cement and diesel fuel contents on the friction angle of kaolinite (*S* soil, *C* cement, *W* water and *DF* diesel fuel)

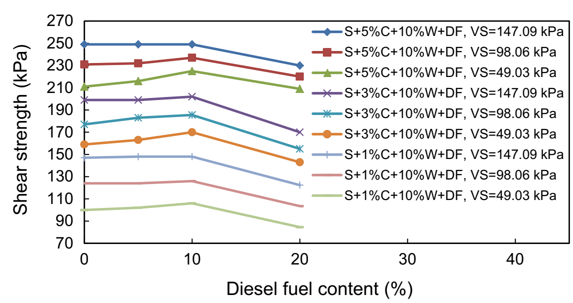

Fig. 15 Influence of different cement and diesel fuel contents on shear strength of kaolinite samples with different vertical stresses (*S* soil, *C* cement, *W* water, *DF* diesel fuel and *VS* vertical stress)

4.2.3 *Rice Husk Ash Stabilization*

According to Figs. 16, 17 and 18, the gained cohesion, friction angle and the shear strength of the rice husk ash stabilized kaolinite are reduced by diesel fuel addition. Despite the low values of strength gained by adding rice husk ash, using this waste material in soils accompanies economical and environmental benefits.

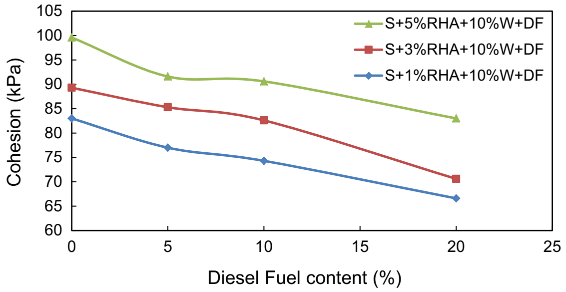

Fig. 16 Influence of different rice husk ash and diesel fuel contents on the cohesion of kaolinite (*S* soil, *RHA* rice husk ash, *W* water and *DF* diesel fuel)

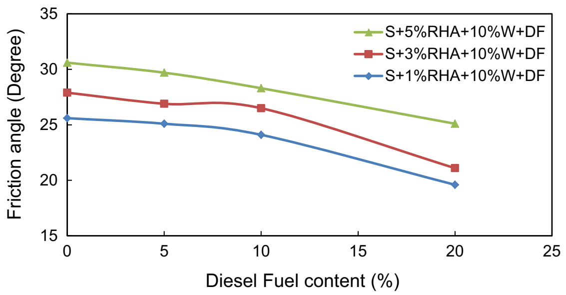

Fig. 17 Influence of different rice husk ash and diesel fuel contents on the friction angle of kaolinite (*S* soil, *RHA* rice husk ash, *W* water and *DF* diesel fuel)

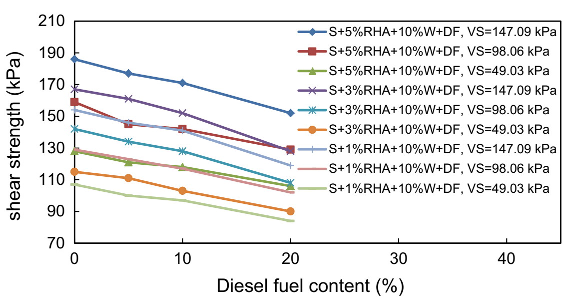

Fig. 18 Influence of different rice husk ash and diesel fuel contents on shear strength of kaolinite samples with different vertical stress (*S* soil, *RHA* rice husk ash, *W* water, *DF* diesel fuel and *VS* vertical stress)

The substantial findings from this paper demonstrate the deficiency of the previous studies on the effect of soil stabilization method on the soils contaminated with oil derivatives. Although the results of this paper showed that the effect of the stabilizer on the contaminated soil strongly depends on the nature of the stabilizer, which can be inhibited to work by the contamination, further microscopic examination should be implemented on the exact influence of diesel fuel on the pozzolanic reactions of the different soil stabilizers.

5 Conclusions

In this study, the effect of soil stabilization method with lime, cement, rice husk ash and RRP-235 Special was studied on the geotechnical properties of the diesel fuel contaminated kaolinite through laboratory program consisted of unconfined compressive strength and direct shear tests. Results indicated that an increase in lime, cement and rice husk ash increases the strength of the clean and contaminated samples. Also lime and cement stabilized contaminated samples showed relatively higher strengths compared to stabilized samples made with only water at the same pore fluid content. The unconfined compressive strength, cohesion and shear strength of the lime and rice husk ash stabilized samples reduced with increasing the diesel fuel content. These parameters however were increased in cement stabilized samples in presence of diesel fuel up to 10% by soil dry weight. The friction angle of the samples stabilized with lime, cement and rice husk ash was decreased with increasing the diesel fuel content. Increasing the contamination up to 20% decreased the unconfined compressive strength, cohesion, friction angle and the shear strength of the lime, cement and rice husk ash stabilized samples. Increasing water content in lime stabilized samples decreased the unconfined compressive strength of all the clean and contaminated samples. The application of RRP did not have any effect on the soil strength. It is recommended that further studies be carried out in the future on the other oil derivatives and also on the stabilizers with different compositions.

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