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Investigation of the Surfactant's Effect on the Physical and Mechanical Properties of Sandy and Clayey Sandy Soils

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ABSTRACT: Due to the development of various industries, surfactants are used in detergents and disinfectants, oil industries, soil washing, petrochemicals, etc., and enter the ground in different ways. Surfactants, after entering the soil composition, change the physical and mechanical properties of soils due to physical and chemical processes. In this study, the pollutant effect of anionic, cationic, and non-ionic surfactants on some properties of sandy and sand with 20% clay soil is investigated. For this purpose, compaction, direct shear, consolidation, and capillary tests were performed on the soil exposed to water with 1% of various surfactants. The results showed that surfactants have a negligible effect on the maximum dry unit weight of the granular soil. Also, Triton and HEC surfactants do not have a significant effect on the optimum moisture content, but other surfactants reduced it compared to water. In general, soil shear resistance decreases in the presence of surfactant solutions compared to clean water. Also, according to the results of consolidation tests performed on the sandy soil with 20% clay, HEC, LABSA, and CTAC surfactants increased the compression coefficient and increased the swelling coefficient compared to clean water. HEC surfactants caused a decrease and CTAC and LABSA surfactants increase the consolidation coefficient (CV) compared to water. Also, all surfactants reduced differently the capillary ascend in the soil.

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1- Introduction

The word surfactant means a superficial active matter. In a simple definition, surfactants are binary molecules that have a polar, hydrophilic part, and a long, non-polar, hydrophobic hydrocarbon chain. These materials are called superficial active factors because their small density of them in a system changes the free energy of the contact surface between the phases in it. The molecule of superficial active materials consists of two distinct building blocks, a hydrophilic (lipophobic) and a hydrophobic (lipophilic). The longer the hydrocarbon chain, the greater the tendency to adsorb on the common surface of the two phases, and thus the more surface tension decreases. Since surfactants are hydrophilic and hydrophobic, the presence of these two species stabilizes the surface layers and thus the stability of the system [1]. Superficial active materials are generally classified into four groups anionic, cationic, nonionic, and amphoteric (bipolar ion) according to the nature of the hydrophilic groups.

Surfactants enter to ground in different ways, for example, industrial and home usage effluents and so on. In geotechnical and geo-environmental engineering, surfactants are usually used for the remediation of contaminated soil by washing methods as detergents, and after this process, some surfactants remain certainly in the soil. The research of Sigh *et al.* (2009) and Rahman *et al.* (2013) are two examples of these studies [2 and 3]. Chemical and physical reactions occur between the surfactant and soil particles, and these reactions change probably some physical and mechanical properties of the soil. In the following, some of the investigations performed in this field are summarized.

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In 2003, Abu-zreig *et al.* investigated the effect of the surfactants commonly used in detergents on the hydraulic properties of soils. The surfactants they used included an anionic surfactant (LABSA) and two nonionic types (Rexol and Rexonic). The researchers studied properties such as hydraulic conductivity, infiltration, and suction on two types of loamy soil and loamy sand. Their results showed that the addition of surfactants reduces the hydraulic conductivity and this amount of reduction depends on the soil texture and the properties of the surfactants and their density and that the use of sulfonic reduces capillary ascending and permeability [4].

Singh *et al.* (2009) studied the effect of the anionic surfactant of Sodium Dodecyl Sulfate as a detergent on poorly graded sand and low-plastic and high-plastic clay contaminated with motor oil. They showed that mixing the three mentioned soil with SDS solutions results in a reduction of unconfined compression strength and cohesion and increasing in compaction settlement and internal friction of two clay soils. They also concluded in sandy soil the internal friction angle increases and California Bearing Capacity reduces in the presence of SDS [5].

In 2010, Kou *et al.* investigated the superficial active materials on the mechanical behavior of low plastic clay collected from a depth of 2.5 m in China. They used sodium benzene sulfonate as a superficial active matter with weight percentages of 1, 2, and 10%. They concluded that the shear strength of soil decreases due to contamination and this contaminant effect on soil increases with an increase in its percentage [6].

In 2011, Vipulanandan and Sunder investigated the effect of surfactants on the suction behavior of clay. They investigated the suction-moisture relations between kaolinite and montmorillonite clays. According to the results, the anionic surfactant has the least effect on kaolinite clay, because it has a very low cationic exchange capacity, and for montmorillonite clay, the suction was reduced by the addition of surfactant [7].

In 2013, Akbulut *et al.* performed a laboratory study of the geotechnical properties of a mixture of organic clay and 4 surfactants. They used two types of cationic surfactants and two types of anionic for this study. They showed that unconfined compression strength, maximum dry unite weight, cohesion and optimum moisture content of all specimens decreased in the presence of surfactants. However, these values increased despite anionic surfactants. In addition, the results of the direct shear test showed that the internal friction angle of the specimens increased. Also, changes in the hydraulic conductivity coefficient were small [8].

In 2013, Rahman *et al.* investigated the effect of sodium sulfate surfactant (SDS) on the geotechnical properties of silt soil, which is used for the purification of contaminated soil. The results of this study showed that the existence of surfactant in the soil can change the mechanical behavior of the soil and reduce the optimum moisture content by increasing the amount of surfactant. They evaluated the shear strength by undrained-unconsolidated triaxial test (UU) and concluded that for 20% of surfactant, undrained cohesion (Cu) extremely decreased, in addition, maximum dry unite weight increased and liquid and plastic limits and permeability decreased [9].

In 2017, Peng *et al.* investigated the effect of a non-ionic surfactant on the saturated hydraulic conductivity of two types of loamy sand and sandy loam soils. They used Aerosol non-ionic surfactant, which is widely used as a non-ionic surfactant in soil improvement. They concluded that the total hydraulic conductivity value decreases for all samples [10].

Geotechnical characteristics including index properties and unconfined compression strength of five fine-grained soils contaminated by surfactant effluent were investigated by Murugaiyan *et al.* in 2014. They stayed that the effect of surfactant effluent on the index properties (Atterberg limits) is different and it depends on the soil nature, whiles, unconfined compression strength is reduced for all soils, mainly due to long periods of effluent contamination [11].

In 2016, Khan *et al.* investigated the geotechnical properties of two types of cohesive soils contaminated with two types of industrial wastewater. Clay soils were typical of kaolinite and illite. They examined properties such as liquid limit, plastic index, optimum moisture, compaction index, maximum dry unite weight, undrained shear strength, and consolidation coefficient on contaminated soil. The results showed that the compaction index of contaminated soil increased and the coefficient of consolidation and permeability decreased. Also, the addition of these two types of pollutants changes the pH of the soil and increases the liquid limit and plastic index of cohesive soils, because of increasing in a specific area due to the addition of pollutants, which leads to high water absorption and affects the Atterberg limits [12].

In 2017, Liu *et al.* investigated the improvement of Methyl tert-butyl ether (MTBE) contaminated sandy soils by diffusion of sodium benzene sulfonate by the compressed air. This is a way, to get less surfactant to the ground. They concluded that this method effectively reduces the concentration of pollutants and modifies it [13].

Different surfactants have been used for many years as cleaners in homes, industries, hospitals, and so on and they enter nature after usage. Also, surfactants are used for washing contaminated soils, and then they will remain in nature after the soil-washing process. Based on the mentioned researches, the soil's physical and mechanical properties will be changed due to the existence of surfactants. Therefore, the subgrade soil of buildings may show unwanted behavior such as settlement, deformation, and even collapse and then damage to structures. Also, it seems that clay soil has different behavior in the presence of surfactants due to its physical-chemical behavior in comparison with coarse grain soils Then, in this paper, the effect of different surfactants on a sandy and a clayey sandy soil is investigated and the effect of the type of surfactant on parameters such as capillary ascending, consolidation properties and shear strength components of soil is investigated and compared with each other.

2- Materials used

The soil used in this study includes two types of sandy soil and sand with 20% clay. The sand used is called sand number 101 obtained from the Firoozkooh region (North of Iran), which is a poor granulated sand (SP) based on the classification of soils in the unified system. The clay used in this research is prepared from the Abyek region (almost the middle of Iran), which is classified as low plasticity clay (CL) based on the classification of soils in the unified system. The physical properties of soil are also given in Table 1.

According to the history of researches, the focus of this research is on common surfactants in industry and home usage [14]. Table 2 shows the properties of the surfactants used in this study.

A modified compaction test according to the ASTM D1557 standard has been used. After testing and determining the wet and dry density and the optimum moisture content (related to the maximum dry density), finally, the compaction curve is obtained according to Fig. 1 [15]. Based on this figure, the maximum dry unit weight and optimum moisture content of sandy soil and sand with 20% clay are equal to 16.35 (kN/m^3), 11.8%, and 17.87 (kN/m^3) and 12.2%, respectively.

Table 1. Physical properties of the used soils.

Properties	Sand 101	Abyek clay
Liquid limit (LL)	-	33
Plastic limit (PL)	-	21
Plastic index (PI)	-	12
Specific density (G_S)	2.69	2.77
Maximum dry unit weight (γ_{dmax})	(kN/m^3) 16.35	17.5 (kN/m^3)
Optimum moisture content (ω_{opt})	11.8 (%)	17.25 (%)
C_U	1.81	-
C_C	1.02	-
Soil classification	SP	CL

Table 2. Properties of the used surfactants.

Type	Surfactant	Commercial name	chemical formula
	Sodium dodecyl sulfate	SDS	$NaC_{12}H_{25}SO_4$
Anionic	Sulfonic acid	LABSA	C18H30SO3
	Sodium lauryl ether sulfate	SLES	C14H29SO5Na
Cationic	tri methyl ammonium chloride	CTAC	$C_{19}H_{42}ClN$
	Hydroxyacetyl cellulose	HEC	$C_{36}H_{70}O_{19}$
Non-ionic	Triton X-100	Triton X-100	$C_{14}H_{21}(C_2H_4O)_nOH$
	Tween 80	Tween 80	$C_{64}H_{124}O_{26}$

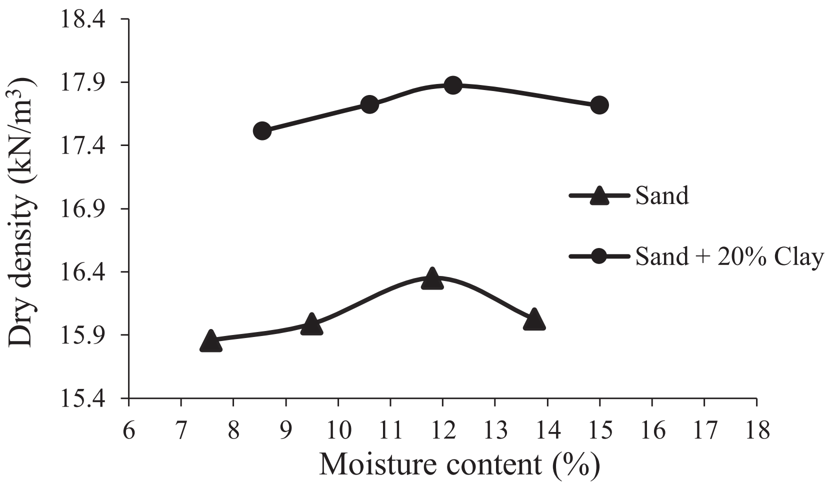

Fig. 1. Compaction diagram of the used soil.

Table 3. Some experiments performed: soil A (sand) and soil B (sand with 20% clay).

Total	Water	Non-ionic		Cationic		Anionic			Type of pollutant	
		Tween 80	Triton X-100	HEC	CTAC	SLES	LABSA	SDS	Pollutant	
		1%							Percentage of pollutants	
										Test
8	1	1	1	1	1	1	1	1	Soil A	Compaction
8	1	1	1	1	1	1	1	1	Soil B	
24	3	3	3	3	3	3	3	3	Soil A	Direct Shear
12	3	-	-	3	3	-	3	-	Soil B	
4	1	-	-	1	1	-	1	-	Soil B	Consolidation
8	1	1	1	1	1	1	1	1	Soil A	Capillarity
8	1	1	1	1	1	1	1	1	Soil B	

3- Performed Experiments

Before preparing the specimens and to increase their uniformity, the clay required for making each specimen is first passed through sieve number 40 to separate the coarse grains and lumps in it and then left in the oven for 24 hours to dry. According to the weight of the soil and the percentage of moisture, the amount of surfactant and water is calculated, and by using a mixer device it homogenizes well. Notice that the surfactant solution and water were added to the soil as a percentage of moisture. Also, the weight percentage of each type of surfactant is constant and, in all compounds, a 1% solution of surfactant is used. Except for the compaction test, all surfactants were used in sand specimens and three types of selected surfactants were used in clayey sand specimens, which are described below. Because in this study, the effect of curing on different samples is not seen, after specimen preparation, each specimen was immediately tested. According to Table 3, in addition to the compaction test, several direct shear tests and one-dimensional consolidation tests were performed to determine the mechanical parameters of the described soils based on ASTM D3080-98 and ASTM D2435, respectively [16, 17]. Also, some capillary height determination tests were done on soil samples to investigate the effect of surfactants on the capillary property of the mentioned soils.

4- Experiments Results

The results of the experiments on compressibility, shear strength, consolidation, and capillary are explained in separate sections.

4- 1- Effect of surfactants on the soil compaction properties

The results of the compaction test on sand and sand with 20% clay under the influence of water and anionic, nonionic, and cationic surfactants are shown in Figs. 2 and 3, respectively. As can be seen, with the addition of surfactants as well as the change in the type of surfactant, the compaction behavior is affected. The results show that in sandy soils, in all anionic surfactants, the optimum moisture content decreases compared to water. Excluding LABSA surfactant, other surfactants reduce the maximum dry unit weight. Tween and Triton surfactants also have a similar effect on the maximum dry unit weight, except that Triton leads to more optimum moisture content rather than Tween. Both surfactants increase the maximum dry unit weight and decrease the optimum moisture content compared to clean water in clayey sandy soil. HEC and CTAC surfactants reduce the maximum dry unit weight and optimum moisture content compared to water. It is also observed that, by adding clay to sand, this reduction effect is modified compared to the base soil and causes an increase in maximum dry unit weight compared to water. The results showed that in all surfactants in the existence and absence of clay, after optimum moisture content, dry unite weight decreases significantly. The cause of this phenomenon is the foaming property and the soap effect of the surfactants due to contact with water. As the amount of soil moisture increases, the effect of this foaming increases and causes an increase in the distance between the solid particles of the soil [18]. The amount of foaming varies among the surfactants, so the dry unit weight loss is different for each surfactant. In all specimens containing surfactant, the maximum dry unite weight increases in the existence of 20% clay compared to the absence of clay mode. The important point is the effect of clay on Triton, Tween, and CTAC surfactants performance, in which in the sandy soil, the maximum dry unit weight is lower than in clean samples, and the addition of clay to sand results in a higher maximum dry unite weight in comparison to clean samples, and generally adding 20% clay to sand for these three types of surfactants improves the compaction behavior of soil. Changes in the optimum moisture content of sandy soils and sand with 20% clay show that with the addition of clay, the optimum moisture content in the existence of Tween surfactant has increased significantly compared to

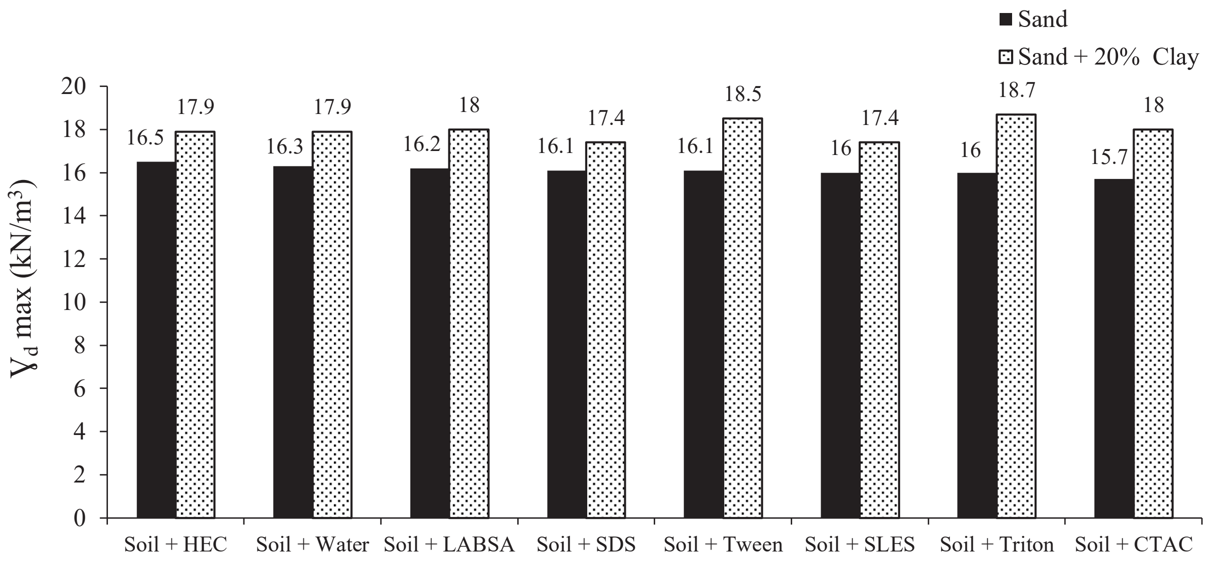

Fig. 2. Maximum dry unite weight for sandy soil and sand with 20% clay exposed to water and 1% of surfactants.

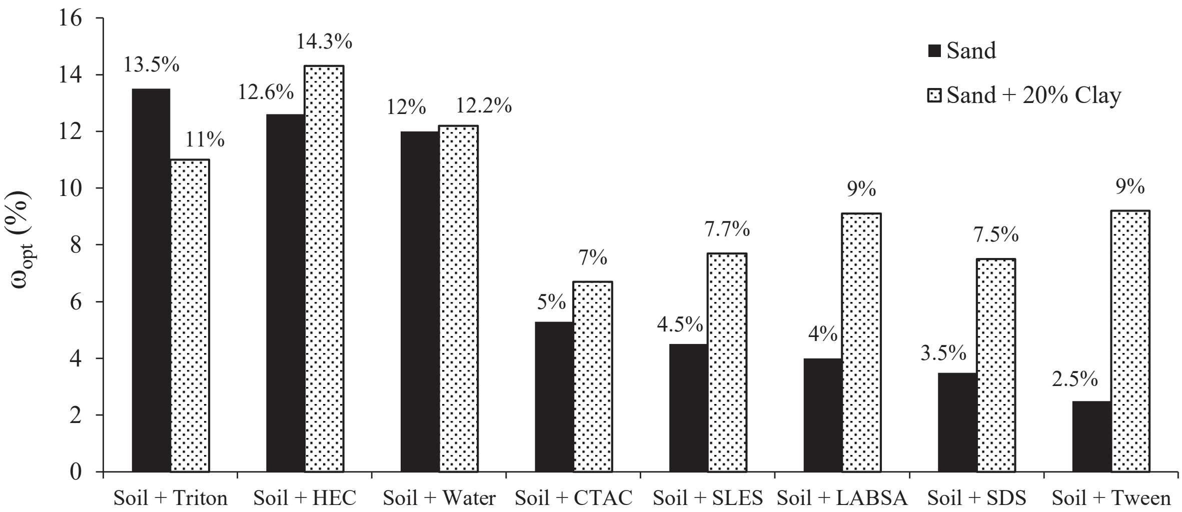

Fig. 3. Optimum moisture content for sandy soils and sand with 20% clay exposed to water and 1% of surfactants.

the absence of clay mode. Excluding Triton surfactant, in the existence of other surfactants, the optimum moisture content has increased compared to the absence of clay. In sandy soil, Triton has the highest optimum moisture content and Tween has the lowest, and with 20% clay, HEC has the highest and CTAC has the lowest optimum moisture content, respectively.

4- 2- Effect of surfactants on the direct shear test results

In this section, the results of the direct shear test on sandy soil and sand with 20% clay expose to water and water with 1% surfactant made with a compaction percentage of 0.95 is investigated. Notice that in the experiments performed on the sand, all surfactants were used, while in clayey sandy soil, the effect of three selected anionic, non-ionic, and cationic surfactants was evaluated. Experiments were performed at 3 normal stresses of 50, 100, and 200 kPa under drained consolidated conditions at a rate of 0.05 mm/s loading, immediately after contamination. 36 direct shear tests were performed. Fig. 4 shows the shear stress-horizontal displacement behavior obtained from the direct shear test for a sand with 20% clay sample which has been contaminated with various surfactants and under a 50 kPa normal load. In the following because of the briefness, only the results of maximum shear and residual strengths are presented.

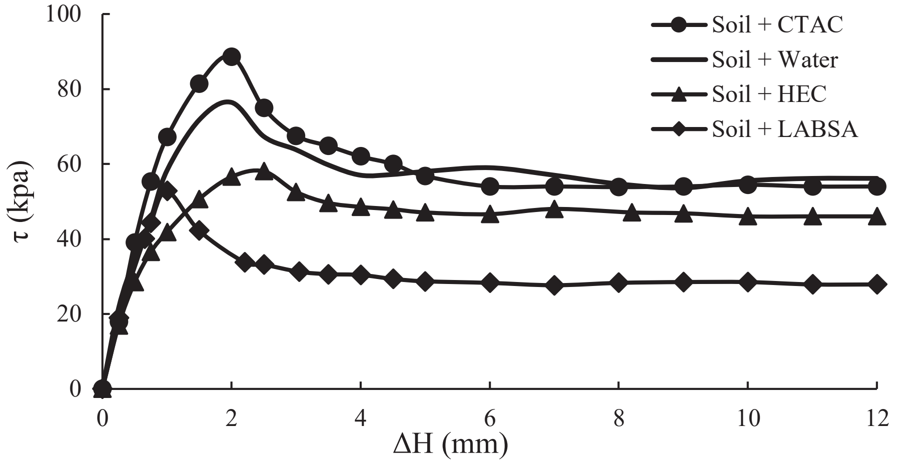

Fig. 4. Shear stress-horizontal displacement of sand with 20% clay at a normal stress of 50 kPa expose to water and water with 1% of CTAC (cationic), HEC (nonionic), and LABSA (anionic) surfactants.

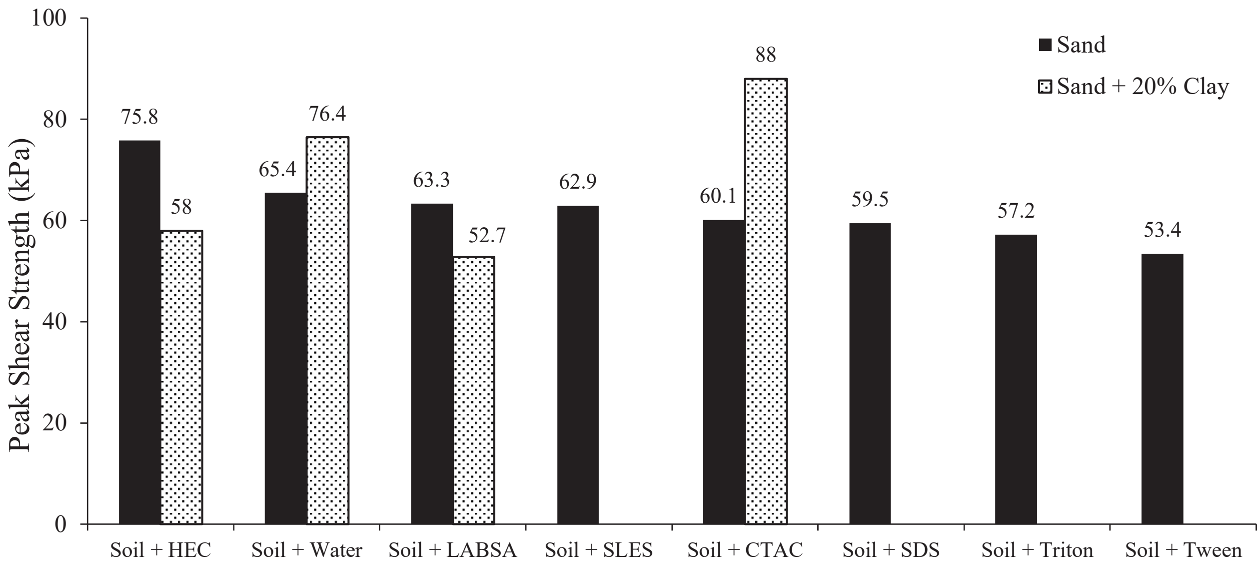

Fig. 5. Maximum shear strength for sandy soil and sand with 20% clay at a normal stress of 50 kPa.

4- 2- 1- Resistance changes under 50 kPa normal stress

Figs. 5 and 6 show the changes in maximum shear strength as well as residual strength for a combination of sand with various surfactants and clayey sand with anionic, non-ionic, and cationic surfactants under 50 kPa normal stress. At normal stress of 50 kPa, the highest residual shear strength for sandy soil is related to non-ionic surfactant HEC and the lowest is related to non-ionic surfactant Tween. For sandy soil with 20% clay, water, CTAC, and HEC surfactant have the highest residual shear strength, respectively, and LABSA has the lowest residual shear strength. By adding 20% clay to sand, the residual shear strength of samples containing water and CTAC surfactant increase similar to the maximum shear strength, and HEC and LABSA reduce it compared to sandy samples. In clayey sand combination, CTAC cationic surfactant and LABSA anionic surfactant led to the highest and lowest maximum (and also residual) shear strength, respectively, compared to water. Also, in the sand with 20% clay, CTAC cationic surfactant and LABSA anionic surfactant resulted in the highest and lowest maximum (and also residual) shear strength, respectively, compared to water. Kou *et al.* stated that the shear strength of low plastic clay soil decreases in the presence of superficial active contamination [6].

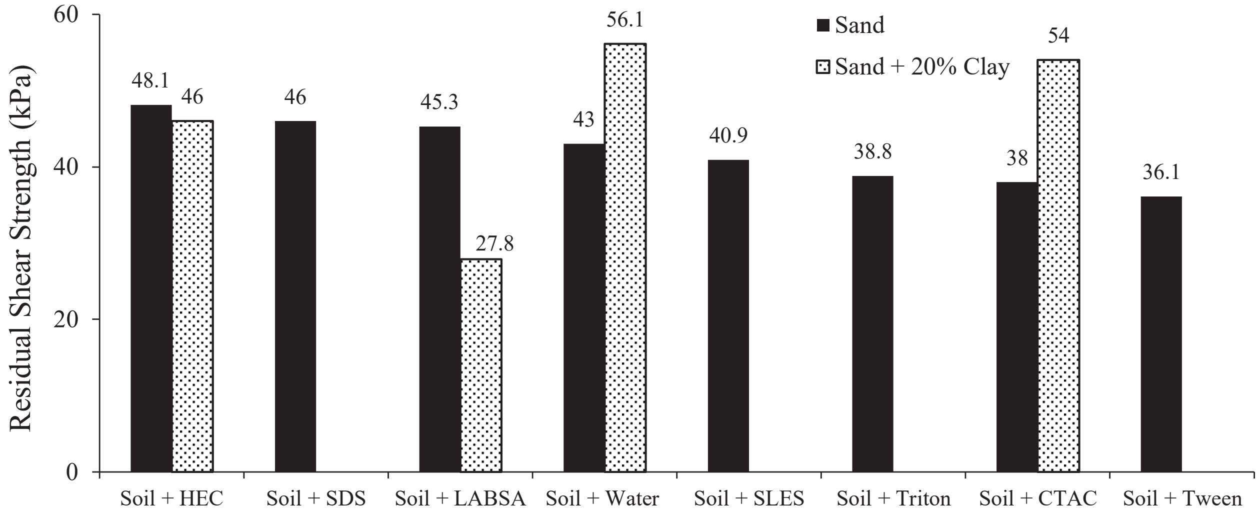

Fig. 6. Residual shear strength for sandy soils and sand with 20% clay at a normal stress of 50 kPa.

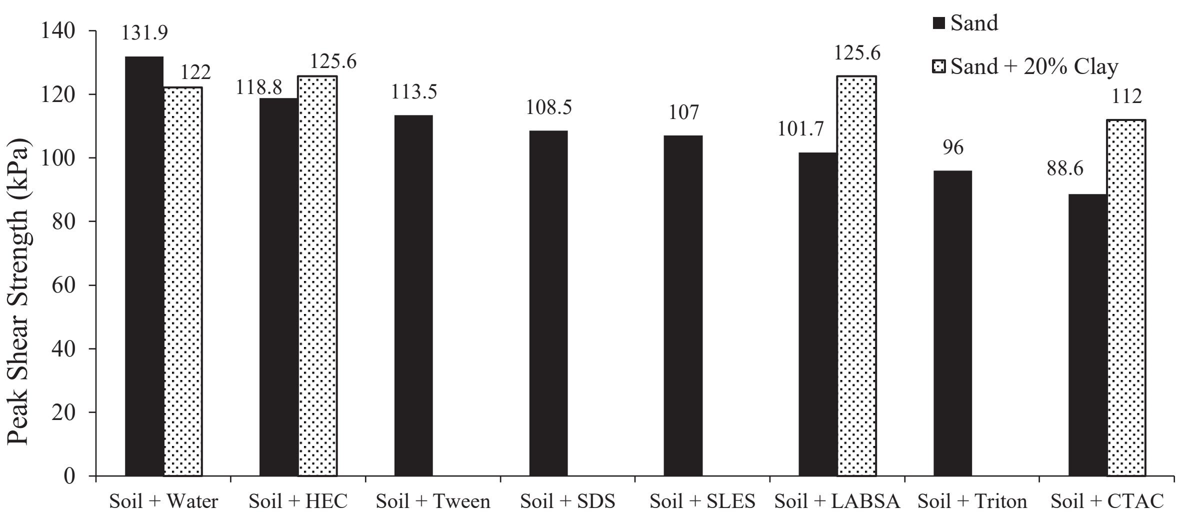

Fig. 7. Maximum shear strength for sandy soils and sand with 20% clay at a normal stress of 100 kPa.

4- 2- 2- Resistance changes under 100 kPa normal stress

Fig. 7 shows the maximum shear strength of sandy soils and sand with 20% clay exposed to water and 1% surfactant solutions at a normal stress of 100 kPa. As can be seen for sandy soil, the highest amount of maximum shear strength is related to water and other surfactants reduce the maximum shear strength compared to water so that the non-ionic surfactant HEC has the highest and the cationic CTAC has the lowest maximum shear strength. In the existence of 20% clay, the shear strength of all surfactants increases compared to clean sand, but the maximum shear strength of samples containing water decreases compared to the previous mode. Also, according to Fig. 8, in sandy soil, the highest amount of residual shear strength is related to water, and similar to the maximum shear strength, all surfactants reduce the maximum residual shear strength of soil compared to water. The highest amount of residual shear strength among surfactants is related to SDS anionic, HEC non-ionic, and SLES anionic surfactants, respectively, and the lowest is related to CTAC cationic. By adding 20% clay, the residual shear strength of the samples increases compared to the absence of clay mode.

4- 2- 3- Resistance changes under 200 kPa normal stress

Fig. 9 shows the maximum shear strength of sandy soils and sand with 20% clay exposed to water and 1% surfactant solutions at a normal stress of 200 kPa. As can be seen, for sandy soil, water has the highest amount of maximum shear strength and other surfactants reduce the maximum shear strength. So that Tween non-ionic surfactant has the highest

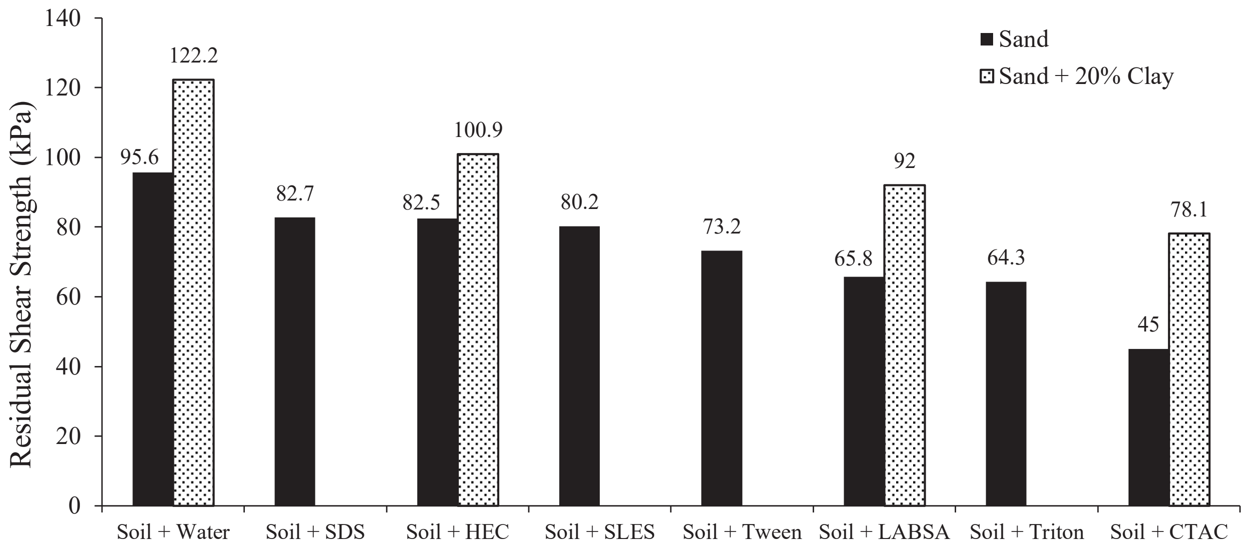

Fig. 8. Residual shear strength for sandy soils and sand with 20% clay at a normal stress of 100 kPa.

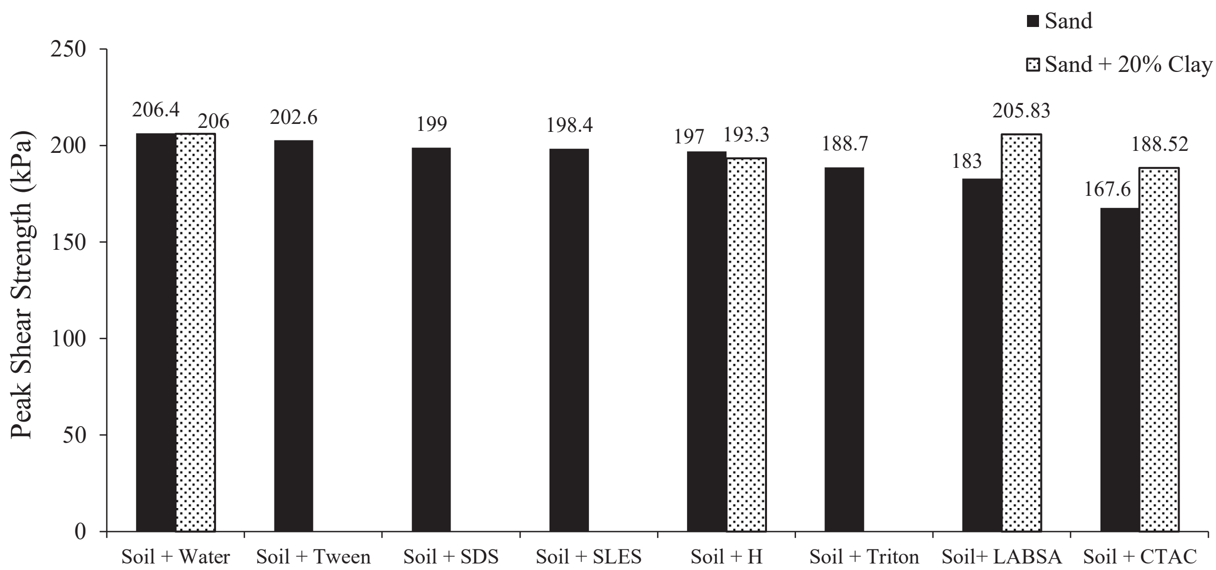

Fig. 9. Maximum shear stress for sandy soil and sand with 20% clay at a normal stress of 200 kPa.

and CTAC cationic has the lowest amount of maximum shear strength. In the existence of 20% clay, LABSA and CTAC surfactants increase the maximum shear strength compared to the absence of the clay mode; however, the maximum shear strength of samples containing water and non-ionic surfactant HEC is not changed much in comparison to sandy soil. In the existence of 20% clay, water and LABSA surfactant have the highest amount of maximum shear strength and CTAC has the lowest amount. Also, Fig. 10 shows the residual shear strength of sandy soils and sand with 20% clay exposed to water and 1% surfactants at a normal stress of 200 kPa. According to the obtained results, in sandy soil, the highest residual shear strength is related to non-ionic surfactant Triton, and HEC, LABSA, and CTAC surfactants, reduce the residual shear strength compared to water, and other surfactants increase the residual shear strength. By adding 20% of clay, the residual shear strength of all samples increases compared to the absence of clay mode.

The effect of water and 1% of surfactant solutions on the shear strength parameters of sandy soil in the existence and absence of 20% clay is shown in Table 4. As can be seen, the effect of surfactants on the shear strength parameters is divided into three categories compared to water. The first group of surfactants that increase the internal friction angle and

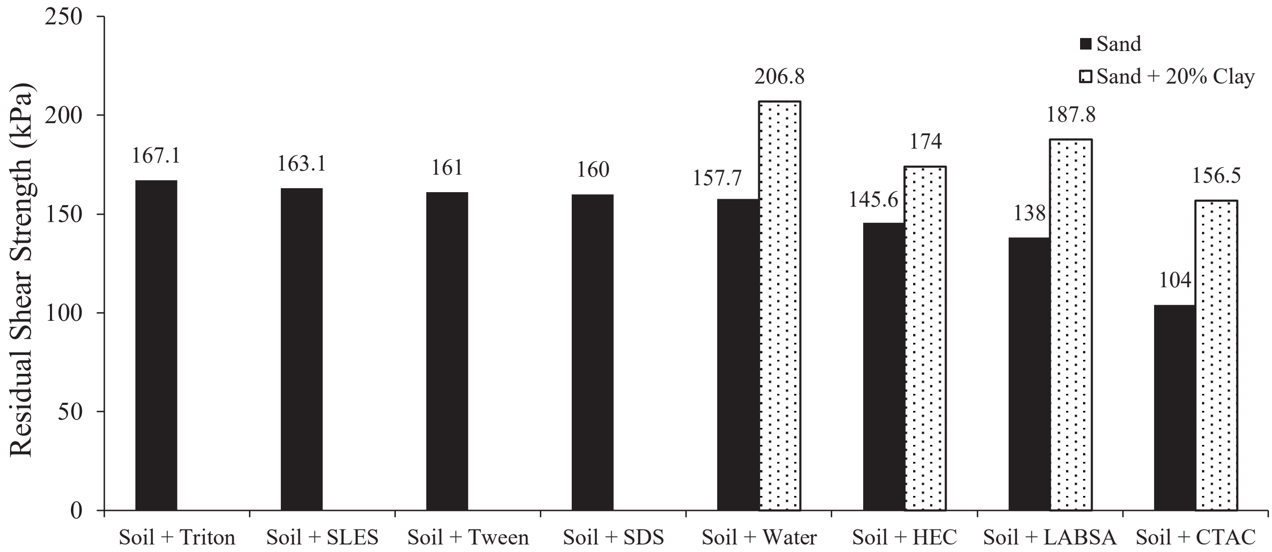

Fig. 10. Residual shear strength for sandy soil and sand with 20% clay at a normal stress of 200 kPa.

Table 4. Shear strength parameters of the contaminated and clean soil compositions.

Water	Cationic	Non-ionic				Anionic		Type of surfactant	Soil type
	CTAC	Triton	HEC	Tween	SLES	LABSA	SDS	Surfactant	
42.4	36	41.5	38.8	44.4	42.1	38.7	42.8	Φ_{Peak}	Sand 101
28.2	20.7	10.9	36.7	8.8	2.2	22.7	14.3	C_{Peak}	
36.6	24.7	38.5	39.9	38.2	39.1	32.3	37.3	$\Phi_{Residual}$	
12	8.6	0	16.6	0	0	9.2	7.4	$c_{Residual}$	
40.9	34.2	-	41	-	-	44.7	-	Φ_{Peak}	Sand 101 +% 20clay
34	50.4	-	24.2	-	-	12.7	-	C_{Peak}	
35.7	35	-	39.9	-	-	42.5	-	$\Phi_{Residual}$	
18	14.6	-	9.5	-	-	0	-	$c_{Residual}$	

decrease the cohesion compared to water, including Tween and SDS, the second group of surfactants that reduce the internal friction angle and increase the cohesion compared to water, including HEC, the third group of surfactants that reduce both parameters of shear strength compared to water, which includes CTAC, Triton, SLES and LABSA. In these three groups of surfactants, the highest increase in the peak internal friction angle of sandy soil is Tween (about 44%), the highest decrease is CTAC (about 36%), and for peak cohesion, the highest increase is HEC (about 37%), and the highest decrease is SLES (about 92%) compared to water. Also, in sandy soil with 20% clay, the effect of surfactants on the shear strength parameters is divided into two groups compared to water. The first group of surfactants that increase the internal friction angle and reduce the cohesion compared to water, including HEC and LABSA, the second group of surfactants that reduce the internal friction angle and increase the cohesion compared to water including CTAC, in which, LABSA surfactant has the highest increase in peak internal friction angle (about 9%), CTAC has the highest decrease (about 16%), and CTAC has the highest increase in peak cohesion (about 48%), and LABSA has the highest decrease (about 63%) compared to water. Again, for sandy soil with 20% clay, the effect of surfactants on the residual shear strength parameters is divided into two categories compared to water. The first group of surfactants that increase the internal friction angle and reduce cohesion compared to water, including HEC and LABSA, the second group of surfactants that reduce the internal friction angle and increase the cohesion compared to water including CTAC, in which, LABSA has the highest

Table 5. Consolidation parameters of sandy soil with 20% clay exposed to the effect of 1% surfactant solutions and water.

Soil + Water	$C_V\ (\frac{cm^2}{min})$	0.0215
	C_C	0.006
	C_S	0.0008
Soil + HEC	$C_V\ (\frac{cm^2}{min})$	0.00831
	C_C	0.03
	C_S	0.009
Soil + LABSA	$C_V\ (\frac{cm^2}{min})$	0.0198
	C_C	0.018
	C_S	0.004
Soil + CTAC	$C_V\ (\frac{cm^2}{min})$	0.0306
	C_C	0.016
	C_S	0.003

increase in the internal friction angle and CTAC has the highest decrease, and for cohesion, CTAC has the highest increase and LABSA has the highest decrease compared to water. Akbulut *et al.* showed that the internal friction angle of the organic clay specimens increased in the presence of surfactants [6], then it is seen that the kind of surfactant and probably the kind of soil and clay mineralogy are affective parameters on the soil's internal friction angle.

4- 3- Effect of surfactants on the consolidation parameters

To investigate the changes in the parameters obtained from the consolidation results in both non-contaminated and contaminated with different surfactants, the results are presented only for sandy soil with 20% clay. Changes in compression, swelling, and consolidation coefficients in sandy soil with 20% clay under the effect of 1% of selected surfactants solutions including anionic LABSA, non-ionic HEC, and cationic CTAC are shown in Table 5. Samples were prepared as a direct shear test with a density of 95% maximum dry unit weight. It is observed that all surfactants increase the compression coefficient (*Cc*) compared to water, in addition, non-ionic HEC, anionic LABSA and cationic CTAC surfactants, samples have the highest amount, respectively. Also, HEC surfactants with 400%, LABSA with 200%, and CTAC with 166% increments have the highest effect in compression coefficient (*Cv*) compared to water. All surfactants increase the swelling coefficient (*Cs*) compared to water and non-ionic HEC, anionic LABSA and cationic CTAC surfactants have the highest amount, respectively. Also, HEC surfactants with 1025%, LABSA with 400%, and CTAC with 275% increments have the highest effect compared to water. Also, LABSA and CTAC surfactants increase and HEC decreases the consolidation coefficient compared to water, so that, HEC surfactant has the highest reduction with 61% and CTAC has the highest increase with 42% compared to water.

Table 5 shows that surfactant pollutions lead to compression and swelling coefficients. It may be said that the presence of pollution between the clay particles results in structural changes of soil being flocculated or dispersed. Increasing compression and swelling demonstrated that the clay structure tends to be flocculated, in which volume changes increase due to loading and unloading. Also, the numbers in this table show that three different contaminations have different effects on the coefficient of consolidation and the results oscillated. Also, notice that the increasing compression coefficient is related to soil permeability-increasing and vis versa. Perhaps, this table is the most important result of a clayey sandy soil polluted with surfactants, due to increasing consolidation and swelling coefficients. As shown in this table, the consolidation coefficient has been 2.7, 3, and 5 times for soil samples polluted with surfactants of CTAC, LABSA, and HEC compared to clean samples, respectively, it means the increase of consolidation settlement of structures built on this type of soil, in which could damage them. Certainly, this phenomenon could be more predominant for soils with more clay content.

4- 4- Effect of surfactants on capillary height

To evaluate the height of capillary ascent in soil under the influence of water and surfactants, a capillary ascent test by Marriott bottle was used (Fig. 11). Fig. 12 shows the capillary height and changes in the capillary height of sand and sand with 20% clay compared to water under the influence of 1% surfactants for 24 hours. Fig. 13 also shows the differential ratio of the capillary height of sand and sand with 20% clay under the effect of 1% surfactant to water. Nonionic surfactants have different capillarity behavior and as can be seen, Tween, Triton, and HEC differ greatly in the height of capillary ascent. But anionic surfactants have a similar capillarity behavior, and for LABSA, SDS, and SLES there is

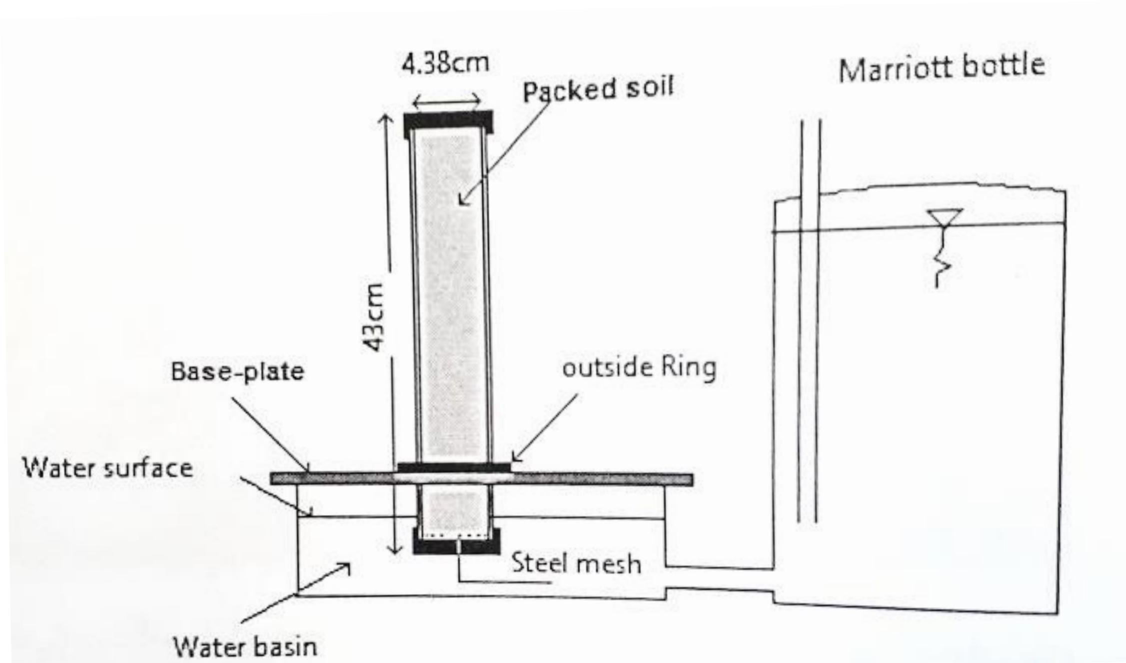

Fig. 11. The Marriott bottle used for capillary ascent in soil.

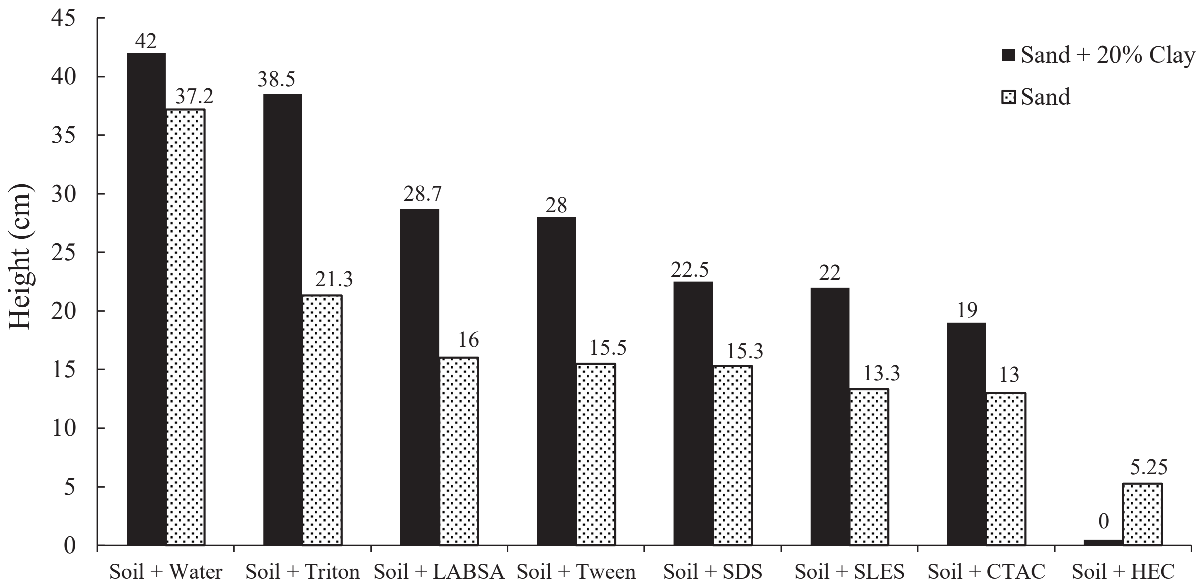

Fig. 12. Capillary height of sand and sand with 20% clay under the influence of water and 1% surfactant for 24 hours.

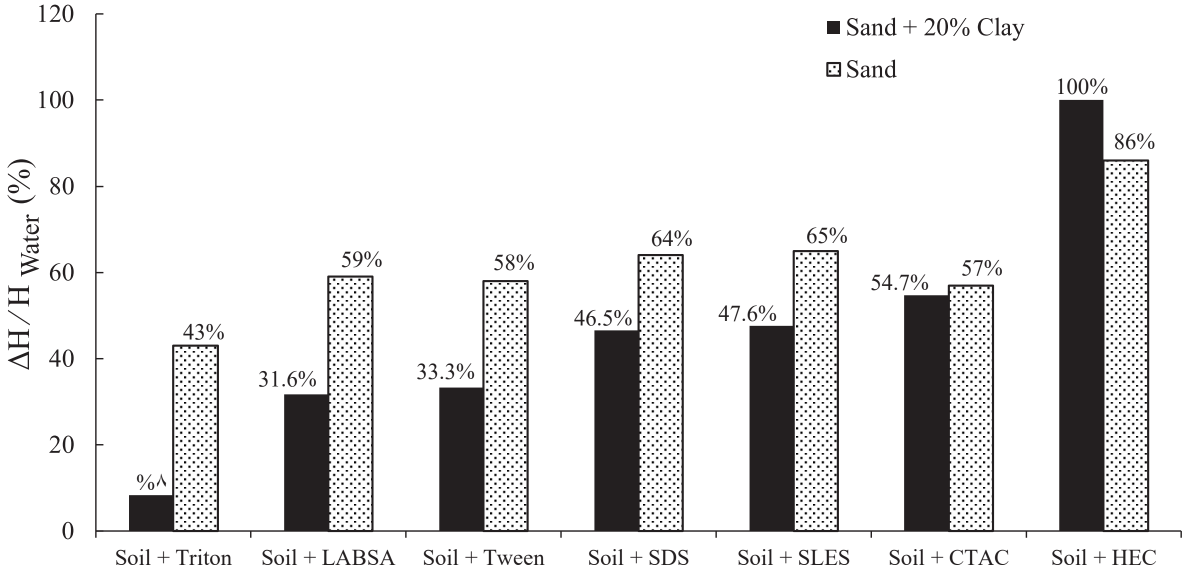

Fig. 13. The differential ratio of the capillary height of sand and sand with 20% clay under the effect of 1% surfactant to water.

little difference in the height of capillary ascent. Non-ionic surfactant HEC and anionic surfactants SLES, SDS, LABSA, non-ionic Tween, cationic CTAC, and non-ionic Triton, have the highest reduction effect, respectively. After water, Triton non-ionic surfactant has the highest rise in 24 hours and HEC non-ionic surfactant has the lowest rise. Test results in both sandy soil and sand with 20% clay are somehow like to each other. As can be seen, similar to the sand results, the non-ionic surfactant HEC has the highest reduction and the non-ionic surfactant Triton has the lowest reduction among the surfactants compared to water. As mentioned in the introduction, Abu-zreig *et al.* also concluded that the use of sulfonic reduces capillary ascending [2]. Capillary height descending in the presence of surfactant contaminations shows the reduction of surface tension of water. Furthermore, this descending depends on the kind of surfactant, so HEC has the most reduction effect and Triton has the least effect on the surface tension of water. According to these figures, surfactants as an impurity reduce the water surface tension and then capillary ascending in soil. However, considering to oscillation and variation of capillary ascending between three types of surfactants, it could not be concluded which type of cationic, anionic, or non-anionic is more effective. Notice that, the temperature and pH value of the solution (mixture of water and surfactant) are also two effective factors in water surface tension and capillary ascending, which were not measured in this research.

5- Conclusion

In this research, the physical and mechanical effects of different types of anionic, cationic, and non-ionic surfactants on two types of sandy soil and clayey sandy soil were investigated using compaction, direct shear, consolidation, and capillary tests. According to the mentioned tests, the following main results were obtained:

1. In sandy soil, HEC surfactant increases the maximum dry unit weight by 1.22% and other surfactants decrease it from 0.6 to 3.6% compared to clean water. Therefore, it can be said that surfactants do not have a significant effect on the maximum dry unit weight of the granular soil. Also, Triton and HEC surfactants do not have a significant effect on the optimum moisture content, but other surfactants reduce it from 56 to 79% compared to water.

2. In sandy soil with 20% clay, similar to granular soil, surfactants do not have a significant effect on the maximum dry unit weight compared to clean water, so SDS and SLES surfactants reduce it by 2.8%, and Tween and Triton increase it by 4.5%, compared to water. Other surfactants behave similarly clean water. HEC surfactant also increases the optimum moisture content by 17% and other surfactants reduce it from 10 to 45%, compared to water.

3. According to the results obtained from the direct shear test, in sandy soil, surfactants reduce the peak shear strength by up to 32% compared to water, while the residual shear strength in the case of contaminated surfactants is reduced by about 40% compared to water.

4. In sandy soil with 20% clay, surfactants reduce the maximum and residual shear strength by about 32% compared to water.

5. In sandy soil with 20% clay, HEC, LABSA, and CTAC surfactants increase the compression coefficient by 400, 200, and 166%, respectively, and increase the swelling coefficient by 1025, 400, and 275%, respectively, compared to water. HEC surfactants also reduce the consolidation coefficient by 61% and CTAC and LABSA surfactants increase it by 42 and 8% compared to water, respectively.

6. All surfactants reduce capillary height. Non-ionic HEC and anionic SLES, SDS, LABSA and non-ionic Tween, cationic CTAC, and non-ionic Triton surfactants have the highest reduction effect, respectively.

In the end, some practical recommendations can be given to civil engineers as follow:

- Almost all surfactant contaminations increase the consolidation settlement, therefore it could damage the structures.
- Surfactants have positive or negative effects on the sandy and clayey-sandy soil shear strength parameters, but the effect is not as important as consolidation.
- Surfactants have a low effect on the maximum dry unit weight of the soil but a considerable effect on the optimum moisture content, therefore it should be investigated before using surfactant-polluted soils.

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