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Geotechnical properties of gas oil-contaminated kaolinite

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ABSTRACT

The leakage of petroleum products contaminates the soil and changes its physical and mechanical properties. This paper is a part of an extensive laboratory program aimed at promoting greater understanding of the influence of petroleum-derived contaminants on the geotechnical properties of soils. The laboratory tests included basic properties, Atterberg limits, consolidation, direct shear, and unconfined compression tests, all of which were carried out on clean and contaminated kaolinite specimens at the same relative compactions. Contaminated specimens were prepared by mixing kaolinite with different gas oil contents. Results indicate an increase in the cohesion and a decrease in both the friction angle and compressibility of kaolinitic soils with increasing the gas oil content. Results are intended to provide an alternative to the treatment methods currently used in practice for petroleum-contaminated sites and help bridge/narrow the gap between research and practice in environmental protection of the sites.

1. Introduction

The leakage and spillage of gas oil (also known as diesel fuel) from old and corroded storage tanks, pipelines, processing plants, and petroleum transportation facilities contaminate the surrounding soil. The extent of contamination depends on the filtration and retention properties of the soil (Fine et al., 1997). Such contamination not only results in immediate or future damage to the soil environment, but also changes the physical and mechanical properties of the soil. A variety of remediation methods such as vacuum extraction and separation by centrifuge, biological methods, and soil washing methods have been used to clean up the contaminated soil (Riser-Roberts, 1998). However, it is recognized that their implementation in practice is limited, especially for widely contaminated areas, due to the huge expense demanded. A clever solution could be the use of contaminated soil in civil engineering practice, including embankments, road bases, and backfills. In addition to the environmental concerns about groundwater pollution and other possible effects, an investigation on the geotechnical characteristics of the contaminated soil is required. The investigation can also be used to design a storage tank foundation in order to ensure that the foundation will satisfactorily serve its purpose during the tank's lifetime. The investigation also provides knowledge to revise the foundation design of the existing structures subjected to the contamination.

A number of studies have already been carried out on the geotechnical properties of the soils contaminated by petroleum hydrocarbons. Cook et al. (1992) experimentally investigated the compaction, compression, and strength properties of uniformly graded sands contaminated by crude oil. They reported that although oil contamination had no significant effect on the compaction characteristics, it decreased the friction angle and considerably increased the compressibility of the sand. Similar results were obtained by Puri et al. (1994) and Meegoda and Ratnaweera (1994) for sandy and clayey soils, respectively. Furthermore, the geotechnical properties of oil-contaminated Kuwaiti sand were studied by Al-Sanad et al. (1995). Again, results indicated a small reduction in strength and permeability as well as an increase in the compressibility of the sand. Later, Al-Sanad and Ismael (1997) reported an increase in the strength and stiffness for the oil-contaminated Kuwaiti sand due to aging and oil content reduction. Aiban (1998) investigated the influence of temperature on the geotechnical properties of the oil-contaminated sands and reported the insensitivity of their shear strength to the temperature in contrast to the compressibility of the soil which increased with temperature. A drastic reduction in the bearing capacity of a shallow strip foundation constructed over oil-contaminated sand was observed by Shin and Das (2001).

Studies on the geotechnical characteristics of fine-grained soils have just recently gained momentum. Khamehchiyan et al. (2007) studied the geotechnical properties of the oil-contaminated clayey and sandy soils and found a reduction in strength, permeability, maximum dry density, optimum water content, and Atterberg limits of these soils. Singh et al. (2008) found an increase of 35%–50% in the consolidation settlement of fine-grained soils upon contamination with petroleum hydrocarbons. They also introduced a correction factor to the empirical equation proposed by Skempton and Jones (1944) to estimate the

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compression index from the liquid limit. The model was further developed by Di Matteo et al. (2011) to predict the compression index of kaolinite contaminated with the ethanol–gasoline mixture. Recently, Kermani and Ebadi (2012) reported an increase in the friction angle, maximum dry density, compression index, and Atterberg limits with a reduction in optimum water content and cohesion of fine-grained soils in the presence of oil. A study on the behavior of piles embedded in sand contaminated with oil can be found in Nasr (2013).

The survey above shows that there is not a fair agreement among the findings of the studies performed on the geotechnical properties of oil-contaminated fine-grained soils. Also, the influence of specific fractions of petroleum such as gas oil, gasoline, or naphtha on the geotechnical properties of soils, especially fine-grained soils, has not been fully investigated. This paper summarizes the results of a part of an extensive laboratory program that was conducted to investigate the influence of gas oil on the geotechnical characteristics of kaolinite (Khosravi, 2010). There were two key reasons why pure kaolinite was selected for this study. First, kaolinite is one of the most common minerals in southern Iran, where most of Iran's refineries are located and the risk of soil contamination from oil fractions is high (Khamehchiyan et al., 2007). Second, it is presumed that the lack of a fair agreement among the results of the studies surveyed above could be partly attributed to the significant difference in the chemical components of the soils investigated. Therefore, restricting the investigations to a particular mineral (e.g., kaolinite) could provide valuable insights into the contribution of each mineral constituting a fine-grained soil to the interaction of the soil with the contaminant. It could also serve as a benchmark for future studies.

The laboratory program included Atterberg limits, consolidation, direct shear, and unconfined compression tests. High-resolution micrographs generated by the scanning electron microscope were used to show the content and spatial variation of gas oil in the contaminated kaolinite. Results show that increasing the gas oil content (in the range studied) increases the cohesion and decreases both the friction angle and compressibility of the contaminated kaolinite.

2. Materials

Pure kaolinite was chosen as a representative type for clays in this study. Table 1 summarizes the results of an X-ray diffraction (XRD) analysis used to identify and characterize the composition of kaolinite. Fig. 1 shows the grain size distribution of the kaolinite, determined by a hydrometer, according to ASTM D422.

Water pycnometer was used to determine the specific gravity, G_s, following ASTM D854. The plastic and liquid limits were determined based on ASTM D4318. The pH was also determined according to ASTM D4972. The modified Proctor compaction tests were carried out on the clean kaolinite specimens in order to determine the maximum dry density, based on ASTM D698. Results summarized in Table 2 indicate that kaolinite is classified as low plastic clay (CL), according to the United Soil Classification System (ASTM D2487). Table 3 includes the properties of the gas oil used in this study.

3. Specimen preparation

All specimens for the shear and consolidation tests were remolded in the test mold with static compaction in order to achieve homogeneity and uniformity as well as the required relative compaction. The sample preparation process is summarized in Fig. 2. The amount of kaolinite required for each test was first passed through Sieve #4 in order to remove clusters and agglomerated particles. The sample was then dried in a temperature of 105 °C for 24 h inside an oven. In the case of contaminated samples, the amount of gas oil was calculated as a percentage by the weight of the dried kaolinite. The percentages used in this study were 2, 4, 6, 12, 16, and 20. The range of contaminant content was chosen in accordance with the observed contamination level in contaminated sites as well as the ranges studied in literature (Khamehchiyan et al., 2007; Singh et al., 2008). The gas oil was then sprayed on a predetermined weight of dried kaolinite and manually mixed with it in order to obtain a visually homogenous mixture. Fig. 3 shows the kaolinite before and after contamination with 16% gas oil. The difference is not readily visible, which might be due to the natural color of gas oil and the low level of contamination. The mixture was placed in a covered container and kept in an oven in the temperature of 30 °C for 7 days to come to equilibrium. This period of time is consistent with the 3–7 day period proposed in the literature for soil–contaminant mixtures (Singh et al., 2008). The temperature was chosen according to the average temperature within a reasonable depth in the refineries and oil facility locations. The contaminated kaolinite sample was then used to prepare specimens for each test.

The gas oil evaporation from the specimens was examined by measuring the daily change in the weight of samples contaminated with different percentages of gas oil and kept in the oven at the temperature of 30 °C. Results showed that the evaporation occurred at a fairly high rate during the first week, but it continuously decreased with time until it ceased completely after almost four weeks. It was observed that the total gas oil evaporated from the samples was less than 3% of the amount of gas oil used to contaminate the soil. Therefore, the change in the gas oil content due to evaporation was considered insignificant. The relative compaction of all specimens in this study was kept constant and equal to 60% ($\gamma_d = 10.14$ kN/m^3). The relative density was also chosen according to the average relative densities reported at reasonable depths within the vicinity of the refineries and oil facilities (Khosravi, 2010).

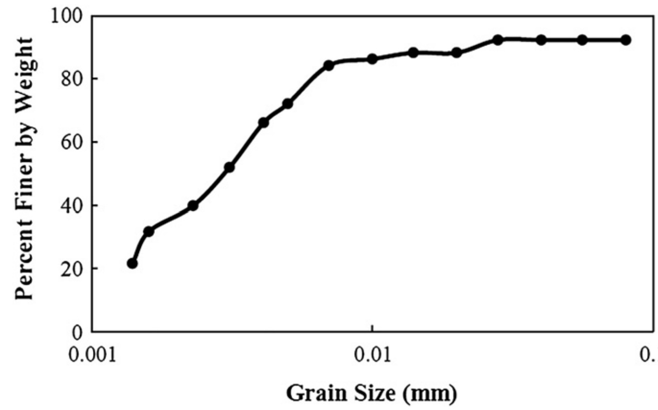

Fig. 1. Grain size distribution curve of the soil.

4. Tests and results

4.1. Scanning electron microscopy (SEM)

Scanning electron microscopy (SEM) was used to observe the microstructure of the specimens before and after contamination. Its results

Table 1
XRD analysis of the kaolinite.

Chemical component	SiO_2	Al_2O_3	CaO	Fe_2O_3	K_2O	MgO	Other
Percentage	67.51	26.33	1.89	0.49	0.44	0.40	2.94

Table 2
The kaolinite properties.

Uniformity coefficient, C_u	Coefficient of gradation, C_c	Specific gravity, G_s	PL	LL	PI	pH	USCS classification	$\gamma_{d_{max}}$ kN/m^3	w_{opt} %
2.5	0.45	2.60	26	45	19	9.6	CL	16.9	20