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Review of geotechnical characteristics of soil contaminated with hydrocarbon substances and residues from a burnt oil refinery

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ABSTRACT

Soil contamination by petroleum contaminants and their derivatives has harmful effects on the soil environment. The structure and geotechnical parameters of the soil will change as a result of the interaction between the contaminant and the soil. The double layer thickness of the clay will change, and the structure of the clay soil will become similar to that of the granular soil. In the present study the effect of contamination by burnt-oil waste from refineries on the compaction and resistance behavior of clayey sand soils was investigated. The geotechnical characteristics of soil types contaminated with different percentages of hydrocarbons from previous research were also reviewed and analyzed. The primary effects were decreases in the internal friction angle, California bearing ratio and permeability of the soil and increases in the cohesion and Atterberg limits of the soil. The shear strength of the contaminated soil did not show a definite or constant trend of change. When contaminated with acidic sludge, despite an increase in the cohesion of the soil, a decrease in the internal friction angle caused a decrease in the shear strength. When contaminated with dirt filter residue, the shear strength of the soil increased with the substantial increase in cohesion, despite a decrease in the internal friction angle.

Introduction

In recent years, the effects of hydrocarbon pollution on soils have received increasing attention (Tumanyan et al., 2017; Errington et al., 2018). Such pollutants not only damage the soil ecosystem and alter its physical and mechanical properties, but also threaten the safety of civil engineering structures (Haghsheno and Arabani, 2022). Petroleum is used to produce valuable products such as plastics, chemical fertilizers, and as a raw material for the production of chemicals. More than two million tons of oil are produced worldwide every day, and about 10% of petroleum and its derivatives leak into groundwater from storage tanks, pipelines, tankers, and as waste from factories. In addition to reaching groundwater, the contamination spreads horizontally through the soil by capillary forces, contaminating even more soil (Prasanna and Manoharan, 2016; Tajik, 2004; Tuncan and Pamukcu, 1992). Studies conducted between 1978 and 1992 reported that33% of water and soil contamination was due to improper storage and transportation and 67% resulted from defects and accidents during the transportation of oil products through pipelines and oil tankers (Kermani and Ebadi, 2012). Although washing, as well as chemical and biological methods, have been introduced to clean contaminated soil, they are costly and have limitations (Riser-Roberts, 1998; Yulin et al., 2024). A detailedstudy of the geotechnical behavior of contaminated soil indicates that it would be more economical to use contaminated soil in placefor road

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infrastructure or other construction projects (Al-Rawas et al., 2005; Virkutyte et al., 2002).
Crude oil and its derivatives are mainly composed of hydrocarbons, nitrogen compounds, sulfur, organic metal compounds and mineral salts (Jukic, 2013). The duration of contamination, the type of contaminant and the type of soil will affect the geotechnical properties of the contaminated soil (Cyrus et al., 2010). Any change in the shear resistance and other engineering characteristics of contaminated soil layers can cause a decrease in the stability of slopes, reduce the bearing capacity and increase the total and relative settlement of structural foundations (Khoshgoftar et al., 2021; Mohammadi and Hosseinabadi, 2019; Afsari et al., 2021).
Haji (2016), by examining the clayey gravel soil contaminated with 12% gas oil, reported a 9 degree reduction in the internal friction angle of the soil, and Karkush and kareem (2017) showed a 7.5 degree reduction in the internal friction angle of the soil with 10% crude oil contamination in clay soil.
Rahgooy et al. (2024), using numerical modeling with Abaqus, show that adding oil contamination in the range of 0 to 16% to clay soils increases the maximum displacement of the trench to five times that of the clean state.
The rate of penetration of oil contaminants into the soil depends on the soil characteristics (porosity, permeability, water content, etc.) as well as the type and amount of compounds in the contaminant (Fine et al., 1997; Nudelman et al., 2002). Fine-grained soils are more likely to be contaminated with petroleum substances and their derivatives because they have a larger specific surface area than coarse-grained soils. Fine et al. (1997) introduced a parameter called the sensitivity index ranging from 0 to 1 for different types of soil. This index for sand should fall into the range of 0.01 to 0.1 and for clay in the range of 0.6 to 0.9.
Contamination in coarse-grained soil causes physical interactions where the contaminant is bound to the soil by a weak van der Waals bond. In fine-grained soil, it will cause physical and chemical interactions because the contaminants are generally bound to the soil by covalent bonds. In clay soils, it will cause a decrease in the bilayer thickness and a decrease in the dielectric constant, resulting in flocculation of the clay soil (Singh et al., 2009).The soil investigated in the current study was exposed to pollutants and waste from a petroleum plant. This included the waste from burnt oil from a refinery. Some studies have been conducted on the effect of hydrocarbons and petroleum pollutants, including crude oil, gasoline, diesel, motor oil and burnt motor oil in fine and coarse soils, but few studies have been conductedon soil contamination by waste from burnt oil from refineries. (Baiazidi et al., 2013; Hamidi and Karimi, 2021; Nasehi et al., 2016). Large-scale oil refinery fires have occurred in Iran and many other countries. The resulting waste products spread into the ground, causing extensive soil contamination. In this research, the soil contaminated by residues from a burnt oil refinery in Salafchegan Industrial Town of Qom was investigated. A literature review showed that the contamination of different types of soil by hydrocarbons will cause different changes the soil geotechnical parameters. The results of these studies should be compared and analyzed; therefore, a complete and accurate study of the mechanisms of hydrocarbon contamination and its derivatives on the characteristics of the soil is required. The present study was carried out to investigate the changes in geotechnical parameters including compaction parameters, resistance parameters, Atterberg limits, permeability and changes in soil texture of all types of soils contaminated with hydrocarbons, especially acidic sludge and dirt filter residue, both waste products from a burnt oil refinery.

Data and method

In previous studies, different types of soils with different percentages by weight of crude oil and its derivatives were mixed and then tested to determine the effect of the contaminant on the shear strength, compaction, Atterberg limits, permeability, etc. of the soil. In the current research, in order to study the effect of soil contamination caused by different percentages of acid sludge and dirty filter residue resulting from the treatment of burned oil (0%, 3%, 6%, 9%), compaction tests were performed on the contaminated soil samples according to ASTM D698. An important basis for the selection of contaminant levels is the possibility of comparison with the results of other researchers. Also, the specific conditions of the tests, such as temperature, humidity, etc., were tried to be similar to the environmental conditions of the soil sampling site.The choice of these contaminant levels is to study the effect of low levels of contamination on the geotechnical properties of the soil, because at high levels of contamination it is taken into account and cleaned up, while at low levels of contamination it can be ignored. Shroff also stated that the maximum percentage of crude oil contamination in soils is about 10% (Shroff, 1997). With the increase of contamination by 9%, the lubrication between the grains reached the maximum level and the further increase of contamination has no effect on the internal friction angle of the soil (khoshgoftar et al., 2021).

A direct shear test according to ASTM D3080 was also performed on contaminated soil samples using a 10 cm2 box. The shear strength results of the sandy clay soil with a specific gravity of 1.9 g/cm3 were evaluated using the direct shear test data.The results of changes in the parameters of the contaminated soil were extracted evaluated and analyzed using the data available from other researches with the help of appropriate software (Get Data Graph Digitizer). Tables and graphs obtained from the research were compiled. Scanning Electron Microscope (SEM) images are analyzed and compared to study the microstructural behavior of the contaminated soil.

Soil properties and study area

Burnt oil refineries are common in the industrial area of Salafchegan in the province of Qom in Iran. Waste has been buried in this area in the past and soil depth 2 m from these areas were extracted and used for study. The soil samples were collected according to ASTM D422 and have been classified as clayey sand (SC) and the location of the study region is 34˚26'43.7"N and 50˚27'37.1"E. The soil classification information is shown in Table 1 and the grain size distribution curve is shown in Fig. 1.

Table 1. Properties uncontaminated soil

Parameter	Coefficient of uniformity C_u	Grading factor C_c	Liquid Limit LL (%)	Plastic Limit PL (%)	Maximum dry unit weight $\gamma_{d\,max}$ (kN/m^3)	Minimum dry unit weight $\gamma_{d\,min}$ (kN/m^3)	Natural moisture content ω (%)	Optimum moisture content ω (%)	Contamination content (%)
Value	333.9	4.52	30	15	20.48	14.72	3.5	8.9	0,3,6,9

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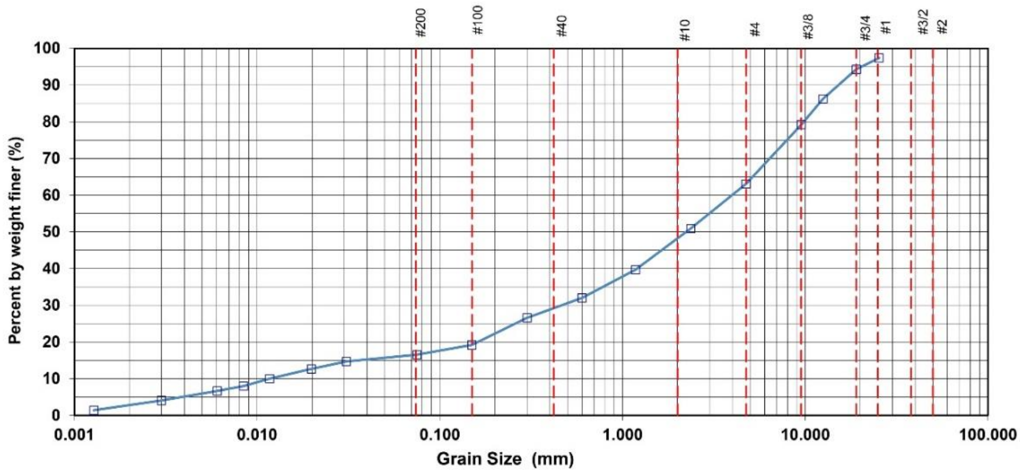

Fig. 1. Grain-size distribution curve of soil

Contaminant properties

The contaminants studied were acidic sludge and dirty filter residue generated as waste from the acidic disposal process used in petroleum refining. The major constituents of the contaminants, as determined by X-ray fluorescence (XRF) analysis, were ferrum, cuprum, plumbum, zinc, phosphorus, dust, halogenated compounds, glycols, carbon, polymers, asphaltene, polymethacrylates, phenols, sulfonates, amines, phosphonates, and thiophosphate. The results of XRF testing are shown in Table 2.

Table 2. XRF test results on contaminants

Acid Sludge	**L.O.I**	**Na2O**	**MgO**	**Al2O3**	**SiO2**	**P2O5**	**SO3**	**Cl**	**K2O**	**CaO**	**Cr**	**Mo**
	86.87	0.425	0.09	0.079	0.322	1.207	6.683	0.008	0.099	2.941	0.01	0.019
	Mn	**Fe2O3**	**Ni**	**Cu**	**Zn**	**Sr**	**Zr**	**Pb**				
	0.007	0.428	00.04	0.018	0.784	0.002	0.001	0.004				
Dirt Filter	**L.O.I**	**Na2O**	**MgO**	**Al2O3**	**SiO2**	**P2O5**	**SO3**	**Cl**	**K2O**	**CaO**	**TiO2**	**Mn**
	37.25	0.073	1.44	6.67	47.734	0.04	2.418	0.073	0.358	3.041	0.067	0.028
	Fe2O3	**Ni**	**Zn**	**Rb**	**Sr**	**Zr**	**Ba**					
	0.736	0.004	0.007	0.002	0.016	0.005	0.04					

Effect of contamination on soil geotechnical parameters

Effect of contamination on soil compaction parameters

Figure 2 shows that, Generally, with the increase of the polluting substance, the maximum dry specific weight of clayey sand soil decreases but when the percentage of water is zero with an increase the hydrocarbon material from the dirt filter residue and acidic sludge to the clayey sand soil to 4.2% and 5.1%, respectively, the maximum dry specific weight of the soil increased. The reason for this could be the ease of movement of the soil particles relative to each other after they were contaminated with acidic sludge, which reduced the void ratio of the soil. A further increase in the percentage of contaminants filling the pores between the soil grains caused a decrease in the specific dry weight of the soil.

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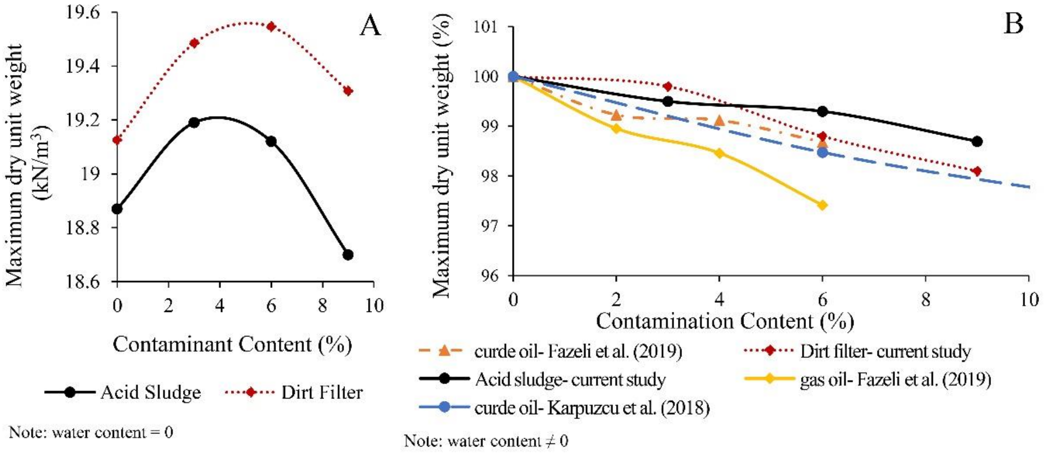

Fig. 2. Maximum specific dry weight of clayey sand soil vs. Contamination content: (a) in current research; (b) in current and other research.

Table 3 and Table A from the appendix show that with the contamination of the soil by hydrocarbon substances and its derivatives, the maximum dry weight of the soil and the optimum moisture content generally decreased. Figures 3 and 4 show these results for soil contaminated with gas oil.

Table 3. Optimal moisture percentage and maximum specific dry weight of soil types contaminated with hydrocarbon and non-carbon materials

References	Soil type	Type of contamination	Content (%)	curing period	Maximum dry density (MDD)	Optimum moisture content (OMC)
Current Research	SC, Iran	Acid Sludge	0-3-6-9	One day	First increased and then decreased	-
Fazeli et al. (2019(	SC, Iran	Gas oil	0-2-4-6	One month	Decreased	Decreased
		Crude oil			Decreased	Decreased
Safehian et al. (2016)	CH, Iran	Gas oil	0-4-8-12-16-20	A week	Decreased	First increased and then decreased
Khamehchiyan et al. (2007)	SP, Iran	Crude oil	0-4-8-12-16	One month	Decreased	Decreased
	SM				Decreased	Decreased
	CL				Decreased	Decreased
Nasehi et al. (2016)	SP, Iran	Gas oil	0-3-6-9	One month	Decreased	Decreased
	CL				Decreased	Decreased
	ML				Decreased	Decreased
Abdelhalim et al., (2022)	SM, Malaysia	Engine oil	0-3-5-8-10-15-20	Three days	Increased	Decreased
Abdelhalim et al. (2022)	SC				Increased	Decreased
Yazdi and Sharifi (2021)	ML, Iran	Gasoline	0-3-6-9-12	A week	Decreased	Decreased
				One month	Decreased	Decreased
Karpuzcu et al. (2018)	SC, Turkey	Crude oil	0-6-12	two weeks	Decreased	Decreased

	CL				Decreased	Decreased
Hamidi and Karimi (2021)	SC-SM, Iran	Crude oil	0-3-5-7	A week	Decreased	Decreased
Karkush and Jihad, (2020) Karkush and Jihad (2020)	CH, Iraq	Kerosene	0-10-20-30-40-50-60	One month	Increased	Decreased

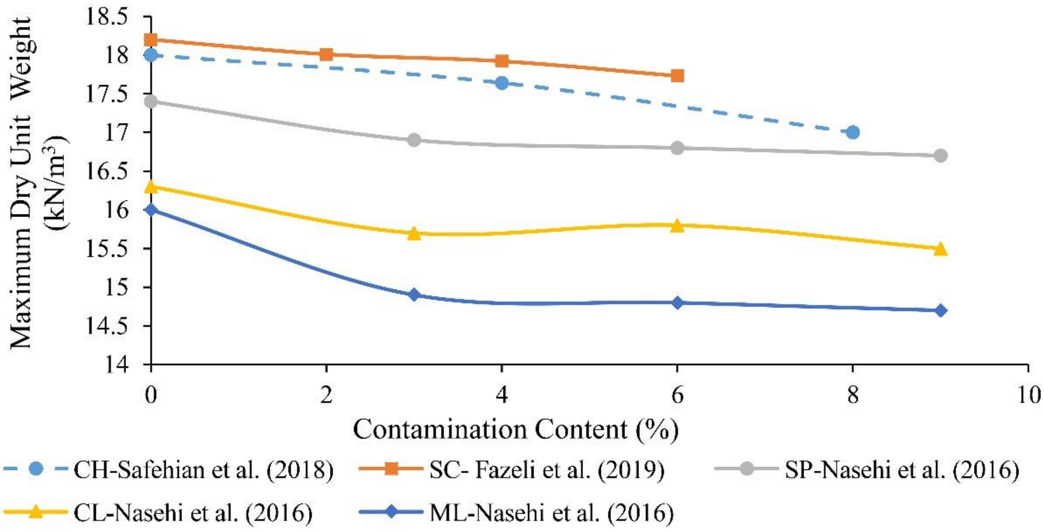

Fig. 3. Maximum specific dry weight of soil contaminated with gas oil

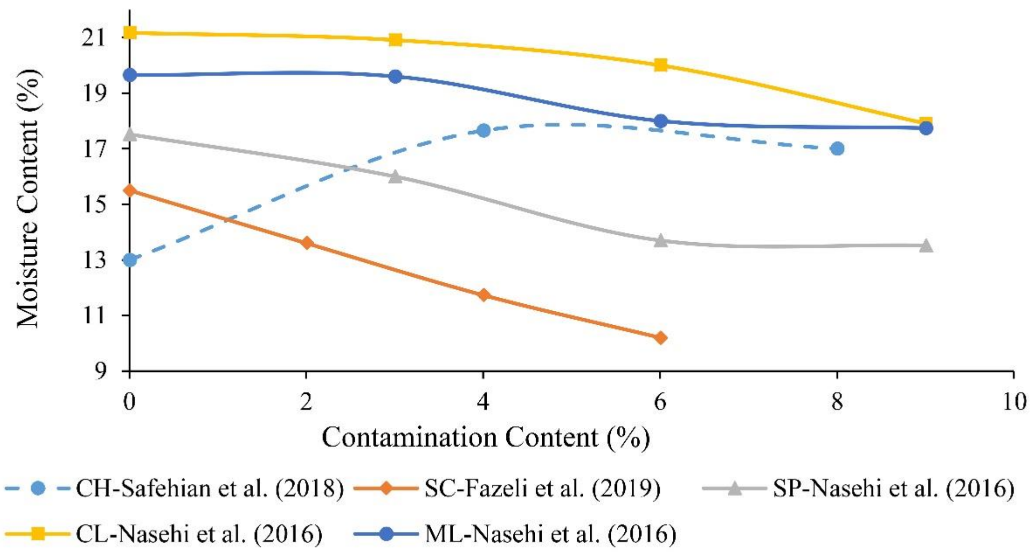

Fig. 4. Optimal moisture percentage of soil contaminated with gas oil

Shin et al. (1995) and Baiazidi et al. (2013) studied sandy soil contaminated with gas oil and stated that, when gas oil surrounded the soil particles, the capillarity created between the contaminated particles and water caused the soil grains to be trapped. Since boththe water and contaminant have low densities and are nearly incompressible compared to soil, this caused a decrease in the maximum dry weight of the soil. The decrease in the optimum moisture percentage resulted from the space between the soil grains being filled with pollutant. The soil then reached the maximum dry weight at a lower optimum moisture percentage. This caused an improvement in the compaction parameters of the soil (Khoshgoftar et al., 2021; Rajaee et al., 2012).

In fine-grained soil, because petroleum compounds have a very low dielectric constant and exhibit non-polarity, they become separated from the surface of the clay grains and the double layer and move into the pore fluid, causing a gap between the clay particles and acting as a load insulator. This act is electrical and has a negative effect on the electrostatic attraction field of clay particles (fine-grained soil acts like coarse-grained soil) and contributes to a reduction in the amount of water required for compaction of samples (Fazeli et al., 2019).

The addition of a hydrocarbon to the soil will produce about half of the amount of soil compaction that the addition of water will because water molecules are bipolar and hydrocarbon molecules are non-polar and the clay particles do not tend to absorb them (Safehian et al., 2016). Figures. 5 and 6 show that the addition of 12% crude oil to the soil caused a 2.5% decrease in the maximum dry weight and a 50% decrease in the optimum moisture content (Karpuzcu et al., 2018). Karkush and Jihad (2020) and Ghadyani et al. (2019) stated that soil contaminated by hydrocarbon substances will reach the maximum dry weight of the soil at a lower optimum moisture percentage.

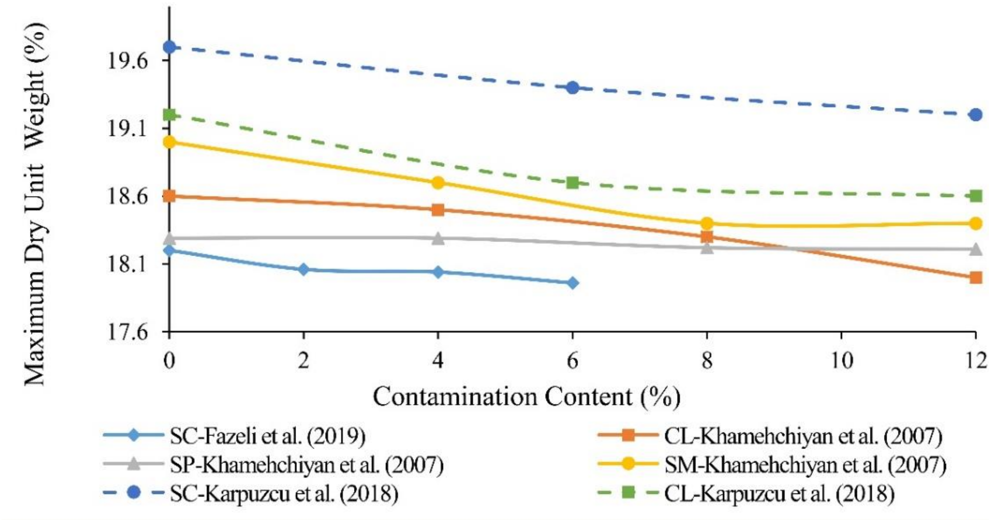

Fig. 5. Maximum specific dry weight of soil contaminated with crude oil

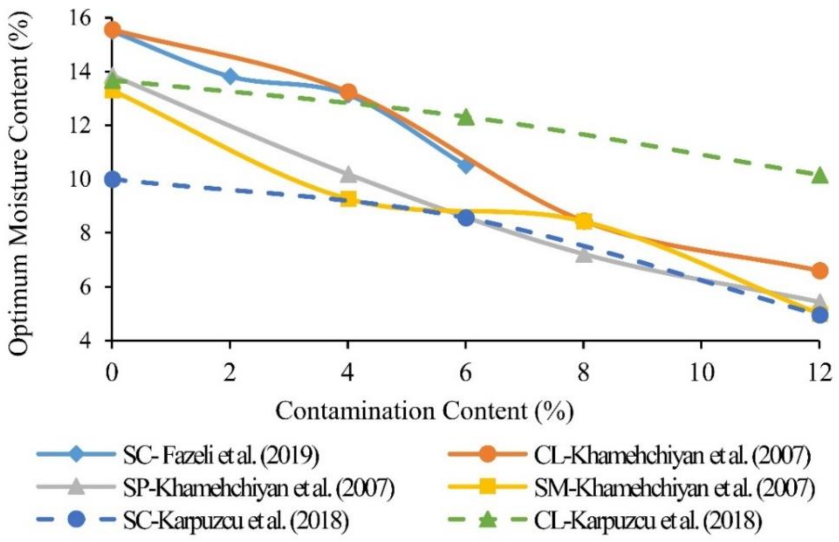

Fig. 6. Optimum moisture percentage of soil contaminated with crude oil

Effect of contamination on soil resistance parameters

Internal friction angle and soil cohesion (direct shear test)

When the soil is contaminated with acid sludge, the contaminant settles between the soil particles, and the non-polar acid sludge compounds and active soil surface materials, including SiO2, are bound together by van der Waals interactions. An increase in contaminant content will increase the van der Waals force, resulting in an increase in soil cohesion. Soil cohesion will also increase as the dirt filter residue increases due to the inherent structure of the contaminants. In the current study, the dirt filter residue acted like fine-grained soil when added to granular soil, which increased soil cohesion. Table 4 shows the increase in soil cohesion with increasing contaminant levels.Other researchers also have reported an increase in soil cohesion due to the high viscosity of hydrocarbon materials, but some researchers also have reported a decrease caused by contamination of the soil with hydrocarbons. Karkush and Kareem (2017) reported a decrease in the cohesion of clay soil with low plasticity properties when contaminated with 20% crude oil. This decrease could be due to a decrease in the dielectric constant and in the double layer thickness of the clay soil and change the structure of the soil to a scattered state (fine-grained soil will resemble granular soil).

Table 4. Soil cohesion resulting from dirt filter residue and acidic sludge

Oil type	Vertical stress (kPa)	Contaminant content			
		0	3	6	9
Acid sludge	10-30-50	0.13	0.225	0.167	0.192
	50-100-150	0.06	0.207	0.229	0.258
Dirt filter	10-30-50	0.129	0.16	0.182	0.342
	50-100-150	0.06	0.393	0.364	0.5

Table 5 shows changes in the internal friction angle of the soil with the addition of both acidic sludge and dirt filter residue. As shown, the acidic sludge hydrocarbons moved between the soil particles and eliminated direct contact between them. As a result, the soil particles were able to slide relative to each other, resulting in a reduction in the soil friction angle. In addition, the addition of soil filter residue caused the soil grains to be surrounded by a cover of filter particles, which reduced the roughness of the soil particles and the internal friction angle of the soil.

Table 5. Soil internal friction angle resulting from dirt filter residue and acidic sludge

Oil type	Vertical stress (kPa)	Contaminant content			
		0	3	6	9
Acid Sludge	10-30-50	49	41	39	38
	50-100-150	47	41	37	33
Dirt filter	10-30-50	49	48	44	43
	50-100-150	47	45	34	34

Figure 7 shows that the shear strength of soil contaminated with acidic sludge, which is dependent on the combined effects of the internal friction angle and soil cohesion, had no clear and constant trend of change. In general, except at a vertical stress of 0.1 kg/cm^2, the shear resistance of the soil decreased. It is evident that, with an increase in the vertical stress of the soil, its shear resistance increased as the soil grains grew close together and the grains locked.

Low vertical stresses such as 0.1 kg/cm^2, contamination caused an increase in the shear resistance of the soil. At a higher vertical stress, the soil shear resistance decreased when contaminated with pollutant. The reason for this could be that, under a vertical stress of 0.1 kg/cm^2, the addition of a pollutant to the soil caused filling of the space between the grains and eventually caused them to lock. This increased the shear resistance of the soil. Under vertical stresses, with the closeness of the grains, the addition of a pollutant increased the distance between the grains and made it easier for the soil grains to slide relative to one another. As a result, the shear resistance of the soil decreased.

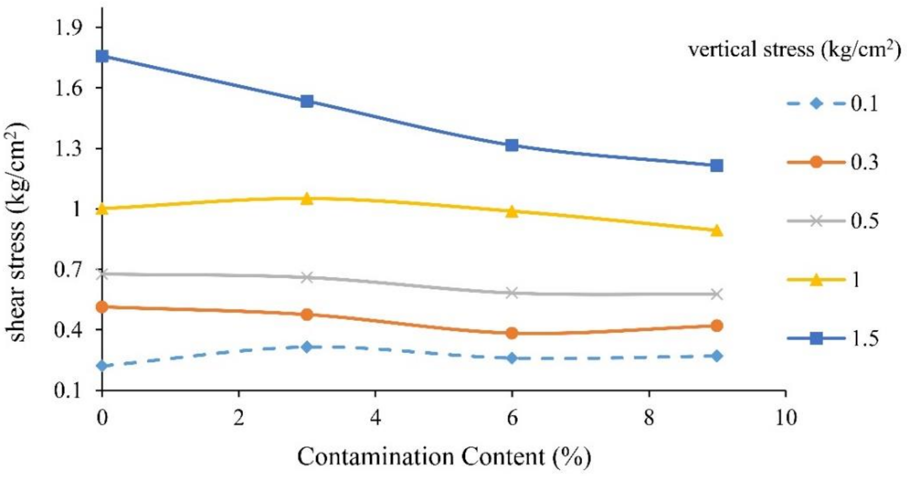

Fig. 7. Shear strength of soil contaminated with acidic sludge under vertical stress (0.1, 0.3, 0.5, 1, 1.5 kg/cm^2) at a specific dry weight of 1.9 g/cm^3

Figure 8 shows that the shear strength of soil contaminated with dirt filter residue increased at all vertical stresses except 1.5 kg/cm^2. Under a vertical stress of 0.1 kg/cm^2, with the addition of 9% dirt filter residue to the soil, its shear strength increased from 0.221 to 0.479 kg/cm^2.

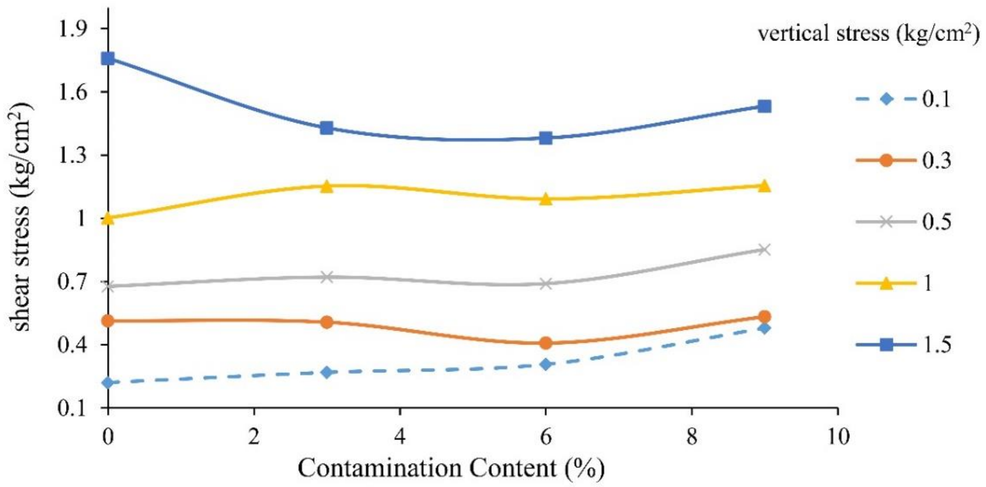

Fig. 8. Shear strength of soil contaminated with dirt filter under vertical stress (0.1, 0.3, 0.5, 1 and 1.5 kg/cm^2) at specific dry weight of 1.9 g/cm^3

Table 6 and Table B in the Appendix show the results for other researchers. The changes in the internal friction angle and cohesion of the contaminated soil generally decreased, depending on the type of soil and the contaminant. For granular soil, lubrication between the grains which caused sliding of the grains and a decrease in the internal friction angle. Saberian and Khabiri (2016) reported an 18% decrease in the internal friction angle with the addition of 8% of gas oil to poorly grained sandy soil.

Khoshgoftar et al., (2021) reported that the addition of 9% acidic sludge and dirt filter residue from burnt oil treatment decreased the tightness of the connection between the soil particles. The roughness of the soil particles and the ease with which the soil grains slid relative to one another caused a 24% decrease in the internal friction angle at a compression level of 1.7 g/cm^3 under vertical stresses of 50, 100 and 150 kPa. In fine-grained soil, the internal friction angle generally increased because of flocculation of the clay soil with the increase of hydrocarbon pollutants (Khamehchiyan et al., 2007). Clay with a low plasticity property of 16% showed an 8° increase in the internal friction angle.

Table 6. Cohesion and internal friction angles of soil contaminated with hydrocarbons by maximum specific dry weight density

References	Curing period	Vertical stress (kPa)	Content (%)	Type of contamination	Soil type	Soil friction angle (°)	Soil cohesion (kPa)
Current Research	One day	50-100-150	0	Acid sludge	SC	42	11
			3			35	13.5
			6			34	21
			9			34	26.3
			0	Dirt filter		42	11
			3			41	26.5
			6			40	26.7
			9			34	16.9
	A week	50-75-100	0	Crude oil	CL	27	24.2

Shirdel and Makarchian (2020)			10			27	28.3
			20			31	27.9
			30			24	27
			0	Gas oil		27	24.2
			10			29	23.4
			20			35	22.6
			30			*	*
Abdelhalim et al. (2022)	Three days	14.3-24.1-43.7	0	Motor oil	SM	40	17.5
			3			37	17.9
			5			33	18.6
			8			32	18.6
			10			29	19.1
			0		SC	35	35
			3			30	35.7
			5			28	33.9
			8			27	31.3
			10			25	26.4
Yazdi and Sharifi (2021)	A week	10-20--40	0	Gasoline	ML	24	20
			3			22	23
			6			20	28
			9			19	30
			12			18	32
	One month		0			24	20
			3			21	19.7
			6			18	20.1
			9			17	20.8
			12			16	22
			3			35	5.6
			6			33	6.4
			9			32	6.8
			12			31	7.1
			15			30	7.3
Karkush and Jihad,)2020)	One month		0	Kerosene	CH	21	53
			10			20	41
			20			18	36
			30			18	32

California bearing ratio (CBR)

One of the most important soil resistance tests for evaluation of contaminated soil for use in road construction is the CBR test. With an increase in the percentage of hydrocarbon pollutants in the soil, the CBR will generally decrease because of the effect of lubrication between the soil grains which allows them to slide relative to each other. Table 7 shows some of the most important studies in this area. As can be seen, the soil resistance generally decreased in soil contaminated with hydrocarbons and the granular and clay soils behaved differently.

Figure 9 shows the CBR values for sandy and clay soils contaminated with burnt engine oil, which revealed that the CBR for all types of sandy soil initially increased and then decreased. In clay soil, with a high specific surface area for the clay particles, the amount of pollutant surrounding the particles per unit volume was higher and caused more slippage of particles and, subsequently, a greater decrease in the CBR compared to granular soil.

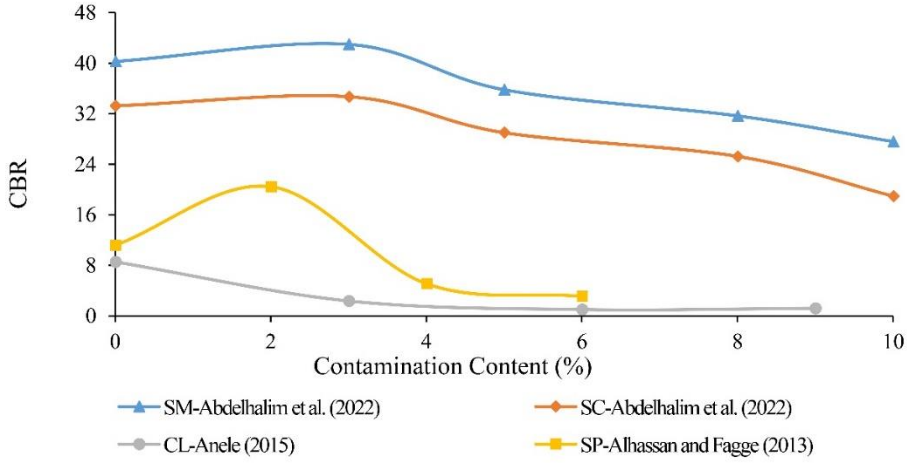

Fig. 9. CBR vs. increase in burnt oil residue for all soil types

Table 7. CBR of soil contaminated with hydrocarbons

References	Soil type	Type of contamination	Content (%)	curing period	CBR
Abdelhalim et al. (2022)	SM	Motor oil	0-3-5-8-10	Three days	Decreased
	SC				First decreased and then increased
Al-Sanad et al. (1995)	SP	Crude oil	0-2-4-6		First increased and then decreased
Anele (2015)	CL	Waste engine oil	0-3-6-9-12	Three day	Decreased
Rasheed et al., (2014)	SPSM	Gas oil	0-3-5-7.5	One day	Decreased
		Kerosene			
Choura et al., (2009)	SP	Crude oil	0-5-10-15		Increased
Hewayde et al., (2019)	OL	Engine oil	0-5-10-15		Decreased
Alhassan and Fagge, (2013)	SP	Crude oil	0-2-4-6		Decreased
		Used engine oil			Decreased
	CL	Crude oil			Decreased
		Used engine oil			Decreased
Karpuzcu et al., (2018)	CL	Crude oil	0-6-12	Two weeks	Decreased
	SC				Increased

Effect of oil contamination on Atterberg limits

When the soil is contaminated with the hydrocarbons found in oil and its derivatives, changes in the repulsive force, cation exchange capacity and viscosity cause changes in the plastic limit, liquid limit and plasticity index of the soil. Table 8 and Table C in the Appendix show the Atterberg limits by the type of soil contaminated based on the type of pollutant, duration of pollution and type of soil. In general, with an increase in the soil contamination, leading to an increase in cohesion between the soil grains, the Atterberg limits increased. With an increase in pollution, the Atterberg limits decreased slightly and then remained the same. With an increase in the length of the contamination period, the Atterberg limits decreased.

As can be seen in Figure 10, with the passage of time (about 1 month) after gasoline pollution, the liquid limit of the soil decreased compared to a shorter period (one week) (Yazdi and sharifi, 2021).

Table 8. Atterberg limits of soil types contaminated with hydrocarbon and non-carbon materials

References	Soil type	Type of contamination	Content (%)	Curing period	Plastic limit (PL)	Liquid limit (LL)	Plastic index (PI)
Fazeli et al., (2019)	SC	Gas oil	0-2-4		Decreased	Decreased	Decreased
	Iran	Crude oil			Decreased	Decreased	Decreased
Roshanqhiyas and Bagheripour, (2019) Roshanqhiyas and Bagheripour (2019)	CL Iran	Crude oil	0-2-4-6-8-10	One month	Decreased	Decreased	Decreased
Zomorodian et al., (2017)	CH Iran	Gas oil	4-8-12-16	A week	First decreased and then increased	Increased and then decreased	Increased and then decreased
Hamidi and Jedari, (2013) Hamidi and Jedari, (2013)	CH Iran	Kerosene	0-3-6-9	A week	Increased		
		Gas oil			Increased		
	CL Iran	Kerosene			Increased		
		Gas oil			Increased		
Abdelhalim et al., (2022)	SC	Motor oil	0-3-5-8-10	Three days	Decreased	Decreased	Decreased
	Malaysia						
	SM				Decreased	Decreased	Decreased
	Malaysia						
Yazdi and sharifi, (2021)	ML Iran	Gasoline	0-3-6-9-12	A week	Up to 6% pollution increased and then decreased	Up to 6% pollution increased and then decreased	Up to 6% pollution increased and then decreased
				One month	Up to 6% pollution increased and then decreased	Up to 6% pollution increased and then decreased	Up to 6% pollution increased and then decreased
Kermani and Ebadi, (2012)	CL Iran	Crude oil	0-4-8-12	A week	Increased	Increased	Decreased
Karkush and Kareem, (2017)	CL Iraq	Fuel oil	0-10-20	Four days	Increased	Decreased	Decreased
Hamidi and Karimi, (2021)	SC-SM	Crude oil	0-3-5-7	A week	Increased	Increased	Increased
	Iran						
Eissa (2016)	CH	Gasoline	0-2-4-8-10-16	Ten days	Decreased	Decreased	Decreased
	Egypt						

Karkush and Jihad, (2020)	CH	Kerosene	0-10-20-30-40-50-60	One month	Increased	Increased	Increased
	Iraq						
Singh et al., (2008)	CH	Diesel oil	0-3-6-9				Increased
	India	Gasoline					Increased
		Kerosene					Decreased
	CL	Diesel oil					Increased
		Gasoline					Increased
		Kerosene					Decreased

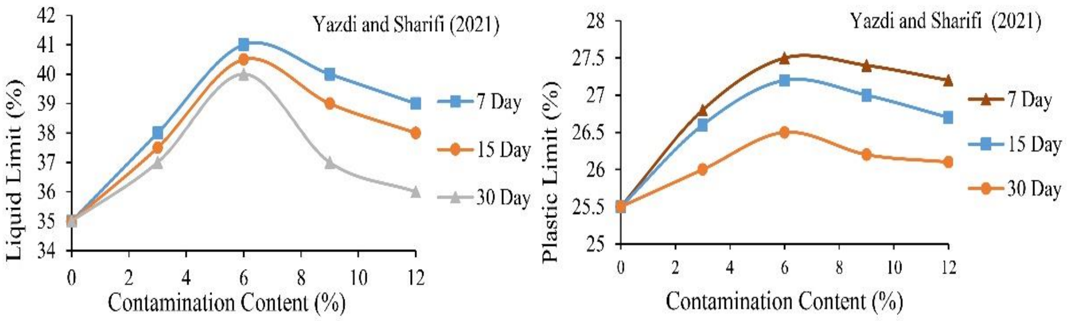

Fig. 10. Liquid and plastic limits of ML soil contaminated with gasoline

Figures 11, 12, 13 and 14 show the trend of change in the plastic and liquid limits from the data of other researchers. Comparison of the data for clay with high plastic properties and clay with low plastic properties allow evaluation of the changes in the Atterberg limits. Figure 11 shows that the plastic limit of clay with high plastic properties contaminated with hydrocarbons showed a slight increase with an increase in the duration of contamination. This could be because most hydrocarbons are not soluble in water and their physical dielectric, water and soil suspension characteristics will remain constant (Ahmed et al., 2007; Zomorodian et al., 2017). Eissa (2016), unlike other researchers, showed a 50% decrease in the clay limit with the addition of 10% gasoline.

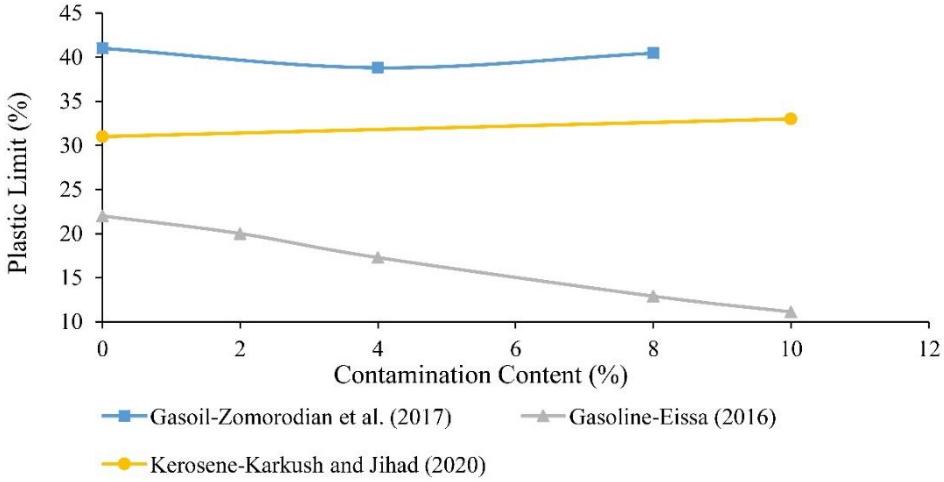

Fig. 11. Soil plastic limit of soil CH based on type of contaminant

Figure 12 shows that changes in the Atterberg limits depend on the types of soil and pollutant. Singh (2008) showed a 14% increase in the liquid limit of the soil with a 9% increase in diesel oil contamination that could be attributed to the high viscosity of the fluid which increased cohesion between the clay particles. In order to change the phase from solid to liquid and overcome stickiness, more water was required. Hamidi and Jedari (2013) reported that, with the addition of gas oil to the soil, the liquid limit initially increased from 85 to 95 and then subsequently decreased to 93 because of the non-polarity of gas oil molecules. Unlike water, gas oil molecules are not able to form a double layer with the soil. As a result, the moisture content initially increased. Then, because of the lubricating property of gas oil, the moisture content decreased (Zomorodian et al., 2017).

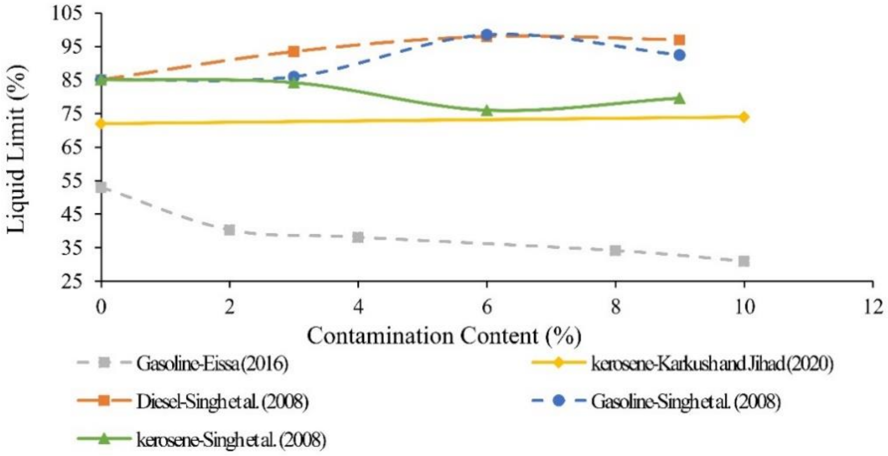

Fig. 12. Liquid limit of soil CH based on type of contamination

Figure 13 shows changes in the plastic limit of clay soil with low plasticity that has been contaminated with oil and its derivatives. Rajaee et al. (2012) contaminated the soil with 10% used engine oil and recorded a 22% decrease in the plastic limit of the soil. He stated that the decrease in the plastic limit was caused by the non-polarity of the used engine oil molecules, which were hydrophobic. When contaminated, clay particles became surrounded by a thin layer of petroleum which prevented water from reacting with the charged clay particles. As a result, the double layer of water that usually forms around the clay became very thin, which led to a reduction in the repulsive forces. With the coagulation of the soil, the behavior of fine-grained soil became like that of coarse-grained soil.

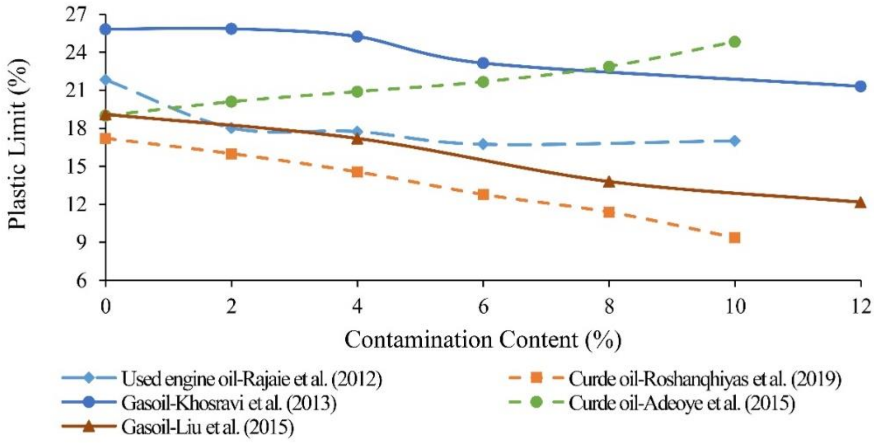

Fig. 13. CL soil plastic limit by type of contamination

Figure 14 shows the changes in the liquid limit of clay soil with an increase in the percentage of different pollutants. Kermani and Ebadi (2012) added 0%, 4%, 8% and 12% crude oil to the soil and recorded liquid limits 46, 53, 59 and 62, respectively. Singh et al. (2008), on the contrary, showed a decrease in the liquid limit of the soil contaminated with kerosene from 33 to 26.

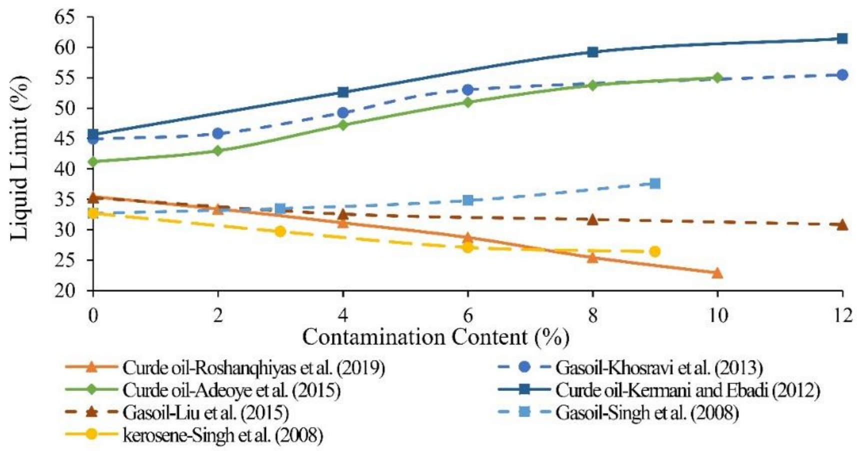

Fig. 14. Liquid limit of CL soil by type of contamination

Effect of oil contamination on soil permeability

Table 9 and Table D in the appendix show that, with the contamination of all types of soil with hydrocarbons, the permeability generally decreases. Iloeje (2016) recorded a decrease 27% with 8% crude oil contamination of clay soil. The reason for the decrease in permeability can be due to the filling of the space between the soil grains by the hydrocarbon materials, which are of high viscosity and make movement through the space between the soil grains more difficult. Baiazidi et al. (2013) and Gillott (1987) reported that, because of the hydrophobic nature of hydrocarbons, they form an impermeable curtain in front of the water and some of the water's energy is used to tear this hydrocarbon layer. They also stated that, in fine-grained soil, when water-soluble materials enter the water-rich soil particles, water and other cations that surround the water-rich layer (double layer of clay minerals) may be absorbed by the components. The substitutes for the organic molecules can enter the interlayer spaces and cause swelling of the clay layer.

Some researchers have reported that, with soil pollution by hydrocarbons, the dielectric constant and the thickness of the double layer will decrease, which will cause flocculation of the soil particles and increase the space and permeability between the grains (Hamidi and Karimi, 2021; Ostovar et al., 2021). As this pollutant has a high pH, soil particles could dissolve in it, which would increase the space between the grains and the soil permeability.

Table 9. Permeability of soil types contaminated with hydrocarbon substances

References	Soil type	Type of contamination	Content (%)	Curing period	Main results	Mechanism
Baiazidi et al., (2013)	GM Iran	Diesel	0-3-6-8-11		Decreased	Due to the hydrophobicity of hydrocarbon materials and the swelling of clay particles
	SM Iran				Decreased	
Oyediran and Enya, (2022)	SW Nigeria	Crude oil	0-10	Two months	Decreased	Due to the high viscosity of crude oil and the filling of the empty space between the grains
Hamidi and Karimi, (2021)	SC-SM Iran	Crude oil	0-3-5-7	A week	Increased	With the increase in pollution, due to the decrease in the dielectric constant and the thickness of the double layer of the coagulated soil grains, the space between the grains increases.
Iloeje (2016)	CL Nigeria	Crude oil	0-2-4-6-8	24 hours	Decreased	Filling the empty space between the grands
Ostovar et al., (2021)	SW	Crude oil	0-4-8-12-16	72 hours	First increased and then decreased	First, the oil caused lubrication between the grains and K increased, and finally, by filling the empty space between the grains, K decreased.
	SP				First increased and then decreased	
	SM				First increased and then decreased	
	SC				Increased	With the increase in pollution, due to the decrease in the dielectric constant and the thickness of the double layer of the coagulated soil grains, the space between the grains increases.
Jedari and Farahani, (2018)	CL Iran	Kerosene	0-3-6-9	A week	Decreased	Due to the high viscosity of hydrocarbon materials, water flow becomes difficult
		Gas oil			Decreased	
	CH Iran	Kerosene			Decreased	
		Gas oil			Decreased	

Effect of oil on soil structure

Clay particle placement can be categorized as mass or complex, coagulated or non-coagulated. (Lagaly, 1978; Mohammadi et al., 2021; Mohammadi et al., 2022). Therefore, the particles tend to be oriented face-to-face in a

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dispersed or divergent structure. If the forces are attractive, the particles tend to be oriented corner-to-face or corner-to-corner depending on the complex structure of the particles (Mitchell, 1976).

Considering that the structure of soil particles depends on the charge capacity of the electrostatic field, when clay is contaminated by hydrocarbons, their low dielectric constant and non-polarity will reduce the absorption capacity and force between the particles. This has a function similar to insulation; thus, it will affect the overall structure of the clay particles. As a result, the electrostatic field between the particles will push them towards repulsion and the degree of flocculation of the structure will decrease, giving it a scattered appearance (Fazeli et al., 2019).

Figure 15 shows that, with the addition of crude oil contamination to clay soil, the stickiness and low dielectric constant of the crude oil will cause a decrease in the double layer thickness that will cause edge-to-edge or edge-to-side formation of the soil particles. This means that, practically, the soil will become coagulated or flocculated.

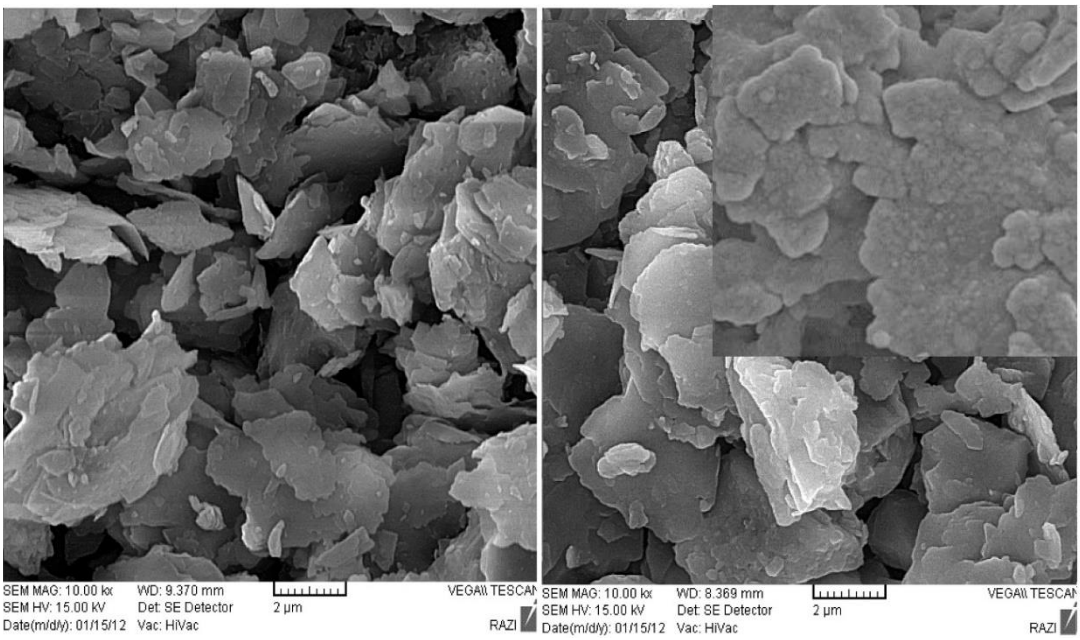

Fig. 15. SEM images of soil texture at 10,000× for uncontaminated samples and 20% crude oil contamination (Kangani et al., 2012).

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Figure 16 shows that the addition of crude oil pollutants to a mixture of sandy and clay soil caused it to become flocculated with a scattered structure. The specific surface area of the soil decreased. This decreased the specific surface area of the soil and indicated a decrease in the resistance of the soil affected by the crude oil contamination (Vaziri et al., 2020).

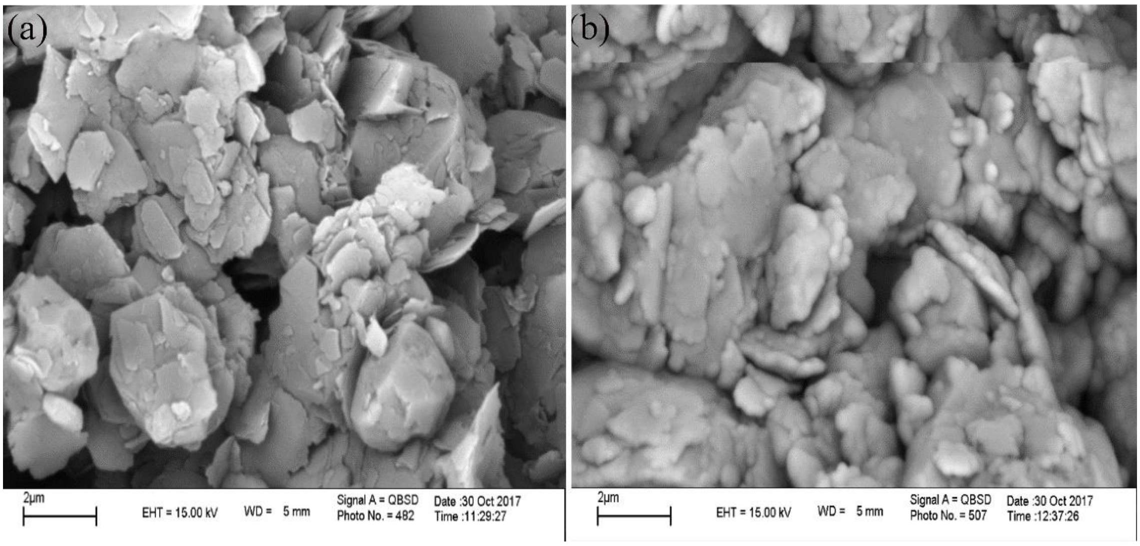

Fig. 16. SEM images of soil texture at 20000× of samples of: (a) 60% kaolinite + 40% sand; (b) 60% kaolinite + 40% sand + 16% crude oil (Ghadimi, 2018)

In granular soil, unlike fine-grained soil where the structure of the soil changes, the contaminant will surround the soil grains. The high viscosity of the hydrocarbon materials will cause lubrication between the soil grains and ultimately lead to a decrease in the surface tension between soil grains.

Discussion

The effect of the contamination is greater in fine-grained soil than in coarse-grained soil (Ijimdiya, 2013). This effect is physical in granular soil and changes the soil texture and structure in cohesive fine-grained soil. With the contamination of the soil by hydrocarbons, the trend of change in the Atterberg limits generally increases but, in some cases, decreases. The high viscosity and non-polarity of the petroleum molecules surrounding the soil particles prevents the formation of a double layer. This means that more water is required to change the shape of the soil, which will cause an increase in the Atterberg limits. Also, decreases in the cation exchange capacity and the dielectric constant cause coagulation of the soil and a decrease in the Atterberg limits.

The contamination of soil with petroleum substances will either decrease or increase the maximum specific dry weight of the soil. The increase occurs because the high viscosity of pollutants makes them act as a lubricant that allows the particles to slide relative to each other and become closer and denser. However, the decrease in the maximum specific dry weight of the soil occurs because of the lower density of the pollutants compared to water, as well as the energy loss due to their presence during the compaction test.

Contamination of soil with hydrocarbon substances generally reduces the optimal moisture content as the empty space between the soil grains are filled by hydrocarbon particles and reduce the spacing between the clay particles because of the low dielectric constant of the pollutants. Research conducted on permeability of the soil has shown that the filling of the empty spaces between the soil grains by hydrocarbon pollutants and their high viscosity and hydrophobicity generally causes a decrease in permeability.

Based on studies conducted on the resistance behavior of soil contaminated with hydrocarbon substances, it can be said that the effect of lubrication between the soil grains and sliding of the soil grains relative to one another will generally cause a decrease in the CBR. The internal friction angle of granular soil also will decrease due to the sliding of the soil grains relative to one another. In fine-grained soils, the internal friction angle generally increases because of the flocculation of the clay soil. The soil cohesion will increase because of the high viscosity of the hydrocarbon materials; however, in some cases, the decrease in the dielectric constant and the double layer thickness will cause a change in structure. The soil will become dispersed and the cohesion of the soil will decrease.

An investigation of the effect of pollutants on the behavior of the soil indicates that it will be affected by various factors. These include the type and percentage of pollutant, the duration of the pollution and the type of soil. The permeability of the soil will decrease and the cohesion and Atterberg limits of the soil will increase.

It should be noted that the presence of oil in fine-grained soils leads to chemical reactions between the oil and the soil, depending on its mineral type.

Conclusion

The main results of the current study are as follows:

- Soil contamination by hydrocarbon substances affects the structure and geotechnical parameters of the soil, but these changes differ according to the type of soil, type of pollutant and the duration of pollution.
- The rate of change of some of the geotechnical parameters of the contaminated soil decreased with the passage of a long time (one month compared to one week), but the rate of change of other parameters increased.
- Soil contamination with 4.2% acid sludge increased the maximum unit dry weight from 18.85 to 19.23 kN/m3 due to the lubricating effect of the acid sludge, which reduced the soil void ratio. The hydrocarbons in the acid sludge fit between the soil particles, eliminating strong interparticle bonds. They act as a lubricant, making it easier for particles to slide past each other and reducing the soil friction angle. The 5.1% dirt filter contaminant level increased the maximum dry unit weight of the soil from 19.13 to 19.56 kN/m3.- The low dielectric constant and non-polarity of hydrocarbon contaminants reduced the double layer thickness in clay, causing it to flocculate and form a granular soil structure.
- As the clay soil was contaminated, the changes in the Atterberg boundaries generally increased.
- In granular soil, the contaminant surrounded the soil grains and, due to its high viscosity, caused lubrication of the soil grains, which reduced the internal angle of friction and increased the compaction parameters of the soil.Generally, the angle of internal friction of soil contaminated with oil substances is reduced and the cohesion of soil could be increased, and the shear strength of soil depends on the type of polluting substance can increase or decrease.
- Contamination by hydrocarbon substances caused filling of the empty spaces between the soil grains. This, along with the high viscosity of the petroleum substances caused a general decrease in permeability.

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Appendix

Table A (cont. of Table 3). Optimum moisture content and maximum specific dry weight of soil contaminated with hydrocarbon and non-carbon materials.

References	Soil type	Type of contamination	Content (%)	Curing period	Maximum dry density (MDD)	Optimum moisture content (OMC)
Roshanqhiyas and Bagheripour, (2019)	CL Iran	Crude oil	0-2-4-6-8-10	One month	Increased	Decreased
Al-Sanad et al., (1995)	SP Kuwait	Crude oil	0-2-4-6		Increased	Decreased

George et al., (2014)	SM India	Gas oil	0-4-8-12	A week	Increased then decreased	
Choura et al., (2009)	SP	Crude oil	0-5-10		Decreased	Decreased
Sarmadi et al., (2019)	SP Iran	Kerosene	0-3-6-9-12-15	Two weeks	Decreased	Decreased
Ghadyani et al., (2019)	CH Iran	Kerosene	0-3-6-9		Increased	Decreased
		Gas oil			Increased	Decreased

Table B (cont. of Table 6). Adhesion and internal friction angle of soil contaminated with hydrocarbon substances at maximum density vs. approximate specific dry weight.

References	**Curing period**	**Vertical stress (kPa)**	**Content (%)**	**Type of contamination**	**Soil type**	**Soil friction angle (°)**	**Soil cohesion (kPa)**
Safehian (2016)	A week	50-100-150	0	Gas oil	CH	39	52
			4			37	41.3
			8			36	34.5
			12			36	32.5
			16			35	31
			20			34	30.6
Khamehchiyan et al., (2007)	One Month	55-110-160	0	Crude oil	SP	35	0
			4			32	3.3
			8			32	8
			12			29	7.6
			16			27	6.2
			0		SM	33	27.4
			4			33	19.9
			8			32	22.7
			12			26	20.8
			16			26	34
			0		CL	26	74.8
			4			27	28.4
			8			28	19.4
			12			29	19.4
			16			34	18
Saberian and Khabiri, (2018)		55-111-222	0	Gas oil	SP	39	0
			3			35	10.2
			5.25			32	17.4
			8			31	26.7
Nasehi et al., (2016)		24-44-64	0	Gas oil	CL	19	12.1

	One Month		3			14	11.4
			6			6	14.3
			9			6	14.6
			0		ML	21	9.9
			3			18	9.8
			6			14	11.3
			9			11	12.4
			0		SP	20	7.4
			3			19	8.4
			6			15	12.4
			9			14	12.2
Askarbioki et al., (2019)	48 Hours	50-100-150	0	Gasoline	SC	28	14.9
			1			25	13.7
			3			23	13.5
			5			23	13
Rasheed et al., (2014)	One Day		0	Gas oil	SPSM	12	18
			3			17	11
			5			26	4
			7.5			32	1.1
			0	Gasoline		12	18
			3			14	16.5
			5			15	14.2
			7.5			20	12.3
Karkush and Kareem, (2017)	Four Days	50-110-220	0	Crude oil	CL	37	66
			10			30	37
			20			25	22
Choura et al., (2009)			0	Crude oil	SP	31	
			5			52	
			10			40	
Karpuzcu et al., (2018)	Two Weeks	100-200-300	0	Crude oil	CL	26	0
			6			31	42.9
			12			23	67.3
			0		SC	39	24.4
			6			30	102.4
			12			36	139.5
Sarmadi et al., (2019)	Two Weeks	50-100-150 -200-250	0	Kerosene	SW	38	0
			3			35	5.6
			6			33	6.4
			9			32	6.8
			12			31	7.1
			15			30	7.3
			10			20	41
			20			18	36

			30			18	32

Table C (cont. of Table 8). Atterberg limits of soil contaminated with hydrocarbon and non-carbon materials

References	Soil type	Type of contamination	Content (%)	Curing period	Plastic limit (PL)	Liquid limit (LL)	Plastic index (PI)
Rajaee et al., (2012)	CL	Used engine oil	0-2-4-6-10	20 Days	Decreased		
	ML						
	Iran						
Khosravi et al., (2013)	CL Iran	Gas oil	0-2-4-6-12-16	A week	Decreased	Increased	Increased
Adeoye et al., (2015)	lateritic soil (CL)	Crude oil	0-2-4-6-8-10	24 Hours	Increased	Increased	Increased
	Nigeria						
George et al., (2014)	SM	Gas oil	0-4-8-12	A week	Increased and then decreased	Decreased	Decreased and then increased
	India						
Rasheed et al., (2014)	SPSM	Gas oil	3-5-7.5	One Day	Increased	Increased	Decreased
	Iraq	Kerosene			Increased	Increased	Decreased
Mohamed et al., (2009)	SP	Crude oil	0-5-10-15			Increased	
	Tunisia						
Liu et al., (2015)	CL	Gas oil	4-8-12-16-20	48 Hours	Decreased	Decreased	Increased
	China						
Singh et al., (2008)	CH	Gas oil	0-3-6-9				Increased
	India	Gasoline					Increased
		Kerosene					Decreased
	CL	Gas oil					Increased
		Gasoline					Increased
		Kerosene					Decreased
Alhassan and Fagge, (2013)	SP Nigeria	Used engine oil	0-2-4-6		Decreased	Increased and then decreased	
		Crude Oil			Increased and then decreased	Increased and then decreased	

Table D (cont. of Table 9). Permeability of soil contaminated with hydrocarbon substances

References	Soil type	Type of contamination	Content (%)	Curing period	Main results	Mechanism
Aghajani et al., (2017)	SM Iran	Crude oil			Decreased	Due to the swelling of clay particles and the empty space being filled by crude oil
Roshanqhiyas and Bagheripour, (2019)	CL Iran	Crude oil	0-2-4-6-8-10	One month	Decreased	The reason for the high viscosity of crude oil and the filling of the empty space between the grains

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Ahmadi et al., (2021)	SM Iran	Crude oil	0-4-6-8	One month	Decreased	Filling the empty space between the grains
Choura et al., (2009)	SP Tunisia	Crude oil	0-5-10-15		Decreased	
Sarmadi et al., (2019)	SP Iran	Kerosene	0-3-6-9-12-15	Two weeks	Decreased	
Puri (2000(	SP	Crude oil	0-9.5-19-28.5		Decrease	
Khamehchiyan et al., (2007)	SM Iran	Crude oil	0-4-8-12-16	One month	Decreased	Filling the empty space between the grains
	SP				Decreased	
	CL				Decreased	

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شاپا الکترونیکی ۲۹۸۱-۱۶۰۰

مروری بر خصوصیات ژئوتکنیکی خاکهای آلوده با مواد هیدروکربنی و پسماند حاصل از کارخانه‌های تصفیه روغن سوخته

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کلیدواژه‌ها:
ویژگی‌های ژئوتکنیکی، آلودگی نفتی، انواع خاک، ساختار خاک، هیدروکربن.

چکیده

آلودگی خاک توسط نفت و مشتقات آن علاوه بر تاثیرات مخرب زیست محیطی، بر پارامترهای ژئوتکنیکی خاک نیز تاثیرگذار است. در اثر فرآیندهایی که بین آلاینده و خاک رخ می‌دهد، ساختار و پارامترهای ژئوتکنیکی خاک تغییر می‌کند. در خاک‌های چسبنده، به صورت تغییر در بافت و ساختار خاک است، بطوری که ضخامت لایه دوگانه خاک رس تغییر کرده و خاک ساختاری شبیه به خاک دانه ای پیدا می‌کند. در این پژوهش ابتدا به بررسی تاثیر آلودگی ماده حاصل از پسماند کارخانجات تصفیه روغن سوخته (اسلاج اسیدی و خاک فیلتر) بر رفتار تراکمی و مقاومتی خاک ماسه رس‌دار توسط آزمایش پروکتور و برش مستقیم پرداخته شده است سپس خصوصیات ژئوتکنیکی انواع خاک آلوده به درصدهای مختلف مواد هیدروکربنی در سایر تحقیق ها مورد بررسی، تجزیه و تحلیل قرارگرفته‌است. نتایج نشان می‌دهد تغییرات پارامترهای ژئوتکنیکی خاک‌ها وابسته به نوع خاک، نوع ماده آلوده کننده و مدت زمان آلودگی است که عمده تغییرات زاویه اصطکاک داخلی، نسبت ظرفیت باربری کالیفرنیا و نفوذپذیری خاک به صورت کاهشی و چسبندگی و حدود اتربرگ خاک بصورت افزایشی است. همچنین مقاومت برشی خاک آلوده شده به مواد هیدروکربنی روند تغییرات مشخص و ثابتی نداشته است بطوری که با آلوده شدن به اسلاج اسیدی، با وجود افزایش چسبندگی خاک به دلیل کاهش زاویه اصطکاک داخلی خاک مقاومت برشی خاک کاهش می‌یابد اما با آلوده شدن به خاک فیلتر، بدلیل افزایش زیاد چسبندگی با وجود کاهش زاویه اصطکاک داخلی مقاومت برشی خاک افزایش می‌یابد.

مقدمه

آلودگی خاک توسط نفت و مشتقات آن و یا پسماند حاصله از کارخانجات هم در کشورهای صنعتی و هم در کشورهای در حال توسعه پس از مواد رادیو اکتیو اثرات مخرب واری بر محیط زیست گذاشته که این امر یک نگرانی و یک مسئله جدی است (Tumanyan et al., 2017; Errington et al., 2018) براساس مطالعات انجام شده در سال های ۱۹۷۸ تا ۱۹۹۲، ۳۳ درصد از آلودگی‌ها در محیط‌های آبی و خاکی درنتیجه ذخیره سازی و حمل و نقل نامناسب و ۶۷ درصد این آلودگی ها درنتیجه مشکلات موجود و حوادث غیر مترقبه در انتقال محصولات نفتی با خطوط لوله و نفت کش‌ها می‌باشد(Kermani and Ebadi, 2012). میزان نفوذ آلاینده های نفتی در زمین بستگی به ویژگی های خاک (تخلخل، نفوذپذیری، محتوای آب و غیره) و همچنین ماهیت و کمیت ترکیبات موجود در آلاینده دارد (Fine et al., 1997; Nudelman et al., 2002). تاکنون تحقیقات

استناد: خوش‌گفتار، ا.، خداپرست، م. (۱۴۰۳). مروری بر خصوصیات ژئوتکنیکی خاک‌های آلوده با مواد هیدروکربنی و پسماند حاصل از کارخانه‌های تصفیه روغن سوخته. مجله زمین شناسی مهندسی، ۱۸ (۵)، ۶۸۱-۷۱۱. https://doi.org/10.22034/JEG.2024.18.5.104968

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گوناگونی توسط محققین مختلف در خصوص تاثیر انواع مواد آلوده کننده هیدروکربنی و نفتی شامل نفت خام، بنزین، گازوئیل، روغن موتور، روغن موتور سوخته بر روی انواع خاکهای ریزدانه و درشت دانه انجام شده است که در این بین مطالعه اندکی در خصوص آلوده شدن خاک توسط پسماند حاصله از کارخانه‌های تسویه روغن سوخته انجام گرفته است. در این راستا مطالعه حاضر به‌منظور بررسی تفاوت در روند تغییرات پارامترهای ژئوتکنیکی انواع خاک‌های آلوده شده به مواد هیدروکربنی به خصوص اسلاج اسیدی و خاک فیلتر که هر دو پسماند حاصله از کارخانه تصفیه روغن سوخته می باشد را در درصد ها و میزان ماندگاری آلودگی مختلف مورد ارزیابی و تجزیه تحلیل قرار می‌دهد.

مواد و روش ها

در این تحقیق ابتدا به منظور بررسی اثر آلودگی خاک ناشی از دو پسماند حاصله از تصفیه روغن سوخته شامل اسلاج اسیدی و خاک فیلتر در در صدهای مختلف آلودگی (۰، ۳، ۶، ۹ درصد)، آزمایش تراکم بر روی نمونه های خاک آلوده شده بر اساس استاندارد ASTM D 698 انجام شده است. همچنین آزمایش برش مستقیم طبق استاندارد ASTM D3080 با جعبه به ابعاد ۱۰×۱۰سانتیمتر مربع بر روی نمونه های خاک آلوده با هر دو پسماند انجام شده است. نتایج مقاومت بر شی خاک ما سه رس دار با وزن مخصوص ۱،۹ گرم بر سانتی متر مکعب با استفاده از داده های بدست آمده از آزمایش برش مستقیم مورد ارزیابی قرار می‌گیرد (Khoshgoftar et al., 2021). سپس نتایج تغییرات پارامترهای مختلف خاک آلوده شده با انواع ماده های هیدرو کربنی به‌تفکیک با استفاده از داده های موجود در سایر تحقیق‌ها و با کمک نرم افزار مناسب استخراج گردیده و مورد بررسی و تحلیل قرار گرفته و برای مقایسه میزان تفاوت در روند ها، جداول و نمودارهای بدست آمده از پژوهش ها در کنار هم ترسیم می‌گردد.

بحث و نتایج

با آلوده شدن خاک توسط مواد هیدروکربنی روند تغییرات حدود اتربرگ عموما افزایشی و دربعضی موارد بصورت کاهشی می‌باشد. بدلیل لزجت بالای مواد هیدروکربنی و احاطه شدن ذرات خاک توسط مولکول های غیر قطبی نفتی و عدم تشکیل لایه دوگانه به آب بیشتری جهت تغییر فرم خاک مورد نیاز است که منجر به افزایش حدود اتربرگ می‌شود. همچنین بدلیل کاهش ظرفیت تبادل کاتیونی و کاهش ثابت دی الکتریک که منجر به لخته سازی خاک گردیده و حدود اتربرگ کاهش می یابد. در خصوص تغییرات حداکثر وزن مخصوص خشک خاک آلوده به مواد نفتی، آلاینده منجر به کاهش و یا افزایش حداکثر وزن مخصوص خشک خاک می‌گردد. افزایش حداکثر وزن مخصوص خشک آلاینده های نفتی بدلیل ویسکوزیته بالا مواد هیدروکربنی است که به عنوان روان کننده عمل می کنند و اجازه می دهند ذرات به آرامی روی یکدیگر بلغزند و به یکدیگر نزدیک و متراکم تر شوند. اما کاهش حداکثر وزن مخصوص خشک خاک را می‌توان به چگالی کمتر آلاینده های نفتی نسبت به آب، و همچنین اتلاف انرژی ناشی از حضور آلاینده های نفتی در طول آزمایش تراکم نسبت داد. آلوده شدن خاک به مواد هیدروکربنی عموما درصد رطوبت بهینه را بدلیل پرشدن فضای خالی بین دانه های خاک توسط ماده هیدروکربنی و فاصله گرفتن بین ذرات رسی بدلیل پایین بودن ثابت دی الکتریک مواد نفتی، کاهش می‌دهد. همچنین طبق تحقیق های انجام شده در خصوص نفوذ پذیری، پر شدن فضای خالی بین دانه های خاک توسط موادهیدروکربنی و لزجت بالای مواد نفتی و آب گریز بودن آن ها، عموما موجب کاهش نفوذ پذیری می‌گردد.

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براساس مطالعات انجام شده بر روی رفتار مقاومتی خاک‌های آلوده به مواد هیدروکربنی می‌توان عنوان نمود بدلیل اثر روغن کاری بین دانه های خاک و راحت تر لغزیدن دانه های خاک روی یکدیگر نسبت ظرفیت باربری کالیفرنیا عموما کاهش می‌یابد. همچنین زاویه اصطکاک داخلی خاک در خاک های دانه ای بدلیل راحت تر لغزیدن دانه های خاک روی یکدیگر زاویه اصطکاک داخلی کاهش و در خاک های ریزدانه زاویه اصطکاک داخلی عموما افزایش می یابد که این افزایش می تواند بدلیل فولوکوله شدن خاک های رسی باشد. در خصوص تغییرات چسبندگی خاک نیز می توان عنوان نمود، با آلوده شدن خاک توسط مواد نفتی بدلیل ویسکوزیته بالای مواد هیدروکربنی چسبندگی افزایش یافته است اما در بعضی از موارد بدلیل کاهش ثابت دی الکتریک و کاهش ضخامت لایه دو گانه خاک رس و تغییر ساختار خاک به حالت پراکنده، چسبندگی خاک کاهش می یابد. همانگونه که مشاهده شد بررسی تاثیر مواد آلوده کننده بر رفتار خاک به عوامل گوناکونی از جمله نوع آلودگی، درصد ماده آلوده کننده، زمان سپری شده از آلودگی خاک و نوع خاک تاثیر دارد که عمده تغییرات زاویه اصطکاک داخلی، نسبت ظرفیت باربری کالیفرنیا و نفوذپذیری خاک به صورت کاهشی و چسبندگی و حدود اتربرگ خاک بصورت افزایشی است.

نتیجه‌گیری

در مجموع از مطالب ذکر شده در این مقاله می توان مهمترین نتایج بدست آمده را به شرح ذیل بیان نمود:

۱- آلودگی خاک توسط مواد هیدروکربنی بر ساختار و پارامتر های ژئوتکنیکی خاک تاثیر می‌گذارد که این تغییرات در انواع خاک ها متفاوت بوده و وابسطه به نوع ماده آلوده کننده و مدت زمان آلودگی است.

۲- اضافه نمودن ۴/۲ درصد آلودگی اسلاج اسیدی به خاک، وزن مخصوص خشک حداکثر خاک را از ۱۸/۸۵ به ۱۹/۲۳ کیلونیوتن بر متر مکعب می‌رساند که علت این امر می‌تواند تسهیل هر چه بیشتر حرکت روان دانه‌های خاک و امکان فرورفتن دانه ها در فضاهای خالی بین آنها و نزدیک‌تر شدن دانه‌های خاک نسبت به یکدیگر باشد. اسلاج اسیدی بین دانه‌های خاک قرار گرفته و موجب کاهش اتصال محکم بین ذرات خاک و راحت‌تر لغزیدن دانه‌های خاک بر روی یکدیگر می‌شود و در نهایت زاویه اصطکاک داخلی خاک کاهش می‌یابد و از لحاظ فیزیکی در واقع موجب نوعی روغن کاری بین دانه‌های خاک می‌شود. همچنین با افزایش آلودگی خاک فیلتر به خاک به میزان ۵/۱ درصد به خاک، حداکثر وزن مخصوص خشک خاک از ۱۹/۱۳ به ۱۹/۵۶ کیلونیوتون بر متر مکعب افزایش پیدا می‌کند.

۳- در خاک دانه ای آلودگی دور تا دور دانه های خاک را می پوشاند و بدلیل ویسکوزیته بالای مواد هیدرو کربنی، موجب روغن کاری بین دانه های خاک گردیده که عموما موجب کاهش زاویه اصطکاک داخلی و بهبود پارامتر های تراکمی خاک شده است.

۴- مقاومت برشی خاک آلوده شده به مواد هیدروکربنی روند تغییرات مشخص و ثابتی نداشته است بطوری که با آلوده شدن به اسلاج اسیدی، با وجود افزایش چسبندگی خاک به دلیل کاهش زاویه اصطکاک داخلی خاک مقاومت برشی خاک کاهش یافته است اما با آلوده شدن به خاک فیلتر، بدلیل افزایش زیاد چسبندگی با وجود کاهش زاویه اصطکاک داخلی مقاومت برشی خاک افزایش می یابد.