Experimental investigation of the effects of gas oil and benzene on the geotechnical properties of sandy soils

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Abstract
In recent years, there has been a dramatic increase in using oil hydrocarbons such as gas oil and benzene as the primary source of energy in transport and industrial sectors. Soil contamination is a significant public health problem. The contamination of soils by different hydrocarbons is increasingly recognized as a serious, worldwide public health concern and has become a central issue for geotechnical engineers. However, to our knowledge, no systematic studies have been conducted to investigate the effects of gas oil and benzene contamination on the geotechnical properties of sandy soils. Therefore, the present study investigates the impact of different percentages of benzene and gas oil contamination (0, 5, 10 and 15%) by the dry weight of two types of sandy soils on geotechnical properties of soils using several laboratory tests such as direct shear, compaction and permeability tests. The compaction test results showed that optimum moisture content declined in oil-contaminated samples. Moreover, the maximum dry density increased up to 5% oil content and then decreased by adding oil to the sandy soils. The direct shear test indicated that cohesion increased and friction angle decreased after oil contamination. The permeability test result revealed that contamination caused a decrease in permeability of sandy soil and the change was a function of oil content and viscosity of oils.

Keywords Gas oil · Benzene · Sand · Compaction test · Direct shear test · Permeability

Introduction
Soil contamination is one of the ordinary and controversial environmental issues worldwide [1, 2]. One of the major environmental problems today is hydrocarbons contamination resulting from the petrochemical industry’s activities [3]. Hydrocarbons such as gasoline, diesel fuel, gas oil, crude oil, coal oil and benzene have attracted the attention of researchers due to their various applications in different industrial sectors. However, their main problem is the threat posed to the environment by leakage from oil spillage [4], natural deposits [5], transporting petroleum [6], corroding pipelines, contamination during production and separation process [7]. Hydrocarbons contamination, which may occur intentionally or unintentionally, can penetrate into soil in various depths depending on the permeability of the soil, viscosity of the contaminant, etc. Hydrocarbons contamination affects the physical and geotechnical properties of the surrounding soil [7]. Shear strength, cohesion, internal friction angle, Atterberg limits, permeability and consolidation are among parameters that might be changed after contamination [8]. Different methods such as soil washing,
bio-remediation, thermal desorption have been proposed to purify soil from oil compounds [9], which are not economical [10]. The use of oil-contaminated soil in civil projects is a promising and cost-effective solution to reduce its adverse effects on the environment [7]. To date, researchers have carried out different studies to investigate the influences of hydrocarbons contamination on the geotechnical properties of soils [2, 11, 12]. Most studies in the field of oil contamination effects on fine-grained soils have focused on clayey soils [2, 13, 14]. A number of researchers have investigated the impact of pollution on different geotechnical properties such as the unconfined compressive strength, Atterberg limits, permeability, compressibility and consolidation behaviours [15–19]. Moreover, the triaxial shear behaviour of oil-contaminated clay [20] and cyclic behaviour of oil-contaminated clayey soil [21] have been studied. Despite the importance of using hydrocarbons contaminated sand in construction as a cost-effective and environmentally-friendly solution [22], there has been little discussion in this area so far. Much of the research in the field of hydrocarbons contamination sand up to now has been devoted to investigate the effects of engine oil, lamp oil, light crude oil, gasoline and kerosene on the geotechnical properties of sand [7, 8, 23–26], including internal friction angle [7, 8, 23, 24], cohesion [7, 8, 24], compaction behaviour [8, 23, 24], permeability [7, 8, 23, 24], small strain shear modulus [25] and liquefaction potential [27]. However, few studies have investigated the impact of gas oil on the geotechnical properties of sand. Nasehi et al. [15] examined the variation of the friction angle and cohesion of a poorly graded sand (SP) influenced by 3, 6 and 9% of gas oil contamination relevant to their dry weight. Their results showed that raising the gas oil content decreased the friction angle and increased cohesion. In another study, Saberian and khabiri [28] investigated the impact of different percentages of gas oil on the mechanical properties of sandy soil. The results showed that the internal friction angle declined with increasing the percentages of gas oil from 0 to 8%. Furthermore, adding the gas oil to the soil up to 5.25% led to slide the soil particles on each other easily which contribute to soil compaction. However, with increasing the percentage of gas oil from 5.25 to 8%, samples’ compatibility somewhat reduced. The unconfined compressive strength decreased from 105.2 to 69.8 kPa with increasing the gas oil percentage from 0 to 8%. This is mainly due to increasing the soil’s fluidity and reducing friction among particles [28]. In addition, the effects of hydrocarbons contamination on the bearing capacity of shallow foundations constructed on sandy soils, strip foundations near a slope and piles in oil-contaminated sand have also been taken into consideration [29–32].

Joukar and Boushehrian [29] investigated the bearing capacities of a shallow strip footing situated on the sand with gas oil in different thicknesses and percentages. The experimental results indicated that the footing’s bearing capacity located on the sand slope reduced remarkably by increasing the contamination percentage. Moreover, it was reported that the bearing capacity of the footing situated on gas oil decreased to 25, 32, 39 and 40% compared to pure sand as a result of increasing the contamination ratios to 1, 2, 3 and 4, respectively. Bearing capacity ratios showed that increasing the contaminated layer thickness led to a decrease in the bearing capacity for a constant contamination percentage. Besides, increasing the thickness of the gas oil-contaminated layer up to twice the company width reduced the strip footing bearing capacity up to 72%. Mohammadi et al. [30] investigated the impact of gas oil concentrations (2, 4, 6 and 8%) on the pile foundation’s bearing capacity. It was concluded that the net total, toe and shaft bearing capacities of pile decreased gradually with increasing the gas oil concentration up to 8%. However, the effects on the shaft bearing capacity were the most noticeable. Based on the authors’ knowledge, the impact of benzene on sandy soil properties have just investigated by Nasr [32]. It was reported that oil contamination adversely affected the shear strength parameters of sand. It was also observed that the friction angle reduced about 2.5% when the sand was contaminated with 2% of benzene, compared with its value for pure sand. A review of the literatures mentioned above shows that although there are some research studies conducted to investigate the effects of gas oil on the geotechnical behaviour of soils; however, there is a general lack of research on the effect of benzene contamination on sandy soil properties. Besides, no research has been found that surveyed a comparative study on the results of benzene and gas oil contamination effect on the geotechnical properties of sandy soils. Therefore, the aim of this study is to carry out several laboratory tests such as direct shear, compaction and constant head permeability tests on the clean, benzene- and gas oil-contaminated sand to evaluate the effects of contaminations on geotechnical properties of sandy soil.

Materials and methods

Soils and water

The sandy soil used in this study was collected from Shahryar sand and gravel mine located near Shahriar city, Iran. The soil was obtained from a depth of 1.5–3 m [13, 33]. Figure 1 illustrates the particle size distribution curves for two sandy soils used in the present research based on ASTM D6913 [34]. The properties of the used sandy soils are also shown in Table 1. Based on the values of $C_C$ and $C_u$, both samples are poorly graded sand [35, 36]. ASTM D854 [37] and ASTM D2434 [38] were used to determine the specific gravity and the hydraulic permeability of the samples.
respectively. Proctor compaction tests were also conducted following ASTM D698 [39] to obtain the maximum dry density and optimum moisture content of samples. Finally, direct shear tests were performed according to ASTM D3080 [40] to measure strength parameters. The quality of water can also affect the mechanical properties of stabilized soils and cementitious materials [41–43]. Accordingly, distilled water was used for the characterization tests and drinking water for moulding the specimens [44, 45].

**Benzene and gas oil**

The main objective of the present work is to investigate the effects of two different hydrocarbons on the engineering properties of the sandy soils. For this purpose, gas oil and benzene were selected as the target contaminants. The general features of these hydrocarbons, including viscosity and density, are summarized in Table 2.

| Characteristics                  | Results for S1 | Results for S2 |
|----------------------------------|----------------|----------------|
| Specific gravity ($G_s$)          | 2.69           | 2.67           |
| Maximum dry density ($\rho_{\text{max}}$/$\text{cm}^3$) | 1.96           | 1.69           |
| Optimum moisture content ($\omega_{\text{opt}}$%) | 13.76          | 13.05          |
| Permeability (cm/s)              | $72.5 \times 10^{-3}$ | $80.8 \times 10^{-3}$ |
| Void ratio ($q$)                 | 0.54           | 0.7            |
| $D_{10}$ (mm)                    | 0.17           | 0.122          |
| $D_{30}$ (mm)                    | 0.462          | 0.193          |
| $D_{60}$ (mm)                    | 0.94           | 0.257          |
| $C_c$                            | 1.34           | 1.16           |
| $C_u$                            | 5.53           | 2.1            |

**Preparation of contaminated soil**

In order to achieve artificially contaminated samples, the soil samples were dried at an oven temperature of 105 °C for 18 h [8, 15] and then mixed with different percentages of benzene and gas oil (0, 5, 10 and 15%) by the dry weight of sand. At first, benzene and gas oil were sprayed on the samples and the samples were then mixed manually to have a uniform and homogeneous mixture. Afterward, the samples were put inside a plastic container for 14 days to reach an equilibrium condition [49, 50]. The plastic containers were covered by a lid to prevent the evaporation of gas oil and benzene. The name of the samples is tabulated in Tables 3 and 4.

**Results and discussions**

**Compaction test**

The standard proctor compaction tests were conducted following ASTM D698 [39] and [51]. To calculate the moisture content of hydrocarbons contaminated samples, Eq. 1 was used [52].

$$\omega_{\%} = (1 + mn) \frac{W_t}{W_d} - (1 + n)$$  (1)

where $W_t$ is the wet weight of contaminated soil, $W_d$ is the dry weight of contaminated soil, $m$ (%) is the residual...
content of oil after drying and $n$ (%) is the oil content before drying. Figures 2 and 3 show the compaction tests results in the form of moisture content versus dry density. As indicated in Figs. 2 and 3, the bell-shaped compaction diagram for oil-contaminated samples tended towards the left side of the uncontaminated for both benzene and gas oil-contaminated samples. Therefore, the hydrocarbons-contaminated samples reached their maximum dry density in lower moisture content.

According to Fig. 4, the maximum dry density for both benzene- and gas oil-contaminated samples increased up to 5% oil content. Then the maximum dry density declined by increasing oil content in soil samples. Increasing maximum dry density in the hydrocarbons-contaminated samples could result from the lubricating effect of oils which facilitates the compaction [53]. For $S_1$ and $S_2$ samples, after adding 5% oil, the maximum dry density declined by increasing oil content. By increasing gas oil and benzene contents, the excessive volume of fluid in the sample could disperse the energy of the compaction test and the sample cannot be compacted well enough; accordingly, the maximum dry density declined by increasing oil content. The rate of changes in maximum dry density for gas oil-contaminated samples was higher than that of benzene-contaminated samples. This phenomenon might occur because gas oil had a more lubricating effect on the sand than benzene. Similar results have been reported by other researchers [23] and it has been observed that hydrocarbon with higher viscosity resulted in a higher rate of changes in maximum dry density. Furthermore, in the current study, the maximum dry density increased followed by a decrease with increasing the oil content. This trend was reported by other researchers. Shin and Das [23] reported an increase in dry unit weight after hydrocarbon contamination. Alsanad et al. [53] claimed that dry density increased with the presence of oil contamination up to 4% and for 6% oil contamination the dry density decreased.

Figure 5 illustrates the influence of benzene and gas oil content on the optimum moisture content. As indicated in Fig. 5, an increase in oil content for $S_1$ and $S_2$ samples caused a decline in optimum moisture content and other researchers have declared similar results for optimum moisture content [15, 23, 52, 53]. As shown in the previous paragraph, gas oil and benzene had a lubricating effect, which could reduce the friction between the sand particles; therefore, by less moisture content, samples could gain their maximum dry density. Moreover, the same as dry density, variation in moisture content is higher for gas oil-contaminated samples compared to benzene-contaminated samples. In the same way, the lubricating
In the present study, to determine shear strength parameters, the direct shear tests were carried out. Some direct shear tests were conducted on the uncontaminated and hydrocarbons-contaminated samples. The direct shear tests were performed according to ASTM D3080 [40]. The square box was selected with dimensions (10 cm × 10 cm). The direct shear tests were performed with different normal stresses (50, 100, 150, 200 and 250 kPa) under drained conditions. The direct shear tests were carried out under a constant rate of 0.7 mm/min that is proposed by ASTM D3080 [40]. Figures 6 and 7 illustrate the normal stress versus shear stress during direct shear tests. Figure 6 indicates the results of direct shear tests on the $S_1$ samples based on the shear stress versus normal stress. In the same way, Fig. 7 indicates the results of direct shear tests on the $S_2$ samples. As can be seen, increasing the percentage of oil resulted in the slope of the line to decline and the intercept to raise, which shows a decline in the angle of internal friction and an increment in cohesion.

As shown in Fig. 8, increasing gas oil and benzene contents resulted in a decrease in the angle of internal friction for $S_1$ and $S_2$ samples. The rate of changes in friction angle effect of gas oil due to higher viscosity could be the cause of this difference.

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1. According to standard Proctor test results, the bell-shaped compaction diagram for hydrocarbons-contaminated samples showed a tendency to the left side of the uncontaminated sample, which means that hydrocarbons-contaminated samples reached to their maximum dry density in lower moisture content.

2. Based on the results of the compaction tests, maximum dry densities increased up to 5% oil content. By increasing gas oil and benzene contents more than 5%, the maximum dry densities decreased due to the dissipation of compaction energy by excess fluid in the pore space.

3. The rate of changes in moisture content and maximum dry density for gas oil-contaminated samples was higher than that of benzene-contaminated samples, which were attributed to the different viscosity of hydrocarbons.

4. The results of the direct shear tests demonstrated that even though cohesion increased in hydrocarbons-contaminated samples, the internal friction angle decreased.

5. The results of the direct shear tests revealed that the rate of changes in cohesion and internal friction angle for samples contaminated with gas oil was higher than that of benzene contaminated samples. The viscosity of gas oil is higher than the viscosity of benzene resulting in the more lubricating effect of gas oil than benzene.

6. The constant head permeability test showed that gas oil and benzene reduced the hydraulic permeability of samples. The rate of changes in hydraulic permeability was a function of oil content and viscosity.

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Compliance with ethical standards

Conflict of interest There is no conflict of interest.

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