GEOTECHNICAL EVALUATION OF CLAYEY SOIL CONTAMINATED WITH INDUSTRIAL WASTEWATER

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The impacts of industrial wastewater contamination on the geotechnical properties of clayey soil have been studied in the research presented in this paper. The contaminant in question is industrial wastewater released from Thi-Qar oil refinery as a by-product of production, and the soil samples obtained from Thi-Qar oil refinery plant in Al-Nassyriah (a city located in the south of Iraq). The geotechnical properties of contaminated soil samples were compared with those of intact soil to measure the effects of such a contaminant. The soil samples were obtained from three locations in the study area; representing the highly contaminated area, the slightly contaminated area, and the intact area used as a reference for comparison of test results. The results of the tests showed that the contaminant causes an increase of natural moisture content, field unit weight, Atterberg's limits, and maximum dry unit weight, as well as an increase of the compression index and the coefficient of vertical consolidation. Also, the contaminant causes a decrease in specific gravity, the optimum moisture content initial void ratio, the swelling index, the coefficient of permeability, and cohesion between soil particles.

Keywords: contamination, industrial wastewater, petroleum hydrocarbon, clay soil, & geotechnical properties.

1. INTRODUCTION

Soil contamination is a serious environmental problem and its occurrence is growing around the world. Human activities such as agriculture, mining, and heavy industry lead to the contamination of soil in many ways. In general, the most common contamination of soil occurs in the form of

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heavy soil in many ways.In general, the most common contamination of soil occurs in the form of heavy metals, petroleum hydrocarbon compounds, and agricultural pesticides. Petroleum hydrocarbon contamination of soil causes alterations of its geotechnical properties.

Petroleum hydrocarbon contamination of soil causes alterations of its geotechnical properties. The degree of alteration depends on the soil type and the type and concentration of the contaminant [1]. Clay particles are chemically active and their behavior depends on their mineralogical composition [2]. Zulfahmi et al. [3] investigated the effect of hydrocarbon contamination on the geotechnical properties of artificially oil-contaminated soil. Thiyyakkandi and Annex [4] studied the influence of organic content on the engineering properties of Kuttanad clayey soil. The results of the study indicated that organic content significantly alters the engineering properties of this type of clay; an increase of organic content causes a decrease in both shear strength and compressibility. Zulfahmi et al. [5] studied the effects of oil contamination on granitic and met sedimentary soils by adding different percentages of hydrocarbon to the soil. The results showed a decrease in maximum dry density, optimum moisture content, and undrained shear strength (when increasing oil contents in the soil samples).

Kermani and Ebadi [6] studied the effects of crude oil on the geotechnical properties of soil samples obtained from land near the site of the Tehran oil refinery. The results of this study indicated an increase in the angle of internal friction, maximum dry density, compression index, and Atterberg's limits, as well as a decrease in optimum water content and cohesion (when increasing the oil content). Elisha [7] studied the effects of crude oil contamination on the geotechnical properties of soft clay soil. The results of this study showed that contamination causes a decrease in porosity and swelling pressure (when both sorption time and crude oil content is increased). The increase in the strength of the crude oil-contaminated soft clays may be a result of the agglomeration of its particles. Karkush et al. [8] studied the effects of four types of contaminants on the geotechnical properties of clayey soil samples. The contaminants were kerosene, ammonium hydroxide, lead nitrate, and copper sulphate; each was added in two percentages to contaminate soil samples synthetically. The contaminants caused an increase in Atterberg's limits, maximum dry unit weight, the initial void ratio, the compression index, the swelling index, and collapse potential. The contaminants also decreased specific gravity, optimum moisture content, the coefficient of vertical consolidation, and cohesion between soil particles.

Karkush and Resol [9] studied the geotechnical properties of sandy soil samples contaminated with different percentages of industrial wastewater. The results of their study showed an increase of the liquid limit and a decrease the particle size, specific gravity, and maximum dry density (when

increasing the percentage of contamination). Karkush and Abdul Kareem [10] studied the geotechnical properties of clayey soil contaminated with different percentages of industrial wastewater. The results of the study showed a decrease in the the percentage of finer, Atterberg's limits, the coefficient of consolidation, and shear strength parameters when increasing the concentration of contaminant in the soil samples. Akinwumi et al. [11] studied the effects of different concentrations of crude oil on the physical properties of soil. Crude oil in soil resulted in an increase in the Atterberg's limits and a decrease in the specific gravity, optimum moisture content, and maximum dry unit weight. In this research, the effects of industrial wastewater on the chemical, physical, and mechanical properties of clayey soil samples were investigated. Industrial wastewater is a by-product of the Thi-Qar oil refinery which spills directly onto the soil and causes its contamination. This by-product will henceforth be referred to as total petroleum hydrocarbons (TPH) to avoid the complexity of discussing the effects of the individual components of industrial wastewater on the geotechnical properties of soil.

2. STUDY AREA AND SOIL SAMPLING

The soil samples used in this research were obtained from the site of Thi-Qar oil refinery plant in Al-Nassyriah city, located in the south of Iraq with geo-referencing coordinates (N 305916.2, E 0461332.8). A part of this site is considered the disposal area for the by-products of the refinery. The groundwater table is located between 2 and 2.5 m above ground level. The soil samples were obtained from three locations in the study area; these locations represent the highly contaminated area (NA1), the slightly contaminated area (NA2) and the intact area (NA3). The samples can be classified according to USCS as silty clay to clayey silt, and the consistency of the soil is medium to stiff (for intact soil samples) and soft to very soft (for contaminated soil samples). The study area and location of the soil samples are shown in Fig. 1.

Fig. 1: Site of Thi-Qar oil refinery plant and soil samples locations.

Both disturbed and undisturbed soil samples were obtained from three locations designated (NA1, NA2, and NA3), from three depths at each location (0.0, 1.0, and 2.0 m), measured from the existing ground level. The soil samples were placed in airtight plastic bags and labelled, and then transported to the soil mechanics laboratory to study the details of their contamination (the physical, chemical, and mechanical properties). The description and designation of soil samples are given in Table 1.

Table 1: Description and designation of soil samples.

Spot	Depth, m	Zone	GPS Coordinates	Soil Description	Symbol
1	0.0	Highly contaminated soil	N 305922.7 E 0461324.9	Medium to stiff brown to gray clayey silt with salts	NA10*
	1.0			Medium brown clayey silt	NA11
	2.0			Soft to medium brown to grayish silty clay with red and black spots	NA12
2	0.0	Slightly contaminated soil	N 305916.2 E 0461332.8	Very soft black to grayish clayey silt with oil and roots	NA20
	1.0			Very soft brown to gray clayey silt with oil	NA21
	2.0			Soft grayish green sandy silty clay with lot of black pockets of oil residue	NA22
3	0.0	Intact soil	N 305930.2 E 0461353.6	Medium brown clayey silt with sand and salts	NA30
	1.0				NA31
	2.0				NA32

*The first number refers to the sample location (spot) and second number refers to the depth of soil sample.

3. EXPERIMENTAL WORK

A soil classification system emphasizes the importance of information about the quantitative composition of soil, which affects the geotechnical properties through chemical reactions between the particles forming the soil. Experimental work includes testing the chemical, physical, and mechanical properties of the intact and contaminated soil samples to measure the effects of soil contamination. The chemical properties of the samples play an important role in their chemical reactions, especially in the case of clayey contaminated soils. Chemical tests were conducted to determine the existence and quantity of various chemical compounds in the soil samples; for example SO_3 (ASTM D516), CEC (ASTM D7503), organic matter (OM) (ASTM D2974), Gypsum, Cl^{-1} (ASTM D512 A), pH (ASTM D4972), TSS (ASTM D5907), and TPH (UV-160A), using n-hexane as a blank. In this experiment, the industrial wastewater was measured in terms of total petroleum hydrocarbons (TPH). The physical properties of the samples were tested according to ASTM [12]. These tests include particle-size distribution (ASTM D422), field unit weight (ASTM D2937), moisture content (ASTM D2216), maximum dry density, optimum moisture content (ASTM D1557), specific gravity (ASTM D854), liquid and plastic limits (ASTM D4318), and the falling head permeability test (ASTM D2434). The moisture content of soil is normally calculated using Eq. (3.1), where pore fluid is water alone, but when a liquid contaminant is present and the pore fluid is no longer just water, this equation may not be used.

$$(3.1) \qquad \qquad \omega\ (\%) = \frac{Ww}{Ws} * 100$$

In this experiment, since the soil samples tested are both contaminated and intact, the water content of the intact soil samples was determined according to Eq. (3.1) and the contaminated soil samples' moisture content calculated according to Eq. (3.2) [13].

$$(3.2) \qquad \qquad \omega(\%) = (1 + mn)\frac{Wt}{Wd} - (1 + n)$$

where

ω = moisture content;

w_w = weight of water in soil;

w_s = weight of dry soil;

w_t = weight of wet contaminated soil;

w_d = weight of dry contaminated soil;

m = TPH content after drying;

n = TPH content before drying.

The TPH may evaporate at room temperature, where TPH evaporation depends on the physical and chemical properties of the crude oil, and the temperature, humidity, size, and composition of the soil particle. The evaporation of TPH increases with decreasing soil particle size, and decreases with an increase in the oil content under the same environmental conditions [13]. Also, it is further stated that heat transfer in clayey soils is slower than in sandy soils, so oil in clayey soils absorbs more heat, and oil evaporation is also higher as compared to sandy soil. The mechanical properties of soil samples were tested by conducting 1-D consolidation, unconfined compressive strength, and unconsolidated undrained triaxial tests. The consolidation parameters a laterally confined soil specimen undergoes when subjected to external stress are determined by conducting the 1-D consolidation test according to (ASTM D2435). The specimen is prepared by trimming an undisturbed soil sample, or by remolding a soil specimen prepared according to the field unit weight and moisture content (due to difficulty obtaining undisturbed soil samples from contaminated spots). Shear strength parameters c and φ were determined by conducting an unconfined compressive strength test (ASTM D2166) on undisturbed soil specimens with a rate of loading of 1.5 mm/minute, and an unconsolidated undrained triaxial test (ASTM D2850) on remolded contaminated soil samples at the rate of loading of 1.27 mm/min.

4. RESULTS AND DISCUSSIONS

4.1. CHEMICAL PROPERTIES OF SOIL

The results of the chemical tests and x-ray diffraction analysis are seen in Table 2. Contamination of soil samples was measured in terms of TPH, with the results showing an increase in TPH concentration in soil samples NA10 to NA12 in comparison with intact soil samples NA30 to NA32. The concentration of Cl^{-1}, OM, TSS, and pH increased with the increase of TPH content in soil samples, while SO_3, CEC, and Gypsum decreased with the increase of TPH content in soil samples. Also, the non-clay portion of soil sample particles increased with the increase of TPH content.

Table 2: Results of chemical tests of soil samples.

| Soil Sample | SO₃ % | CEC meq/l | OM % | Gypsum % | Cl⁻¹ mg/l | pH | TSS % | TPH ppm | Non-clay minerals | | Clay minerals % |
									CaCO₃ %	SiO₂ %	
NA10	0.07	20.88	0.90	1.0	8250	8.60	7.50	3624	45	42	13
NA11	0.06	20.31	0.92	1.0	1000	8.00	6.15	3559	46	44	10
NA12	0.06	21.30	0.98	1.0	800	8.05	6.09	3417	50	40	10
NA20	0.09	19.41	0.80	2.0	750	8.00	1.70	702.7	54	40	6
NA21	0.09	20.55	0.83	4.0	350	7.95	1.72	1168	50	44	6
NA22	0.05	21.58	0.85	5.0	750	8.07	2.48	1235	47	45	8
NA30	0.12	18.63	0.80	2.0	7000	8.00	1.37	0.0	47	37	16
NA31	0.09	19.33	0.82	2.0	3750	8.07	2.87	0.0	47	40	13
NA32	0.10	19.57	0.82	2.0	4000	7.48	2.67	0.0	54	34	12

4.2. PHYSICAL PROPERTIES OF SOIL

The THP has variable effects on the physical properties of soil samples. The effects of the contamination on the particle-size distribution curve of the samples are shown in Fig. 2. Also, the division of the samples into percentages of sand, silt, and clay is shown in Table 3. The particles of the contaminated soil samples are coarser than those of the intact soil samples, a difference caused by coating the soil particles in the salts of the contaminant [8, 14, 15]. This change depends on the solubility of existing salts in water. Also, the decrease of the percentage of finer may be attributed to the fact that oil affects the physicochemical nature of the clay fraction of the soil [16].
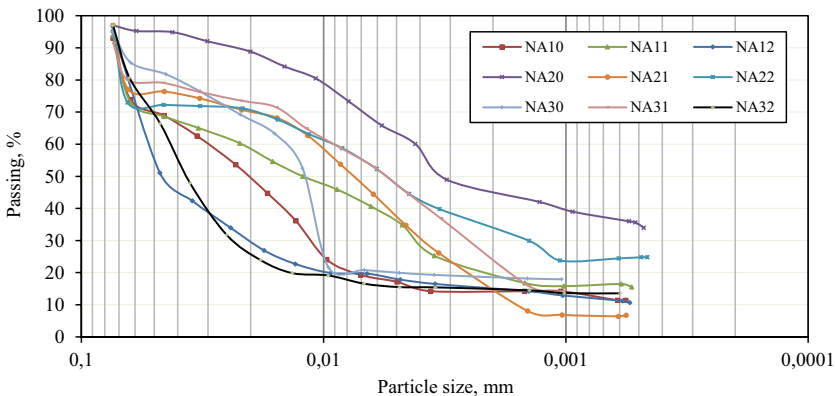

Fig. 2: Particle-size distribution curves of soil samples.

Table 3: Index properties of soil samples.

Soil Sample	Gs	Sand %	Silt %	Clay %	γ_t kN/m³	ω_n %	LL %	PL %	ω_{opt} %	$\rho_{d,max}$ g/cm³	k×10⁻⁷ cm/sec
NA10	2.58	7	79	14	18.74	29	56	35	11	1.913	6.6
NA11	2.60	6	75	19	17.76	30	53	33	14	1.800	3.0
NA12	2.62	5	80	15	17.66	32	50	31	15	1.854	1.2
NA20	2.71	5	51	44	18.25	26	46	28	12	1.913	4.5
NA21	2.72	6	79	15	18.15	28	47	28	15	1.854	2.5
NA22	2.62	4	62	34	18.25	31	49	30	14	1.830	1.4
NA30	2.65	5	77	18	17.66	23	44	30	16	1.825	3.2
NA31	2.71	8	68	24	17.56	24	46	28	13	1.863	2.2
NA23	2.71	5	77	18	18.93	27	43	26	13	1.903	1.8

The results of specific gravity tests, total density and natural moisture content, Atterberg's limits, and compaction tests of soil samples are shown in Table 3. Increasing the moisture content of the contaminated soil samples leads to a decrease in the specific gravity and total density of the samples. This is due to the low density of the contaminant present in the soil samples [8, 11]. The TPH has a viscosity higher than that of water; this fact combined with surface tension promotes the retention of TPH between soil particles. The plastic limit increases with the presence of TPH in soil causes a change in the pore fluid chemistry. Increasing the index properties is based on the fact that the presence of hydrocarbon, which is a non-polarized liquid, acts like adsorbed water (i.e. with electrostatic effect and possible chemical interaction) and causes a reduction of the thickness of the double diffusive layer around the clay minerals. Water is a binding agent between clay minerals and its orientation around the clay mineral provides plasticity characteristics, though this will not happen if these minerals are surrounded by hydrocarbon. Other authors have also reported these results, e.g. [6, 7, 8, 11]. On the contrary, several studies showed a decrease in the liquid and plastic limits of the contaminated soil with petroleum products [3, 4, 6, 13, 17]. The results of compaction tests are shown in Fig. 3 and Table 3.
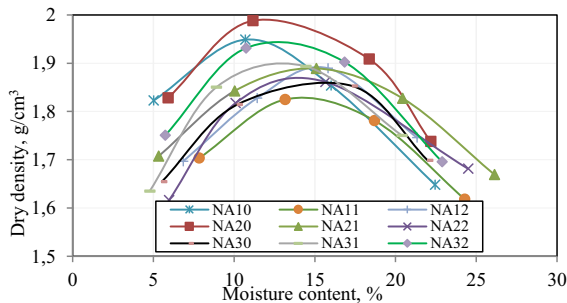

Fig. 3: Compaction curves of soil samples.

The shape of the compaction curve changes with the increase of the amount of contaminant in the samples. The compaction curves shows a decrease in optimum moisture content and an increase in maximum dry density with the increase of the TPH concentration in the samples. A decrease in optimum moisture content (with an increase in TPH concentration) reflects the lubricating effects of TPH, which facilitate the compaction process and reduce the amount of water needed to reach maximum density. Also, the partial occupation of TPH of the inter-particle spaces reduces the amount of water that the void space was supposed to accommodate. Hence, TPH contamination will increase the amount of time required for clay soil to compact, or the soil will instead require more compaction effort to achieve its desired compaction. The results of the falling head tests (FHTs) are given in Table 3. Hydrocarbon has very low solubility in water, and does not change the properties of distilled water used in the permeability test, so standard procedures of the falling head permeability test were used to measure the permeability of the contaminated soil. The result was calculated in the same way for the intact soil. The decrease in the hydraulic conductivity value of the contaminated soil is attributed to clogging of some inter-particle space with TPH, and because of this fact, pore fluid is no longer water alone, but TPH and water. There is usually a boundary layer of soil and water mixture present. TPH in soil will trap some of the water, consequently lowering the coefficient of permeability of contaminated soil.

4.3. MECHANICAL PROPERTIES OF SOIL

The results obtained from the 1-D consolidation tests include; the initial void ratio (e_o), compression index (c_c), swelling index (c_s), preconsolidation pressure (Pc), coefficient of consolidation (c_v), and confined modulus of elasticity (D) are given in Table 4.

Table 4: Consolidation parameters of soil samples.

Soil Sample	e_o	c_c	c_s	Pc kPa	c_v cm²/sec	D MPa
NA10	0.61	0.183	0.066	87	0.0019	8.73
NA11	0.78	0.155	0.035	80	0.0015	16.3
NA12	0.81	0.140	0.026	80	0.0012	13.3
NA20	0.73	0.124	0.034	100	0.0006	14.4
NA21	0.60	0.115	0.046	120	0.00045	18.5
NA22	0.72	0.144	0.046	110	0.0006	15.7
NA30	0.82	0.160	0.071	120	0.0015	14.2
NA31	0.84	0.140	0.020	100	0.0020	27.0
NA23	0.78	0.160	0.020	90	0.0022	14.1

The results of the consolidation tests indicated a noticeable decrease in the void ratio and swelling index with an increase in the concentration of TPH in the samples. This decrease may be a result of an increase of the percentage of fines in the contaminated soil samples [8], but the compression index increases with an increase the concentration of TPH in soil samples. This fact may be attributed to the sliding around of soil particles resulting from oil in the soil voids acting as a lubricant agent. The lubricant role of the oil also accelerates the rate of settlement by increasing the value of the coefficient of consolidation, which may be attributed to the change in the structure that may take place due to the interaction between clay minerals and TPH (which decreases the repulsive force between clay particles). The shear strength parameters of the soil samples were determined by conducting an unconfined compressive strength test and an unconsolidated undrained triaxial test. The results of the unconfined compressive strength tests (UCT) conducted on six undisturbed soil samples (NA20, NA21, NA22, NA30, NA31, and NA32) are given in Fig. 4 and Table 5. Soil samples NA10, NA11, and NA12 were very soft, so it was impossible to extrude undisturbed soil samples from the Shelby tubes used in the unconfined compressive strength test as shown in Fig. 5.
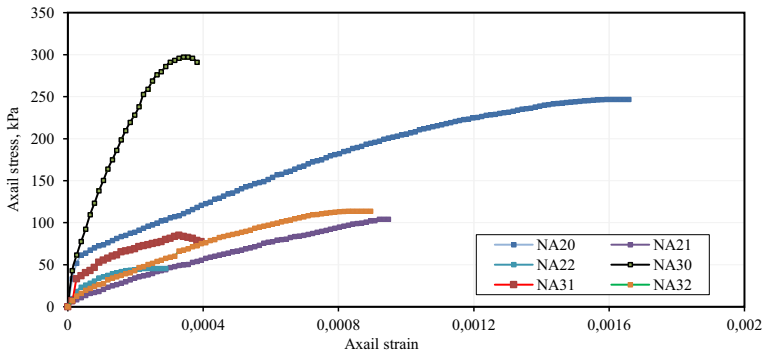

Fig. 4: Stress-strain curves of soil samples tested by UCT.

Table 5: Results of shear strength tests of soil samples.

Soil sample	UCT		UUT	
	q_u, kN/m²	c, kN/m²	c_u, kN/m²	φ,degree
NA10	-	-	15	10
NA11	-	-	23	12
NA12	-	-	34	10
NA20	246	123	-	-
NA21	106	53	-	-
NA22	46	23	-	-
NA30	298	149	-	-
NA31	86	43	-	-
NA32	114	57	-	-

Fig. 5: Soil sample NA10 after extraction from Shelby tube.

Per Table 5 it can be noticed that there is an inverse correlation between qu and TPH content. The particle size distribution affects the homogeneity of the soil samples, and hence the degree of cohesion between the soil particles [5]. The initial increase in qu for sample NA20 could be attributed to the rearrangement of pseudo-sized particles (formed from the bonded fines fraction), which achieved increased bonding between the particles thereby resulting in a greater load resistance. In the UCT tests, it is assumed that the frictional angle (φ) is equal to zero, which means that the soil is a purely cohesive material which has no friction. This assumption is not correct, where the apparent undrained shear strength results principally from the frictional resistance within the soil and the frictional angle are not zero, due to the fact that the specimens are partially saturated. The triaxial test result showed a decrease in the shear strength parameters (φ and c) of the soil samples when the TPH concentration in the soil increased (as shown in Table 5), where similar behavior was observed by others [7, 13, 18]. The TPH has a higher viscosity than water, which causes a decrease in the shear strength parameters of soil samples, where the TPH coats the soil particles and leaves a blanket surrounding the soil particles, and by increasing the TPH contamination the chances of inter-particle slippage will increase resulting in the decrease in the shear strength of the soil. The formation of large sized particles due to the TPH contamination and decreasing the specific surface area also resulted in less cohesion. Also, the lubrication effect provided by the TPH leads to failure within a relatively short period. The failure plane of the contaminated soil sample NA10 is shown in Fig. 6.
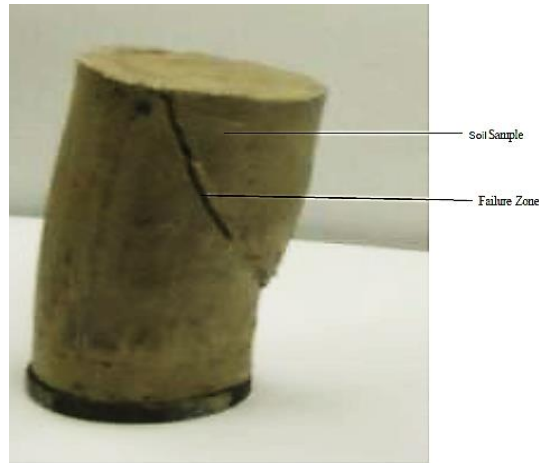
Fig. 6: Failure plane of remolded soil sample NA10 tested by UUT.

5. CONCLUSIONS

TPH soil contamination has different effects on the physical, chemical, and mechanical properties of soil samples. The effects depend mainly on the concentration of contaminant in the soil as well as the type of soil, where the geotechnical properties of the contaminated soil samples were affected significantly with the increase of the concentration of the contaminant. In the study area, the concentration of TPH is variable with location and depth, and therefore several soil samples had undergone testing. The results showed that TPH affects the size of particles; the contaminated soil particles become coarser than the particles of intact soil. Also, TPH contamination causes a reduction in the hydraulic conductivity, specific gravity, liquid and plastic limits, natural and optimum moisture contents, and a slight decrease in field unit weight and maximum dry density of soil samples. The compression index and coefficient of consolidation of the contaminated soil samples increased with the increase of TPH concentration, while the void ratio, swelling index, preconsolidation pressure, and constrained modulus of elasticity of contaminated soil decreased with the increase of the TPH content. The cohesion between soil particles decreased significantly with the increase of TPH concentration in the soil samples. Finally, the angle of internal friction decreased with the increase of the TPH content in the samples.

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OCENA GEOTECHNICZNA GLEBY GLINIASTEJ ZANIECZYSZCZONEJ ŚCIEKAMI

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*Słowa kluczowe***:** zanieczyszczenie, ścieki przemysłowe, węglowodór ropopochodny, gleba gliniasta oraz właściwości geotechniczne.

STRESZCZENIE:

Niniejsza praca została poświęcona badaniu wpływów zanieczyszczeń ściekami na właściwości geotechniczne próbek gleby gliniastej. Czynnikiem zanieczyszczającym są ścieki przemysłowe, uwalniane z rafinerii Thi-Qar jako produkty uboczne produkcji i wyrzucane bezpośrednio na glebę, powodując jej zanieczyszczenie. Ten produkt uboczny będzie dalej określany jako węglowodory ropopochodne (THP), w celu uniknięcia złożoności omawianych wpływów poszczególnych składników ścieków przemysłowych na właściwości geotechniczne gleby. Próbki gleby zostały pobrane z rafinerii Thi-Qar w mieście Al.-Nassyriah, położonym na południu Iraku, o współrzędnych geograficznych (N 305916.2, E 0461332.8). Zanieczyszczone i nierozłożone próbki gleby zostały pobrane w trzech miejscach na badanym obszarze oraz na trzech głębokościach w każdym z tych miejsc. W celu zbadania wpływu różnych stężeń węglowodorów ropopochodnych na właściwości geotechniczne gleby, przeprowadzono badanie trzech lokalizacji o bardzo zanieczyszczonym obszarze (NA1), nieznacznie zanieczyszczonym obszarze (NA2) oraz nienaruszonym obszarze (NA3). Próbki gleby można sklasyfikować zgodnie z USCS, jako glinę mulistą lub muł gliniasty, a konsystencja gleby jest średnia lub sztywna (w przypadku próbek nienaruszonej gleby) oraz miękka lub bardzo miękka (w przypadku próbek zanieczyszczonej gleby). Ponadto, w celu zbadania odchylenia takiego zanieczyszczenia pod kątem głębokości, pobrano trzy próbki gleby z każdego obszaru, a ich głębokości (0.0, 1.0 i 2.0 m) zostały zmierzone od istniejącego poziomu gruntu. Próbki gleby zostały umieszczone w hermetycznych plastikowych torebkach i oznakowane, a następnie przewiezione do laboratorium mechaniki gleby w celu zbadania wpływu zanieczyszczenia na ich właściwości geotechniczne. Obszar badania i lokalizacje próbek gleby zostały przedstawione na Rys. 1. Właściwości geotechniczne próbek zanieczyszczonej gleby zostały porównane z właściwościami geotechnicznymi próbek nienaruszonej gleby, celem przeprowadzenia pomiarów wpływu takiego czynnika zanieczyszczającego na właściwości geotechniczne. Zbadane właściwości geotechniczne próbek gleby obejmują właściwości chemiczne, właściwości fizyczne i właściwości mechaniczne. Właściwości chemiczne obejmują zawartość siarczanów, zawartość chlorków, zdolność wymiany kationów, gips, pH i TSS. Przeprowadzono również badania dyfrakcji rentgenowskiej, w celu oddzielenia minerałów ilastych i minerałów nieilastych. Właściwości fizyczne próbek gleby obejmują rozkład wielkości cząsteczek, ciężar właściwy, przepuszczalność, zagęszczenie i granice Atterberga. Właściwości mechaniczne próbek obejmują jednowymiarową próbę konsolidacji, wytrzymałość na ściskanie w jednej osi oraz nieskonsolidowany nierozcieńczony test triaksalny. Badania mechaniczne zostały przeprowadzone na próbkach gleby nienaruszonej, lecz próbki nalewanej gleby zostały wykorzystane w celu pomiaru tych właściwości próbek zanieczyszczonej gleby ze względu na trudności w uzyskaniu niezakłóconych próbek gleby w zanieczyszczonych strefach.

Zanieczyszczenie gleby THP ma różne skutki dla fizycznych, chemicznych i mechanicznych właściwości próbek gleby. Efekty zależą głównie od stężenia czynnika zanieczyszczającego w glebie i od rodzaju gleby, w której właściwości

geotechniczne próbek zanieczyszczonej gleby miały znaczący wpływ wraz ze zwiększeniem stężenia czynnika zanieczyszczającego. Na badanym obszarze, stężenie THP jest zmienne wraz z lokalizacją i głębokością, a zatem badaniu poddano kilka próbek gleby. Wyniki badań chemicznych i dyfrakcji rentgenowskiej wykazały, że stężenie CI-1, OM, TSS i pH wzrosło wraz ze wzrostem zawartości THP w próbkach gleby, podczas gdy stężenie SO3, CEC i gipsu zmalało wraz ze wzrostem zawartości THP w próbkach gleby. Również ilość niegliniastych cząsteczek próbki gleby wzrosła wraz ze wzrostem zawartości THP.

THP ma zmienny wpływ na właściwości fizyczne próbek gleby. Cząsteczki próbek zanieczyszczonej gleby są bardziej szorstkie niż cząsteczki próbek nienaruszonej gleby, co jest spowodowane powlekaniem cząsteczek gleby solami czynnika zanieczyszczającego [8, 14, 15]. Również spadek zawartości może wynikać z faktu, że ropa wpływa na fizykochemiczny charakter frakcji gliny w glebie [16]. Wzrost wilgotności próbek zanieczyszczonej gleby prowadzi do zmniejszenia ciężaru właściwego i całkowitej gęstości próbek. Jest to spowodowane niską gęstością czynnika zanieczyszczającego obecnego w próbkach gleby [8, 11]. TPH ma lepkość większą niż woda; fakt ten w połączeniu z napięciem powierzchniowym wspiera zatrzymywanie TPH między cząsteczkami gleby. Woda jest czynnikiem wiążącym dla minerałów glebowych, a jej skupienie wokół minerału glinowego zapewnia plastyczność, mimo, że nie dojdzie do tego, jeśli minerały te są otoczone węglowodorem. Inni autorzy również donosili o tych wynikach, np. [6, 7, 8, 11]. Kilka badań z kolei wykazało zmniejszenie granic cieczy i plastiku w zanieczyszczonej glebie, spowodowane produktami ropopochodnymi [3, 4, 6, 13, 17]. Kształt krzywej zagęszczenia zmienia się wraz ze wzrostem ilości czynników zanieczyszczających w próbkach. Krzywe zagęszczenia wykazują spadek optymalnej zawartości wilgoci oraz wzrost maksymalnej suchej gęstości wraz ze wzrostem stężenia TPH w próbkach. Spadek zawartości optymalnej wilgoci stanowi odzwierciedlenie efektów smarowania TPH, co ułatwia proces zagęszczania i zmniejsza zawartość wody potrzebnej do osiągnięcia maksymalnej gęstości. Węglowodór posiada bardzo niską rozpuszczalność w wodzie i nie zmienia właściwości wody destylowanej wykorzystywanej w teście przepuszczalności, dlatego też do pomiaru przepuszczalności zanieczyszczonej gleby wykorzystano standardowe procedury stosowane podczas pomiaru przepuszczalności.

Wyniki testów konsolidacyjnych wykazały zauważalny spadek współczynnika pustki i indeksu pęcznienia, wraz ze wzrostem stężenia THP w próbkach. W rezultacie wskaźnik sprężania wzrasta. Fakt ten można przypisać do przesuwania się cząsteczek gleby w wyniku wycieku ropy do ubytków gleby, pełniących rolę środka poślizgowego. Początkowy wzrost qu dla próbki NA20 można przypisać przegrupowaniu cząsteczek pseudoprocesowych, które zwiększają wiązanie między cząsteczkami, a tym samym zwiększają oporność na obciążenie. THP posiada lepszą lepkość niż woda, co powoduje obniżenie parametrów wytrzymałości na ścinanie próbek gleby, gdzie THP pokrywa cząsteczki gleby i pozostawia warstwę wokół cząsteczek gleby. Ponadto, THP powoduje zwiększenie szans na poślizg między cząsteczkami, co wpływa na zmniejszenie wytrzymał.