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Interface shear between different oil-contaminated sand and construction materials

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Abstract. The aim of this paper was to investigating the effects of soil relative density, construction materials roughness, oil type (gasoil, crude oil, and used motor oil), and oil content on the internal and interface shear behavior of sand with different construction materials by means of a modified large direct shear test apparatus. Tests conducted on the soil-soil (S-S), soil-rough concrete (S-RC), soil-smooth concrete (S-SC), and soil-steel (S-ST) interfaces and results showed that the shear strength of S-S interface is always higher than the soil-material interfaces. Internal and interface friction angles of sand beds increased by increase in relative density and decreased by increasing oil content. The oil properties (especially viscosity) played a major role in interface friction behavior. Despite the friction angles of contaminated sands with viscous fluids drastically decreased, it compensated by the apparent cohesion and adhesion developed between the soil grains and construction materials.

Keywords: internal and interface shear strength; sand; gasoil; crude oil; used motor oil; relative density

1. Introduction

Load transfer between structures and soils is highly dependent on the behavior of a thin layer of soil forming close to the structure surface. This layer which commonly known as the “interface”, acts as a transition zone between two dissimilar materials, namely the stiffer structural material and the softer soil media (Lashkari 2011). In the design of most of the earth structures like shallow foundations, deep foundations (piles), retaining walls, and reinforced soils, it is essential to understand the soil-structure interaction mechanism (Tejchman and Wu 1995). Friction between construction materials and soils is of significant concern in soil structure interaction problem. So, it is necessary to know the friction behavior between soils and different construction materials in order to assess the stability of geo-structures. The mechanical behavior of interfaces is affected by both the surface characteristics of the construction material and the soil properties (Evgin and Fakharian 1996). For the design of geotechnical structures, interface tests have been performed to determine soil-structure interface shear strength. Several researches have been carried out to investigate the soil-structure interaction. Probably, as a first complete and systematic experimental investigation, the interface shear behavior of different soils and construction materials has been studied by Potyondy (1961). He conducted direct shear tests on the interface of sand, sandy silt, cohesive soil and rock flour with concrete, steel, and wood and measured the ratio of skin friction and adhesion. He also proposed ratios for design frictional resistance of construction materials with soils and revealed that the normal load, surface roughness, soil composition, and moisture content have significant influence on the interface strength. Following the forerunner work by Potyondy, the behavior of interface has been the subject of several experimental and numerical investigations. Various methods and different kinds of apparatus were used in the literature to determine the interface friction angle between soil and solid construction materials such as conventional and improved direct shear apparatus (Kulhawy and Peterson 1979, Hryciw and Irsyam 1993, Yin *et al.* 1995, Tejchman and Wu 1995, Shahrour and Rezaie 1997, Ghionna and Mortara 2002, Zeghal and Edil 2002, Hu and Pu 2004, Tiwari *et al.* 2010, Laskar and Dey 2011, Gireesha and Muthukkumaran 2011, Al-Adhadh 2013, Narayanan and Perumal 2015), the ring shear and torsional ring shear device (Yoshimi and Kishida 1981, Lemos 1986, Tika-Vassilikos 1991, Ramsey *et al.* 1998, Hammoud and Boumekik 2006), and the simple shear device (Uesugi and Kishida 1986a,b, Uesugi *et al.* 1988, Uesugi and Kishida 1989, Uesugi *et al.* 1990, Paikowski *et al.* 1995, Evgin and Fakharian 1996, Shakir and Zhu 2009). Despite the formal variance, the devices can roughly be classified into the categories of simple shear test devices and direct shear test devices. Various materials with different roughness have often been employed to highlight the factors controlling the interactions between the two media. Previous studies dealing with interface behavior have shown that the Mohr-Coulomb failure criterion can be used to describe the interface strength (De Gennaro and Frank 2002, Nisha and Divya 2013) and the mobilization of friction depends on various factors, such as the roughness of the interface surface, physical and chemical characteristics of the soils, the relative density of the sand, the stress level, and the sand bed volume change behavior (Ghionna and Mortara 2002).

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Oil and its derivatives such as gasoline, gasoil, kerosene, etc. are the main sources of energy in transportation and industry sectors. For a long time, oil products have been contaminated the soil through storage, transportation, and accidents. Oil products contain some materials that may remain in the soil and adhere to the soil particles for a long time (Wang *et al.* 2009). There is a lot of technologies which have conducted for the remediation of oil-contaminated soils, but most of them were costly and effective in certain sites (Wu *et al.* 2015). Contamination of the soils by the oil products not only affect the quality of the soil but also change the physical and geotechnical properties of oil-contaminated soils. This might resulted in some problems for the stability of the structures that rested on the polluted soils like reduction in the bearing capacity of shallow and deep foundations and differential settlement. Due to the lack of suitable lands for the construction of buildings and other civil engineering structures such as roads, oil refineries, industrial facilities, and water/oil storage tanks, these structures should be constructed on the oil-contaminated sites that are prevalent in the oil-producing countries. In order to study the effect of oil products on the soils having knowledge about the interaction mechanisms between oil and soil grain surfaces could be beneficial. Soil constituents, type and content of oil products and water content in the soil media can influence interaction mechanisms (Rahman *et al.*, 2010). For any action on the oil-contaminated sites including remediation or using as a foundation, having knowledge about the geotechnical properties of them is crucial. In this regard, examining the influence of oil products on shear strength and stress strain behavior of the contaminated soils is important. In recent decades, a lot of research have been conducted on the geotechnical properties of the soils contaminated by chemicals especially oil products. As an early research, Lukas and Gnaedinger (1972) reported the failure of the foundations in the three industrial complexes due to dissolution and chemical reactions in the subsoil materials contaminated by chemicals. After that, many geotechnical parameters including compaction behavior (Cook *et al.* 1992, Al-Sanad *et al.* 1995, Al-Sanad and Ismail 1997, Puri 2000, Khamechiyan *et al.* 2007, Rahman *et al.* 2010, 2011, Shaheen 2011, Nasehi *et al.* 2016), shear strength behavior (Lorincz 1984, Cook *et al.* 1992, Evgin and Das 1992, Puri *et al.* 1994, Al-Sanad *et al.* 1995, Al-Sanad and Ismail 1997, Puri, 2000, Ghali, 2001, Shin *et al.* 2002, Khamechiyan *et al.* 2007, Rahman *et al.* 2010, 2011, Shaheen 2011, Sim and Lee 2012a, Nasehi *et al.* 2016, Mohammadi *et al.* 2019a, b), hydraulic conductivity (Al-Sanad *et al.* 1995, Puri 2000, Shin *et al.* 2002, Khamechiyan *et al.* 2007, Rahman *et al.* 2010, Chew and Lee 2010, Shaheen 2011), and one dimensional compression (Cook *et al.* 1992, Puri 2000, Khamechiyan *et al.* 2007) have been investigated. However, most studies conducted have been focused on the effects of oil contamination on the geotechnical properties of the soils. In addition, the mechanical characteristics of the pure (uncontaminated) soil-solid interfaces have been widely investigated, but a limited number of studies examined the effect of oil-contamination on interface shear behavior of soils and different construction materials. Having a proper knowledge about the oil-contaminated soil-material interfaces have significant importance in analysis and design of piles in oil-contaminated soils. Soil contamination vastly affects the soil-pile interface shear strength (and subsequently shaft friction) and could significantly decrease the ultimate compressive and uplift capacity of piles (Nasr 2013, Mohammadi *et al.* 2019a). As a few rare research in this field Sim and Lee (2012b, 2013) investigated the interface shear behavior of steel and concrete with palm biodiesel contaminated sand by using a direct and a modified simple shear apparatus, respectively. They found that the interface roughness and palm biodiesel content are the most influential parameters that affect the shear behavior. Mohammadi *et al.* (2017) conducted some direct shear tests between crude oil contaminated sand and concrete with different roughness. Based on the results, concrete roughness and oil contents have significant impact on the shear strength of contaminated soil-concrete interface. An important aspect which fails to be accounted for by the existing interface articles is the effect of the oil type (mainly oil viscosity) on the interface friction behavior of sand with different construction materials.

The object of this paper was to assessing the variations of shear strength parameters of different oil-contaminated sand-structural materials interfaces as a function of oil type, oil content, materials roughness, and soil relative density, using a modified large direct shear test apparatus.

2. Materials and methods

2.1 Sand

The air-dried medium crushed quartz sand used in this study was obtained from Silica Sand MFG Company. The sand used was angular and it has very low impurity level with a quartz ($SiO2$) content of 97.5%. For sandy soil, it is possible to obtain desired densities (Nasr, 2013). Laboratory tests were conducted on representative sand samples for gradation (ASTM D422), specific gravity (ASTM D854), maximum and minimum dry density (ASTM D4253 & D4254), and water content (ASTM D2216). From the sieve analysis conducted on the sand samples with reference to Unified Soil Classification System (USCS, ASTM D2487), the sand is classified as poorly graded sand (SP). The physical characteristics and chemical composition of this sand are summarized in Table 1 and Table 2, respectively. The grain size distribution curve of the sand is shown in Fig. 1.

2.2 Interface materials (Construction blocks)

For choosing the structural materials which used in the tests, applicability of these materials in the field of civil engineering were considered. Nowadays, steel and concrete are the most important construction materials which may have direct contact with contaminated soils and thus in this study, one low carbon structural stainless steel interface and two different concrete interfaces with different degrees of roughness have been used for interface friction studies

Table 1 Basic properties of the tested sand

Item	Quantity
Product Name	D1
Effective particle size (D_{10}) (mm)	0.6
Average particle size (D_{50}) (mm)	1.72
Uniformity coefficient, C_u	2.983
Coefficient of curvature, C_c	1.526
Maximum dry unit weight, $\gamma_{d,max}$ (kN/m^3)	18.02
Minimum dry unit weight, $\gamma_{d,min}$ (kN/m^3)	15.64
Maximum void ratio, e_{max}	0.655
Minimum void ratio, e_{min}	0.437
Specific gravity, G_s	2.642
Coarse to medium sand (%)	95
Fine sand (%)	5
Classification	SP
Water content, W_c (%)	0.09

Table 2 Chemical composition of the tested sand

Compound	SiO_2	Al_2O_3	Fe_2O_3	K_2O	CaO	MgO	L.O.I
%	97.5	0.95	0.85	0.19	0.27	0.24	0.0

L.O.I: Loss on Ignition

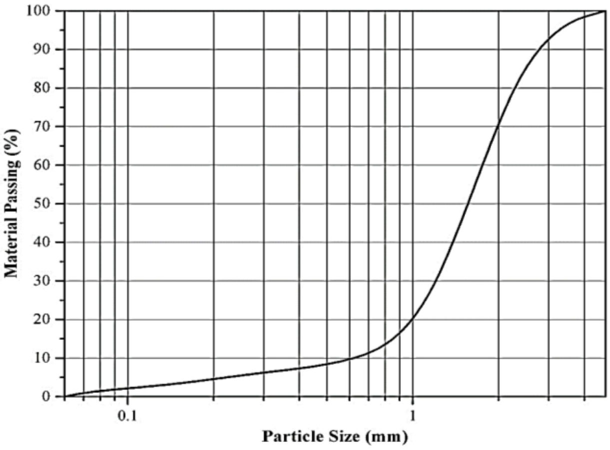

Fig. 1 Grain-size distribution curve for the tested sand

(Potyondy 1961). Stainless steel interface was used to avoid roughness changes during testing due to rust.

The quality of steel was that of common, commercial stainless steel (316L), which is widely used for piles, sheet piles, etc. At first, two pieces of concrete block were made with dimensions of 300 mm*300 mm*75 mm (blocks 1 & 2) and a piece of concrete block was made with dimensions of 300 mm*300 mm*72 mm (block 3). For obtaining a smooth concrete surface, a clean and smooth tile located on the one side of the concrete box (Canakci *et al.*, 2011). Concrete samples were prepared with water:cement (w/c) ratio of 0.58 and cured for 7 days. Prior to curing, a steel brush was used to make grooved surface on block 2, in order to create concrete with rough surface. Moreover, the structural steel was machined into a square plate specimen with the dimensions of 300 mm*300 mm and 3 mm in

Table 3 Summary of surface roughness

Specimen	Surface roughness, R_a (μm)	Relative Roughness, R
Steel	0.384	2.233*10^{-4}
Smooth Concrete	2.93	1.703*10^{-3}
Rough concrete	28.54	1.659*10^{-2}

Table 4 Summary of oil properties

Test Item	Standard	Unit	Gasoil	Crude oil	Used motor oil
Kinematic viscosity (25° C)	ASTM-D7042	mm^2/s	4.418	14.60	260.6
Density (15° C)	ASTM-D1298	g/cm^3	0.841	0.875	0.849
Density (25° C)	ASTM-D1298	g/cm^3	0.834	0.868	0.888
Specific gravity	ASTM-D4052	-	0.836	0.870	0.890
Pour point	ASTM-D97	°C	-9	-36	-27

thickness and pasted on block 3, and the whole blocks were fitted into lower part of the direct shear apparatus.

Many investigators have shown that surface roughness plays a major role in interface behaviour (Uesugi and Kishida 1986a, b, Paikowski *et al.*, 1995). Surface roughness of construction materials and mean particle diameter of the sand are the most important factors that influence the maximum coefficient of friction (Uesugi *et al.* 1990). Thus, the effects of them are combined with the influence of Normalized Roughness. This method was proposed by Subba Rao *et al.* (1998) and by normalizing average roughness with respect to the average diameter of the soil particles D50, the relative roughness R was adopted. The average diameter of the studied soil obtained from the particle size distribution curve (Fig. 1). R is defined as (Hammoud and Boumekik, 2006):

$$R = \frac{R_a}{D_{50}} \tag{1}$$

Hence, measurements of the roughness were made by means of *Perthometer M3* (Mahr, UK). Typical measured surface roughness values of steel and concrete specimens are shown in Table 4. Since the pattern of asperities along the surfaces of steel and concretes was not uniform, the average value of roughness parameters computed in 10 different locations was taken into consideration (Hammoud and Boumekik, 2006). In this study, three extreme surface roughness were used, a smooth steel surface, R_a=0.38 μm, a smooth concrete surface, R_a=2.63 μm, and a rough concrete surface, R_a=28.54 μm.

2.3 Oil properties and contaminated-sand preparation

In this study, three different types of oil were used for the testing program. These are gasoil, crude oil, and used motor oil. Gasoil and crude oil supplied from Tehran Oil Refinery and used motor oil obtained from a domestic supplier. In the case of oil-contaminated soils, the influence of oil on the behavior of soil mainly depends on the characteristics of oil and soil particles (Nasr 2009). Therefore, the type of oil is one of the important factors that affect the angle of internal friction and the interface friction angle of construction materials and sand. Table 4 is a summary of the basic oil properties including kinematic viscosity, density, specific gravity, and pour point. The tests on the oils used were performed at Oil and Fuel Reference Laboratory, at the temperature equal to 25±1°C. The chemical composition of the oils used in the experimental work was a mixture of aliphatic and aromatic hydrocarbons.

In the case of contaminated soil, the amount of oil was calculated as a percent by weight of the air-dried sand. Contaminated-sand layers were prepared by mixing thoroughly the sand with an organic content of 0, 2, 4, and 6% by dry weight to match the field conditions. No water was added to the soil samples during the test, to exclude the effects of free water on the test results. The mixed sand layers were put into covered containers for 3 days before the tests for aging and equilibrium (Khamehchiyan *et al.* 2007). For various reasons, the sand specimens were not oil saturated when conducting interface tests. There is a lack of information in literature on the mechanical behaviour of the oil-saturated sand. Only Evgin & Das (1992) conducted some triaxial tests on clean and saturated motor oil-contaminated sand. Based on their results full saturation with motor oil considerably reduced the friction angle of both loose and dense sand. In order to investigate the effect of density on the internal and interface shear behavior, the sand-sand, sand-steel, and sand-concretes interface shear tests were performed on loose (D_r=30%), medium (D_r=50%) and dense (D_r=70%) soil samples for both clean and oil-contaminated soil samples. For this sand, void ratios, e, of 0.502, 0.546, and 0.590, corresponding to relative density of 70%, 50%, and 30% were used. Sand samples have been reconstituted pouring known amount of dry and contaminated sand inside the upper half of shear box 300 mm*300 mm*75 mm. Density states are controlled by calculating the amount of the sands needed to obtain the desired relative density.

2.4 Direct shear apparatus

To determine the strength of oil-contaminated soils, and skin friction between soils and construction materials, strain controlled large direct shear test apparatus (ELE, England, with dimensions of 300 mm*300 mm*150 mm, Fig. 2) was used to evaluate the shear strength of soil and the frictional resistance between the soil and different types of structural materials. It is now well established in the literature that the ring shear apparatus offers the best means of studying shearing resistance when soils undergo large displacements (Yoshimi and Kishida 1981, Jardine *et al.* 2005, Ho 2007, Yang *et al.* 2010, Ho *et al.* 2011). This is due to the unlimited shear displacement (Kishida and Uesugi 1987), ability of free deformation with little constraint which resulted in failure along the weakest plane during the shearing test (Hu *et al.* 2010) as well as imposing shear displacements in the range of those experienced by the pile shaft (Yang *et al.* 2010). Both because of difficulties in preparing specimen and measuring deformation and because of limited access to this ring shear device, other shear test devices are in use (Ramsey *et al.* 1998, Hammoud and Boumekik 2006, Zhang and Zhang 2009), despite that the ring shear tests matches large-displacement conditions adjacent to a driven pile shaft better than other laboratory tests. As mentioned by a lot of researchers (Kulhawy and Peterson 1979, Yin *et al.* 1995, Hu and Pu 2004, Tiwari *et al.* 2010), the direct shear test, due to its simplicity and relative low testing costs, is an appropriate tool for studying the frictional interaction behavior between sand and solid inclusions. The conventional direct shear devices can only accommodate small size specimens, which impose serious limitations in terms of reproducing real conditions (Vieira *et al.* 2013). Based on this evidence, a large scale direct shear test device able to perform displacement controlled tests was used. This apparatus has a shearing area of 900 cm^2. The data generated from this size of apparatus are considered reliable according to the finding of O'Rourke *et al.* (1990) that the size of test plate (from 60 mm to 305 mm square) has no influence on the values of interface friction angle between sand and solid surfaces. A specific modification has been done on the large direct shear box to evaluate the frictional resistance. The device has a capability of handling interfaces and attaining displacements as large as 300 mm. The shear box is assembled in the testing machine, with the construction material in the bottom half and the clean/contaminated sand placed in the top half of the box. The surface of each half was lubricated to allow the container to follow the deformation of sand mass with minimum friction resistance. The air-dried sand was placed inside the upper shear box, with relative densities of 30%, 50%, and 70%. It was compacted in three layers with 25 mm height to the target unit weight. A porous steel plate is placed above the specimen and below the construction material and gentle pressure on the upper porous plate forced the specimen into the correct position for testing. The loading head is then assembled. Normal and tangential loads are applied by the vertical and horizontal hydraulic cylinders with steel plates and bars. The applied normal load is kept constant during the operation. The tangential load is measured by a proving ring equipped with a dial gage (accuracy: 0.02 mm). The tests were conducted at a constant displacement rate of 1 mm/min at normal loads of 10, 20, and 30 kN (which have been applied before shearing) to show clearly the influence of the normal force level on the behavior of the interface. The displacement of the sand bed was measured in the normal direction to the sand-construction material interface. The steel and concrete surfaces were thoroughly cleaned and degreased by electronic contact cleaner (degreaser spray) before each shear test. Fig. 3 illustrates the process of contaminated sand preparation).

2.4.1 Program of laboratory testing

The testing program included a parametric study to investigate different variables. Table 5 shows a summary of test parameters and their values. To study the effect of contaminated sand, direct shear tests in the clean sand were also tested as a reference. A total of 144 tests were conducted to study the effect of soil contamination on the internal and interface shear behavior of reconstituted sand and construction materials at different relative densities.

Fig. 2 Strain controlled large direct shear apparatus (ELE, England)

Fig. 3 Oil-contaminated soil preparation process

Table 5 Testing Program

Series	Constant Parameters	Variable Parameters	No. of the tests
I	Tests on clean sand, soil-soil interface (S-S) Tests on clean sand, soil-steel interface (S-ST) Tests on clean sand, soil-smooth concrete interface (S-SC) Tests on clean sand, soil-rough concrete interface (S-RC)	D_r= 30, 50, 70 % D_r= 30, 50, 70 % D_r= 30, 50, 70 % D_r= 30, 50, 70 %	36
II	Tests on contaminated sand, S-S, D_r=50%, c=2% Tests on contaminated sand, S-ST, D_r=50%, c=2% Tests on contaminated sand, S-SC, D_r=50%, c=2% Tests on contaminated sand, S-RC, D_r=50%, c=2%	T.O.=G, C, U T.O.=G, C, U T.O.=G, C, U T.O.=G, C, U	36
III	Tests on contaminated sand, S-S, T.O.=G, c=4% Tests on contaminated sand, S-ST, T.O.=G, c=4% Tests on contaminated sand, S-SC, T.O.=G, c=4% Tests on contaminated sand, S-RC, T.C.=G, c=4%	D_r= 30, 50, 70 % D_r= 30, 50, 70 % D_r= 30, 50, 70 % D_r= 30, 50, 70 %	36
IV	Tests on contaminated sand, S-S, T.O.=U, D_r=70% Tests on contaminated sand, S-ST, T.O.=U, D_r=70% Tests on contaminated sand, S-SC, T.O.=U, D_r=70% Tests on contaminated sand, S-RC, T.O.=U, D_r=70%	c=2,4,6 % c=2,4,6 % c=2,4,6 % c=2,4,6 %	36

D_r: relative density, c: oil content, T.O.: type of oil, G: gasoil, C: crude oil, U: used motor oil

Initially, the behaviour of soil-soil interface and soil-material interfaces (steel and concretes) in the clean sand at three different relative densities was determined (series I). In series II, the investigation of the effect of the type of oil was conducted by using three types of oil (Gasoil, Crude oil, and Used motor oil) and 2% oil content at 50% relative density. In series III, the influence of the gasoil-contaminated sand relative density was studied. Series IV involved investigation of the effect of different percentage of the oil content. Regarding the effects of ambient condition on the test results (already addressed in subsection 3.5) and to enable better comparison of the results, the tests were carried out indoors under relatively constant temperature at specific time of the day during a limited period of time to ensure removal of considerable time and temperature effect on the contaminants viscosity within oil-contaminated soils. While performing the tests, essential control of constant temperature was maintained by using a thermometer.

3. Results and discussion

This investigation has analyzed the results of experimentation on the change of skin friction as a function of sand relative density, type of construction material, difference in surface roughness, type of oil, and different oil contents. Four different sets of experimental results (total of 48 test series at three different normal forces) of large direct shear tests on the different interfaces have been considered in order to investigate the effects of oil contamination on the interface shear behavior of sandy soil and construction materials. To understand the mechanism of interface behavior and observe the volume change in the sand mass along the shear tests, the normal (vertical) displacement of sand bed was also measured. The most important factors needed to evaluate the shear strength of soil are internal friction angle (φ) and cohesion (c), whereas the interface friction angle (δ) and adhesion (c') are important to evaluate the interface frictional resistance. The shear failure envelopes for the studied sand-sand and sand-structure interfaces obey the Mohr-Coulomb failure criterion. In this part of paper, because of space limitation, only a part of typically observed results is presented and the shear failure envelopes which the results are obtained were omitted.

3.1 Influence of soil relative density in pure sand (test series I)

To study the influence of soil relative density on the friction behavior of soil-soil and soil-construction materials interfaces, several tests were performed. Table 6 and Fig. 4 show the values of internal (S-S) and soil-construction materials (S-ST, S-SC, and S-RC) interface friction angles in different relative densities in pure (uncontaminated) sand. Fig. 4, also, illustrates the variations of the ratio of interface to internal friction angle (δ/φ) with relative density for the different interfaces. In table 6 (also for tables 7-9), φ and δ are internal and interface friction angles (in degrees), and c and c' are cohesion and adhesion (kg/cm^2). As can be seen, when the relative density was increased from 30% to 70%, the angle of internal friction increased from 35.7º to 40.9º. Also, interface friction angles were increased by increase in

Table 6 Summary of the test results of series I experiments (clean sand)

Relative Density	Soil-Soil (S-S)		Soil-Steel (S-ST)		Soil-Smooth Concrete (S-SC)		Soil-Rough Concrete (S-RC)	
	φ	c	δ	c'	δ	c'	δ	c'
30%	35.7	0	24.6	0	27.8	0	29.6	0
50%	38.1	0	26.7	0	30.1	0	32.0	0
70%	40.9	0	29.4	0	32.7	0	35.2	0

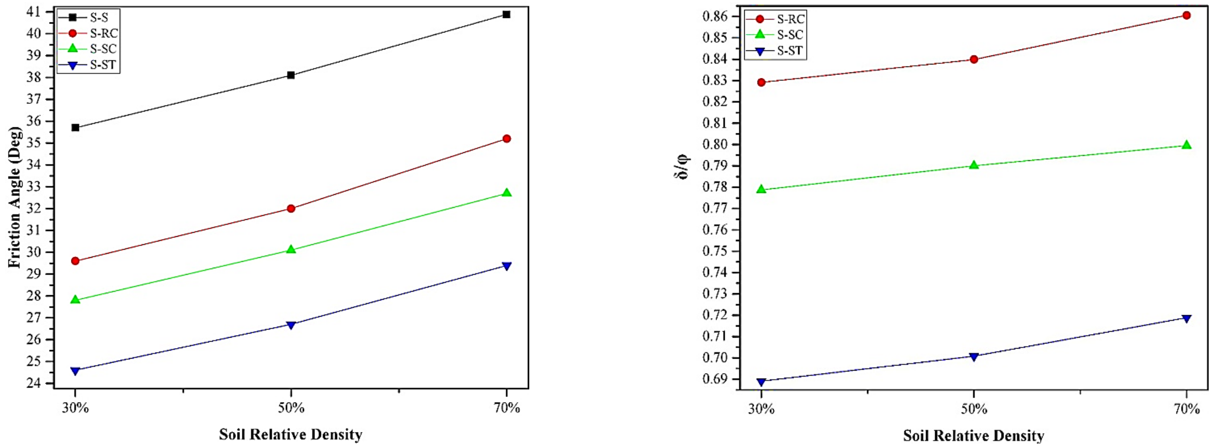

Fig. 4 Variations of internal and interface friction angles (left) and the ratio of interface to internal friction angle (right) with different relative densities for S-S, S-RC, S-SC, S-ST interfaces in uncontaminated sand

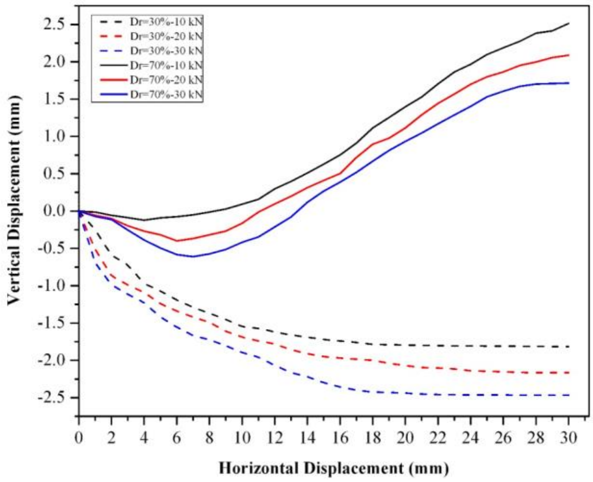

Fig. 5 Vertical displacement-horizontal displacement curve at different normal forces and different relative densities for S-S interface (uncontaminated sand)

sand relative density. Based on the results, the friction angle of soil-steel, soil-smooth concrete, and soil-rough concrete interfaces in relative density of 30% were 24.6º, 27.8º, and 29.6º, respectively, whereas, in relative density of 70%, these values increased to 29.4º, 32.7º, and 35.2º, respectively. Along the shear test, there is some resistance to movement, which tends to carry a volume of soil near the surface and this volume depends on the sand relative density and material surface roughness. By increase in construction material surface roughness and sand relative density, the angle of internal and interface friction as well as volume of dislocated soil will increase. Since the shear strength of sand in the vicinity of the interface is influenced by its density, the sand density can be considered as one of the most influential factors of the frictional resistance. In every case the interface skin friction was lower than the shearing strength of the soil. It is therefore important to determine the ratio between interface skin friction and shearing stress. Potyondy (1961) suggests that it is more convenient to use the angle values of friction both in the designing and in field engineering. The ratio of interface to internal friction angle in pure sand increased with relative density. This ratio had the highest values for the S-RC interface (0.829, 0.840, and 0.861 for relative density of 30%, 50%, and 70%, respectively) and the lowest values for the S-ST interface (0.689, 0.701, and 0.719 for relative density of 30%, 50%, and 70%, respectively). Several studies are reported in the literature which attempt to

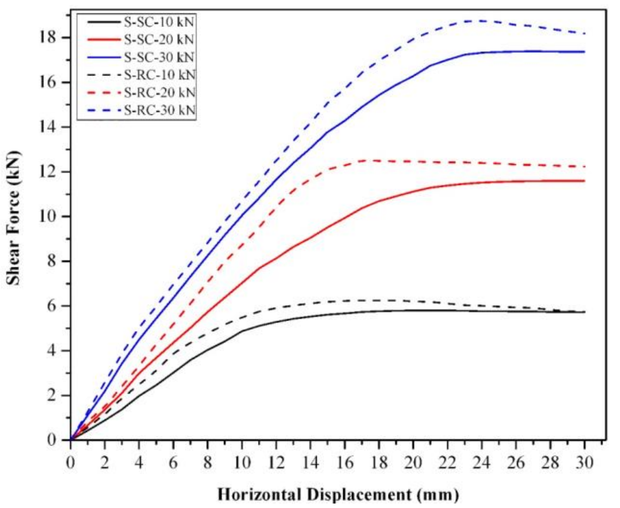

Fig. 6 Shear force-horizontal displacement curve at three different normal forces (10 kN, 20 kN, and 30 kN) for S-SC and S-RC interfaces (pure sand, D_r=50%)

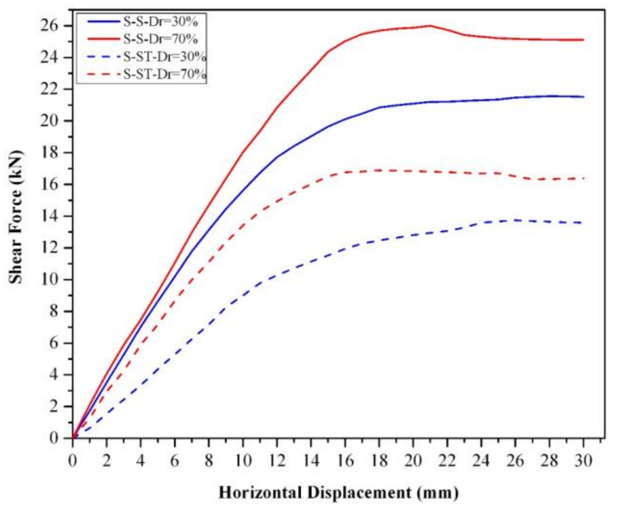

Fig. 7 Shear force-horizontal displacement curve at 30 kN normal force for S-S and S-ST interfaces and two different relative densities (pure sand)

Table 7 Summary of the test results of series II experiments (D_r=50%, c=2%)

Type of Oil	Soil-Soil (S-S)		Soil-Steel (S-ST)		Soil-Smooth Concrete (S-SC)		Soil-Rough Concrete (S-RC)	
	φ	c	δ	c’	δ	c’	δ	c’
G	36.9	0.08	25.1	0.07	27.7	0.08	30.6	0.08
C	36.4	0.1	24.4	0.08	26.9	0.09	29.5	0.1
U	34.3	0.16	21.6	0.13	24.0	0.14	26.4	0.15

estimate δ or μ(=tan(δ)). Potyondy (1961) recommended values of (δ/φ) varying between 0.54 and 0.99 depending on the type of material and surface finish. Meyerhof (1962) suggested value of (δ/φ) ranging between 0.5 and 1.0 depending on surface roughness. Terzaghi and Peck (1967) have given values of tan(δ)=0.55 for concrete with clean sand and 0.35-0.45 for concrete with fine sand, respectively. It is obvious that the interfacial friction should be governed by the properties of the soil such as mineralogical composition, density, grain size and gradation, grain shape, and the properties of the structural surface such as hardness and surface roughness. The curves of internal and interface shear envelopes in case of uncontaminated sand were passed from the origin, thus the values of cohesion and adhesion were equal to zero. This could be related to the absence of any fluid between the dry sand grains.

Fig. 5 shows the normal (vertical) displacement as a function of tangential (horizontal) displacement for the soil-soil interface at three different normal forces and two different relative densities (D_r=30% and 70%) to indicate the effect of soil relative density on the volumetric change of the sand. For loose sand the volumetric change was contractive, whereas, for the dense sand, after an initial contractant stage, the volume change is strongly dilatants and finally stagnates at a certain stage of displacement. Similar results were obtained by the Tejchman and Wu (1995).

Fig. 6 presents some results about the effects of interface surface roughness and normal forces on shear force-horizontal displacement behavior. This figure, which demonstrates the friction behavior of soil-smooth concrete and soil-rough concrete in medium pure sand (D_r=50%), shows that in case of rough surface, shear force-horizontal displacement curve tends to show peak value in the highest normal force (30 kN), but in two other normal forces (10 and 20 kN) the curves reach asymptotically a plateau. This trend for the smooth concrete interface was also as the same.

Fig. 7 presents the evolution of shear force at 30 kN normal force for soil-soil and soil-steel interface for the loose and dense sand. In case of loose sand (D_r=30%), the shear force-horizontal displacement curve reached a plateau for both S-S and S-ST interfaces. However, in dense sand the behavior of interfaces was different and in both S-S and S-ST interfaces showed a clear peak followed by strain softening. This peak in S-S interface was more pronounced than the S-ST interface.

3.2 Influence of type of contaminant (test series II)

In order to investigate the effect of oil type on the internal and interface friction behavior of the sand and construction materials, some shear tests were conducted in 50% relative density and 2% oil content for the gasoil, crude oil, and used motor oil (which the main difference between them was the intense difference in their viscosities).

Table 7 summarized the results of these tests. The variations of internal and interface friction angles and the ratios of interface to internal friction angles (δ/φ) due to the change in the oil type are plotted in Figure 8. This figure shows that the internal and interface friction angles in sand contaminated by gasoil have the highest value and the internal and interface friction angles in sand contaminated by used motor oil have the lowest one. Internal friction angle of the pure (uncontaminated) sand at the relative density of 50% was about 38.1º. By adding 2% of gasoil, crude oil, and used motor oil, this value decreased to about 36.9º, 36.4º, and 34.3 º, respectively. This means that, at the

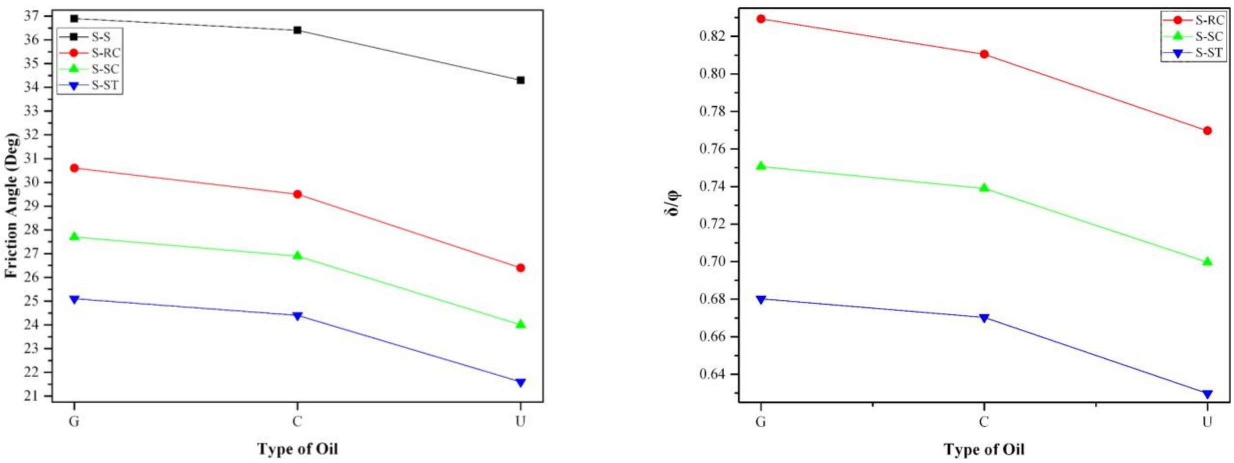

Fig. 8 Variations of internal and interface friction angles (left) and the ratio of interface to internal friction angle (right) with different types of oil for S-S, S-RC, S-SC, S-ST interfaces in D_r=50% and c=2%

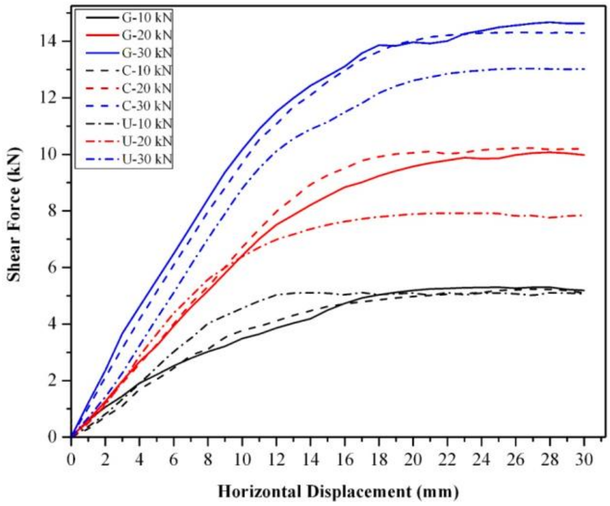

Fig. 9 Shear force-horizontal displacement curve at three different normal forces (10 kN, 20 kN, and 30 kN) for S-ST interface and three different types of oil (D_r=50% and 2% of Gasoil, Crude oil, and Used motor oil)

relative density of 50%, the internal friction angle of the sand would decreased about 3.15%, 4.46%, and 9.97% by adding only 2% of gasoil, crude oil, and used motor oil, respectively. Interface friction angle of soil-steel for pure sand and sand contaminated by 2% of gasoil, crude oil, and used motor oil was about 26.7º, 25.1º, 24.4º, and 21.6º, respectively. These values show that, in 50% relative density, presence of 2% gasoil, crude oil, and used motor oil would reduce the soil-steel friction angle by about 5.99%, 8.61%, and 19.10%, respectively. The amount of decrement for the soil-smooth concrete and soil-rough concrete interface friction angle would about 7.97%, 10.63%, and 20.27% and 4.38%, 7.81%, and 17.5%, by addition of 2% of gasoil, crude oil, and used motor oil, respectively. Like the results of the tests series I, the ratio of interface to internal friction angle (δ/φ) in case of S-RC interface had the highest value followed by S-SC and S-ST interfaces in sand contaminated by different oils. In this case, by changing the type of oil from gasoil to crude oil and used motor oil, the ratio of interface to internal friction angle (δ/φ) decreased drastically, especially for the used motor oil. This can be attributed to the viscosity of the oils, which can create vastly different coefficient of friction. The used motor oil has a much higher viscosity than the gasoil (about 59 times higher). Therefore, sand particles coated with used motor oil vastly reduce friction between particles and facilitate the sliding of particles (Nasr 2013). Because the sand particles are mixed with used motor oil, the size of particles is larger than the ones in clean sand. This is attributed to the oil coating on the individual sand particles. The sand particles covered by gasoil have more resistance to move than covered with crude oil and used motor oil (Nasr 2013). Similar results were observed by Ratnaweera and Meegoda (2006).

As seen in the previous section, values of cohesion and adhesion in the uncontaminated dry sand was equal to zero; however, in case of 2% gasoil, crude oil, and used motor oil contaminated sand, due to existence of viscous fluid between the particles, values of apparent cohesion and adhesion are higher than zero, whether at soil-soil, or at soil-construction material interfaces. Despite the values are not so high, according to Table 7, it may be concluded that c and c’ will increase as the intra-particle fluid viscosity is raised and their value for the whole interfaces such as soil-

Table 8 Summary of the test results of series III experiments (c=4%, gasoil)

Relative Density	Soil-Soil (S-S)		Soil-Steel (S-ST)		Soil-Smooth Concrete (S-SC)		Soil-Rough Concrete (S-RC)	
	φ	c	δ	c’	δ	c’	δ	c’
30%	32.9	0.07	21.1	0.05	23.7	0.06	26.3	0.07
50%	35.1	0.11	22.7	0.09	25.6	0.10	28.4	0.11
70%	37.9	0.13	24.8	0.11	28.4	0.12	31.2	0.13

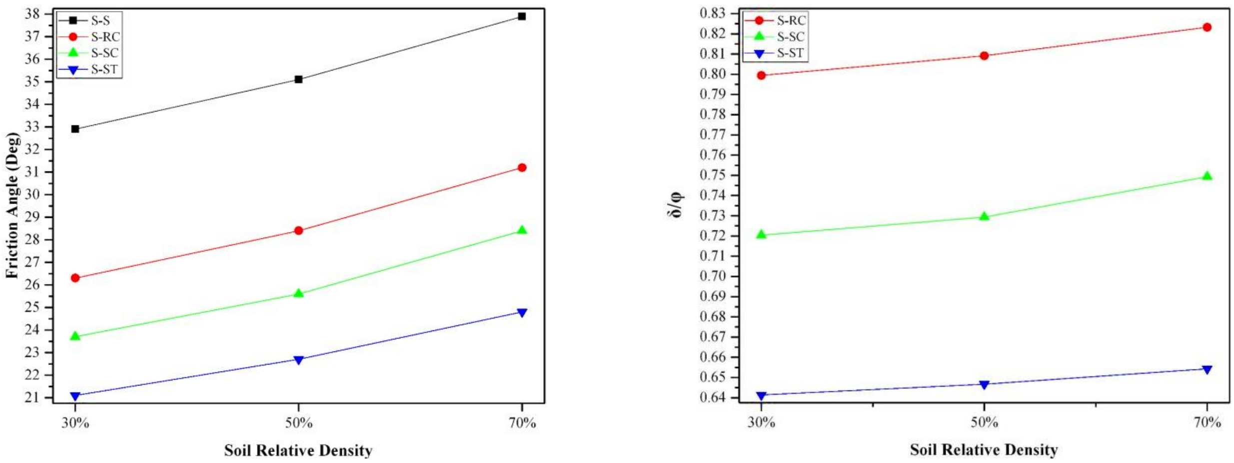

Fig. 10 Variations of internal and interface friction angles (left) and the ratio of interface to internal friction angle (right) with different relative densities for S-S, S-RC, S-SC, and S-ST in 4% gasoil contaminated sand

soil and soil-construction materials in presence of used motor oil among the particles are higher than that of gasoil and crude oil. Moreover, values of c at the soil-soil interface are higher than the c’ values at the soil-construction material interfaces. As the roughness of the interface decreases, the values of c’ is also declined to some extents. Notice that, the apparent adhesion has also been reported by other authors for sand-structure interfaces (Ling *et al.* 2002, Liu *et al.* 2009).

The evolution of the shear force as function of shear displacement, for the 2% of gasoil, crude oil, and used motor oil in sand-steel interface is shown in Fig. 9. It shows that as the normal force increased, the shear force at the soil-steel interface is raised. Moreover, used motor oil has the biggest influence on the soil-steel interface friction and causes the shear strength at the 2% motor oil contaminated soil-steel interface to be significantly lower than that of 2% gasoil or crude oil contaminated soil-steel interfaces. The difference can be attributed to the much higher viscosity of used motor oil in comparison with the other two contaminants (Lim *et al.*, 2015). The large molecules of used motor oil have long chain lengths, so the van der Waal’s attraction forces are the main mode of attraction (Yong *et al.*, 1994). When 2% used motor oil-contaminated sand comes into contact with steel, the interface friction angle drastically decreases; however, because of adhesive nature of used motor oil, the apparent adhesion (c’) of the soil-steel in case of 2% used motor oil contamination interface is higher than that of 2% crude oil or gasoil and would compensate the friction loss to some extents.

3.3 Influence of soil relative density in contaminated sand (test series III)

In order to investigate the effect of sand relative density on internal and interface friction behavior of contaminated sand, a part of direct shear tests were conducted on sand samples contaminated by gasoil with content of 4%. Table 8 summarized the data obtained from these tests. Results of this section, in some extent, were similar to the results of test series I and show that, when the relative density increased from 30% to 70%, the angle of internal friction increased from 32.9º to 37.9º. Also, interface friction angles were increased by increase in relative density. Based on the results, in case of 4% gasoil contaminated soil, the friction angle of soil-steel, soil-smooth concrete, and soil-rough concrete interfaces in relative density of 30% were 21.1º, 23.7º, and 26.3º, respectively, whereas, in density of 70%, these values increased to 24.8º, 28.4º, and 31.2º, respectively. Fig. 10 depicts the variations of internal and interface friction angles and the ratio of interface to internal friction angles with soil relative density in case of 4% gasoil contaminated soil. As expected, the internal friction angle of 4% gasoil contaminated soil is higher than the interface friction angles of soil-construction materials, and the soil-rough concrete interface has the highest friction angle between the three soil-material interfaces. In addition, the ratio of interface to internal friction angles for the S-RC interface was the highest value between the three different interfaces and this ratio increased by increase in relative density for all of the interfaces. As a matter of fact, as the relative density increases, the compressibility of the soil particles and their contact with construction materials increase, thereby raise the value of internal and interface friction angles. In the 4% gasoil contaminated sand, as the relative density increases, values of c and c’, although

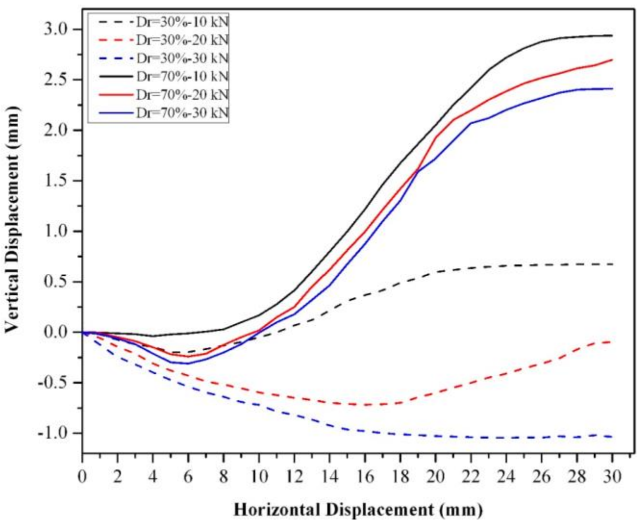

Fig. 11 Vertical displacement-horizontal displacement curve at different normal forces and two extreme relative densities (30% and 70%) for S-SC interface (4% gasoil contaminated sand)

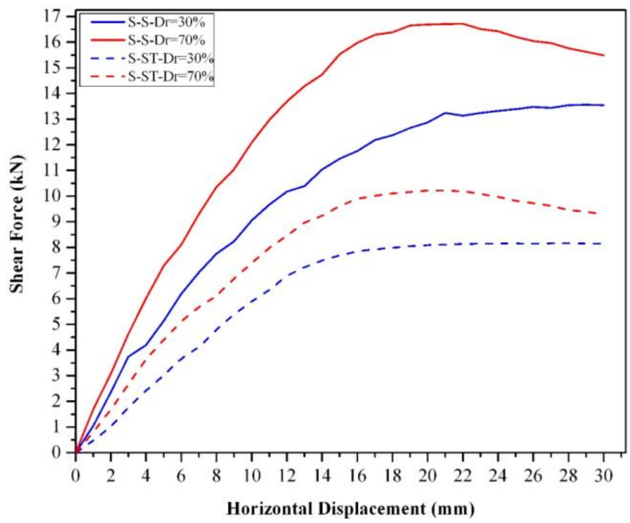

Fig. 12 Shear force-horizontal displacement curve at two different relative densities (30% and 70%) for 20 kN normal force and S-S and S-ST interfaces for 4% gasoil contaminated sand

Table 9 Summary of the test results of series IV experiments (D_r=70%, used motor oil)

Oil Content	Soil-Soil (S-S)		Soil-Steel (S-ST)		Soil-Smooth Concrete (S-SC)		Soil-Rough Concrete (S-RC)	
	φ	c	δ	c'	δ	c'	δ	c'
2%	36.5	0.21	23.0	0.17	26.6	0.19	28.8	0.20
4%	35.2	0.28	22.1	0.24	25.1	0.25	26.9	0.27
6%	32.9	0.34	20.4	0.30	23.1	0.31	24.5	0.33

intangible, will increase. In such conditions, despite the intra-particle fluid properties was constant during all the tests, increase in the relative density leads to lower the distance between the particles. Thus, the contact points between the soil particles and oil increases and some binding interactions between alkyls groups (oil) and soil surface constituents as well as larger van der Waal's attraction, causes higher particle-particle cohesion and particle-construction materials adhesion (Yong *et al.* 1994).

Fig. 11 depicts the vertical displacement as a function of horizontal displacement for the soil-smooth concrete interface at three different normal forces and two different relative densities (D_r=30% and 70%) to compare the effect of soil relative density on the dilative or contractive behavior of the 4% gasoil contaminated sand. As can be seen, in case of loose sand for the normal forces of 10 and 20 kN, the volume change is totally contractive; whereas, for the 30 kN normal force, the volume change initially was contractive followed by dilative behavior. In case of dense sand, for all three normal forces, the trend was the same and by increasing the shear in the S-SC interface, the volume change of the sand was contractive at initial but after some stages it turned to dilation. Shearing under the normal load of 10 kN showed the highest dilative volume change.

The shear force-shear displacement curves (Figure 12) show a well-defined peak shear strength for the dense soil (D_r=70%) for both the soil-soil and soil-steel interfaces and the shear strengths reduce with further horizontal displacement. In loose state (D_r=30%) shear strength-horizontal displacement curves reach plateau and have no peak values.

3.4 Influence of oil content (test series IV)

To assess the effects of oil contents on the internal and interface shear behavior of oil-contaminated sand with different construction materials, some tests were conducted under the relative density of 70% with used motor oil as the contaminant. Table 9 summarize the values of the friction angle and apparent cohesion and adhesion relating to the failure envelopes for the large direct shear tests based on the mentioned circumstances. Fig. 13 depicts the variations of the internal and interface friction angles with the percent of used motor oil. The test results for both internal and interface friction angles show that clean specimen exhibits largest friction angle then followed by specimens contaminated by 2%, 4%, and 6% used motor oil content, respectively. By adding 2% of used motor oil to the pure sand, the friction angle for the S-S, S-RC, S-SC, and S-ST interfaces dropped from 40.9º, 35.2º, 32.7º, and 29.4º to the 36.5º, 28.8º, 26.6º, and 23.0º, respectively. This means that adding only 2% of a fluid with high viscosity resulted to the 10.76%, 18.18%, 18.65%, and 21.77% reduction in the S-S, S-RC, S-SC, and S-ST friction angles, respectively. However, at oil content > 2%, the decrease rate of friction angles was smaller. It can be seen that the friction angle may be reduced to about 32.9º, 24.5º, 23.1º, and 20.4º for S-S, S-RC, S-SC, and S-ST interfaces when the oil content increased to 6%. The main reason for this tremendous reduction is that the introduction of oil with high value of viscosity will coat the soil particles and increase the sand particles size and by increasing the oil content, the slippage of grains on each other will increased and resulted to the reduction in internal and interface friction angles (Nasr, 2013). These results agree with the findings of Shin and Das (2001), Nasr (2009), and Mohammadi *et al.* (2019a).

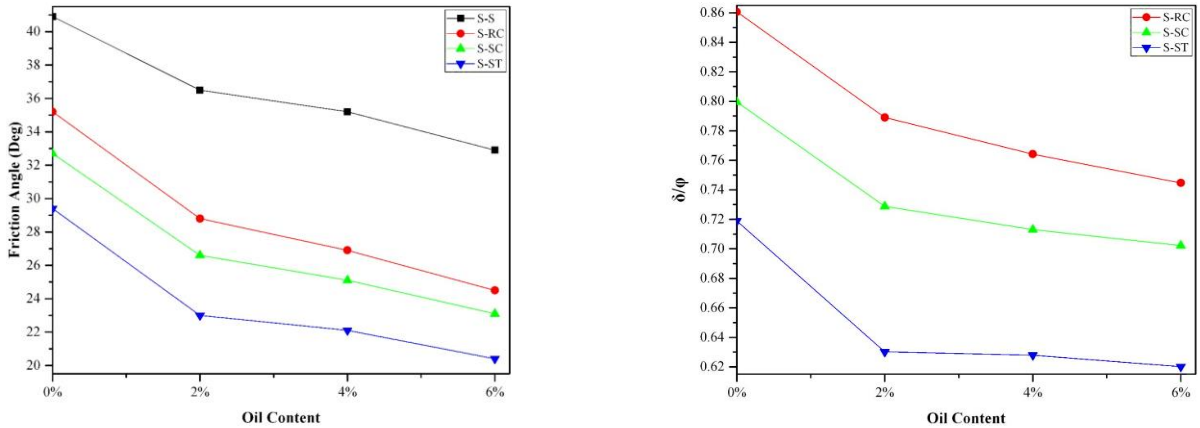

Fig. 13 Variations of internal and interface friction angles (left) and the ratio of interface to internal friction angle with different used motor oil contents for S-S, S-RC, S-SC, S-ST interfaces in D_r=70%

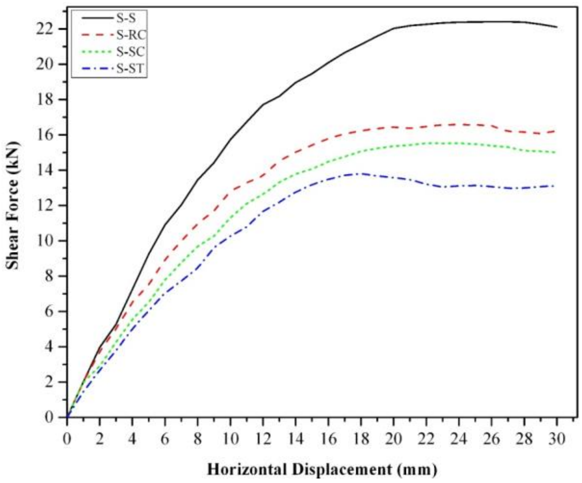

Fig. 14 Shear force-horizontal displacement curve at relative density of 70% and normal force of 30 kN in S-S, S-RC, S-SC, and S-ST interfaces for 6% used motor oil contaminated sand

In the current set of experiments, also, the friction angle for the soil-soil interface was so higher than the values for the soil-material interfaces. Additionally, the rate of decrease in friction angles in case of soil-material interfaces were a little higher than the soil-soil interface; and it can be concluded that the role of oil content on the reduction of soil-material interface friction would be more effective than soil-soil interface friction.

Based on data shown in Tables 6 and 9, the cohesion and adhesion of dry clean sand were calculated equal to zero; whereas, there is an increase in apparent cohesion and adhesion as oil content increases, and it seems that the used motor oil induces cohesion behavior in sand samples. The cohesion of contaminated sand and adhesion of sand-materials increases by increase in oil content. Adhesion in the soil-steel interface has the lowest value and increases by increase in roughness of construction materials. The cohesion of soil grains due to presence of used motor oil was higher than the adhesion of soil-material interfaces.

Fig. 14 illustrates the variations of the shear force as a function of tangential displacement at relative density of 70%, normal force of 30 kN, and 6% used motor oil content for different interfaces. The shear force increases with increasing interface roughness. This observation indicated that the shear strength of soil-soil contact was higher than the frictional resistance between soil and the construction materials. The peak shear strength of this sand at 70% relative density measured 22.41 kN under normal force of 30 kN, which was 35.16%, 44.31%, and 62.40% higher than the shear strength of the S-RC, S-SC, and S-ST interfaces, respectively. The peak internal and interface shear strengths were reached at a shear displacement of 26 mm, 24 mm, 22 mm, and 18 mm for S-S, S-RC, S-SC, and S-ST interfaces, respectively. This means that lubrication of the interfaces by the oil may be lead to failure within a shorter shear displacements.

It worth to note that the obtained results present the short-term effect of oils on the internal and interface friction behavior of the sand and construction materials. These results may be different in case of long-term presence of oils between the soil grains, especially oils with high viscosity; because, with the evaporation of volatile compounds of the oils, only some oil residues remain which have different effects on the soil particles (Al-Sanad *et al.* 1995).

3.5 Influence of time and temperature

Strength of a granular soil depends on both mineral properties and the interactions of minerals with pore fluids at contacts. Changes in physical properties of pore fluid can change the stress–strain behaviour. In other words, with the solid phase of a granular soil being relatively inactive during contamination, contaminant chemicals in pore fluid should play a dominant role in the subsequent mechanical alterations (Mohammadi *et al.* 2019a).

The viscous nature of the pore fluid may lead to the lubrication phenomenon at granules' contact, thereby displaying softening of stress–strain behaviour (Ratnaweera and Meegoda 2006). Therefore, the shear strength of granular soil decreases as the pore fluid viscosity is raised. As a matter of fact, loss of strength of sand and thus the ultimate bearing capacity of foundations are obviously dependent on the mechanical properties of soil, oil quality, soil type, ambient temperature and humidity (Al-Sanad *et al.* 1995, Khamehchiyan *et al.* 2007). The sliding of particles due to lubrication of soil particles causes an increase in compressibility which is enhanced at higher viscosities. However, the quality is mitigated as the temperature is raised above the room temperature (Al-Sanad *et al.* 1995, Khamehchiyan *et al.* 2007).

4. Conclusions

Large direct shear tests were conducted to evaluate the shear strength of soil and the frictional resistance between the soil and different types of structural materials. The soil used in this study was crushed sand and contaminated by different types of oil with various oil contents. The content of oils selected up to 6% according to the typical field concentrations (Al-Sanad *et al.* 1995). The sand was compacted at three different relative densities (30%, 50%, and 70%) to estimate the effect of relative density on the soil strength and the frictional resistance. Different construction materials (steel and concrete) were used in this study to evaluate the effects of surface roughness on the frictional resistance of sand with these materials. In this study three normal forces (10 kN, 20 kN, and 30 kN) were used for each test. The study results helped us to draw the following conclusions:

• The shear strength of soil (soil-soil interface) is always higher compared to the interface between soil and construction materials. It means that the shear failure in all of the tests occurred at soil-materials interfaces.

• The frictional resistance for soil-rough concrete interface is higher than that in soil-smooth concrete and soil-steel interfaces in both pure and contaminated samples. Likewise, soil-smooth concrete interface frictional resistance is higher than the soil-steel interface.

• The internal and interface friction angles increase with density of the sand bed for both clean and contaminated sand.

• The type of oil has significant effect on the internal and interface friction angles of sand in contact with construction materials especially for oils with high viscosities. Heavy used motor oil affects the internal and interface shear strength more than light gasoil and crude oil at all interface textures.

• Viscosity of the oils induced some apparent cohesion and adhesion in the sand that their values enhanced by introducing more viscous and more oil contents.

• By increasing oil content, internal and interface friction angles decreased. Ratios of δ/φ for all three surface types show that rough concrete gives highest value among the three surfaces.

• The effects of aging on the internal and interface shear behavior of oil-contaminated sand and construction materials should be analyzed to compare the results with the results of current study, especially for the high viscosity used motor oil.

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