Innovative Testing Investigations on the Influence of Particle Morphology and Oil Contamination on the Geotechnical Properties of Sand

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Abstract: Shear strength and the permeability in a soil mass are two prime parameters that characterize the geotechnical behaviour of the soil. These parameters (c', Ø', k) help assess the bearing capacity and settlement characteristics of foundations, stability of slopes, lateral earth pressure on retaining walls and fluid infiltration. Geo environmental contamination resulting from chemicals and oil spills are becoming very common news and these alter the inter-particle behaviour of the soil, making it to lose its strength and deformability considerably and also become less permeable. This study focuses on the effects of contamination of sands with different grading size and particle shapes on its shear strength and its coefficient of permeability. Well graded and gap graded sand samples were used in the research. A simple statistical approach was used to define not only the particle size but also its shape distribution. Comparison of the shear strength of these sand samples were tested in an automated motorised direct shear apparatus under both dry and fully saturated conditions (with water and also with oil). The coefficient of permeability of the two sands under clean and contaminated conditions was obtained using a modified falling head permeability test. It was observed that the well graded sand which was submerged in oil apparently had the lowest peak shear strength values. However, a higher order of cohesion was apparent when the soil was contaminated with oil. Permeability was also an issue, as by virtue of its viscosity, the oil hindered the water seepage through the sand samples when compared with clean sands. However, it appeared that with more viscous liquid contaminants, the rate of water infiltration was notably higher. Permeability was also affected by the particle grading and shape distribution. The significant loss in strength and the tortuosity of water flow in the soils can cause major problems such as unwarranted floods and potential failures in civil engineering works. Therefore, the extent of the problem that is caused by oil contamination needs to be truly understood to minimize unwarranted construction risk.

Keywords: Contaminated soil, shear strength, permeability coefficient, particle size and shape distribution.

1. Introduction

Environmental pollution being a crucial issue in today's current news is undoubtedly increasing year by year and causing lasting damage to the earth. In the case of Geo environmental pollution, it is the problem that is related to contamination of the soil from various chemicals, oil spills and etc which resulted in the loss of strength and its permeability to cause poor drainage and unexpected deformations. Oil spills are the main contaminant products which have affected soil related problems in most parts of the world.

The random discharge of petrol oils and grease into farmlands, open vacant plots and water drains is becoming an acute environmental problem. In 1991, almost 240-260 million gallons of crude oil has flowed into the Persian Gulf and around 613 to 798 oil wells were set on fire after the Gulf War in Kuwait, and roughly 20-25 million barrels of ignited crude oil were extinguished using 12 billion gallons of seawater collected in artificial ponds. It formed over 300 large spots of accumulated spill oil in the slightly depressed area of the Kuwait desert as seen in Fig. 1 [1].

As a result, 114 km^2 of the desert was contaminated with oil, one of the biggest oil contaminations in history. On a daily basis, contaminants such as lubricant and hydraulic oil being discharge from vehicles, machineries, generators and storage tanks is also one of the main causes of geo environmental pollutions. As oil spills accumulate and infiltrate into the ground, the soluble elements are dissolved and forms a residue on the soil [2]. The process

Corresponding author:alvinjlms@gmail.com of forming the residual soils includes physical and chemical weathering, incorporation of the humus layer of soil [3]. The contaminated layer of the soil can directly change the soil's physical and mechanical properties, including the shear strength and hydraulic conductivity of the soil. The consequences of this contamination on the hydrology cycle can be evaluated by knowing the changes of hydraulic conductivity (k).

Fig. 1: Oil slicks in the Persian Gulf during the Gulf War oil spill. (Khamehchiyan et. al., 2007)

By taking into account the shape and grading characteristics of soil particles, the inter-particle reaction will significantly be affected by the oil molecules which surround them. In the case of hydraulic conductivity, it is not an exclusive property of the soil alone. It has been recognized that hydraulic conductivity is related to the grain-size distribution of granular porous media as expressed by Freeze and Cherry [4]; Kozeny, 1927; Carmen, 1937 (cited in Das, [5]). The most commonly used correlation is Hazen's relationship for clean filter sands in loose condition:

$$k = Cd_{10}^{2} \qquad (1)$$

where d_{10} is the effective size and C is the coefficient of 0.01 to 0.015. Therefore, it depends on the properties of the soil particles such as their sizes and shapes as well as the permeating fluid. Hydraulic conductivity may change as water permeates and flows in a soil due to various chemical, physical and biological processes. The shear strength of the soil would also be affected as friction between the particles is influenced by the fluids surrounding them.0

This project focuses on the significance of the shape of particles on the hydraulic conductivity and the shear strength of the contaminated sands. It is necessary to know how the hydraulic conductivity changes in contaminated soil to evaluate the consequences on how the contaminant can modify the hydrological cycle of these regions. It is generally believed that hydraulic conductivity is an important aquifer property in hydrogeology as it measures the ability to transmit water. It is also important to measure the extent to which oil contaminated sand that affects shearing strength of the soil. In this project, a series of laboratory experiments were carried out and the results were analyzed to determine the influence of particle shape on hydraulic conductivity and the shearing strength parameters of sand that was contaminated with oil.

2. Materials and Methods Used for Testing

Two sets of materials were used in this study. These are sands classified as well graded (SW) and gap graded (SPg). The sand obtained from Kahang, Johor is generally classified as well graded sands (SW). However careful separation and subsequent mixing of the sand particles using sieves enabled gap graded sands (SPg) to be obtained. The particle size distribution of the samples is shown in Fig. 2, and it is seen that the differences in their grading characteristics can be defined by the uniformity coefficient (C_u). Table 1 shows the index properties of the sand samples used.

The maximum and minimum void ratios (e_{max} and e_{min}) of sand were also determined to obtain the relative density, D_r of the test sand samples. All soil classification tests followed the procedures given in BS 1377-2:1990 [6]. The quantification of particle shapes is based on two important shape parameters; Sphericity (S) and Roundness (R) which are explained in Fig. 3, adopting the work of Krumbein and Sloss [7], and Cho et al. [8]. Comparison of the particle shapes between both the samples were made using a simple digital microscope shown in Fig. 4 to quantify the shapes. Scanning electron microscope was not used as the it is rather tedious compared to the digital microscope as the latter provided adequate image quality for the analysis.

The Sphericity is defined as the diameter of the largest inscribed sphere relative to the diameter of the smallest circumscribed sphere. Roundness however is quantified as the average radius of curvature of features relative to the radius of the maximum sphere that can be inscribed in the particle. A total of 150 particles from each sand sample was analysed to obtain its shape parameters.

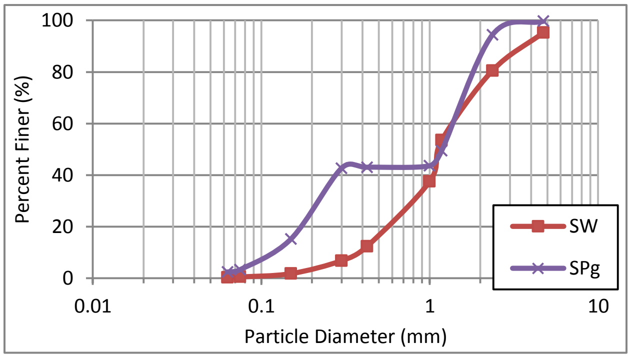

Fig. 2: Particle size distribution of the tested materia

Table 1: Properties of the tested samples

Type of Sand	D_{60}	D_{10}	C_u	S_G	e_{max}	e_{min}	Average S	Average R
SW	1.36	0.38	3.58	2.64	0.914	0.398	0.605	0.18
SPg	1.37	0.12	11.42	2.64	0.776	0.395	0.62	0.21

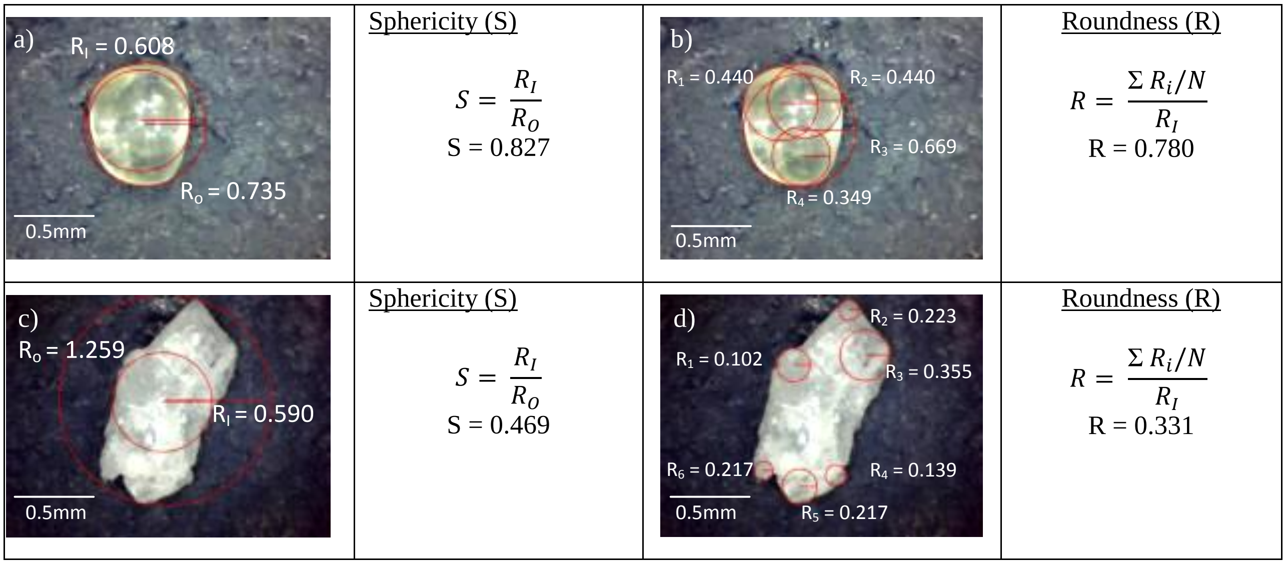

Fig. 3: Analysis of the quantification of the extreme shape particle of (a and c) sphericity and (b and d) roundness

Fig. 4: Digital microscope used for particle shape quantification

A constant head permeability test as shown in Fig. 5 was used to determine the permeability of the granular soils. It involves a flow of water under constant pressure difference through a specially design container with dimensions of 5cm x 5cm x 5cm as seen in Fig. 6. The testing apparatus is equipped with an adjustable constant head reservoir and an outlet reservoir which allows to maintain a constant head during the test. The amount of water flowing through the sample cube is then measured for given time intervals.

The hydraulic conductivity can be calculated as the values of the height of the soil sample column L, the sample cross section A, and the constant pressure difference Δh, the volume of passing water Q, and the time interval ΔT is known. The study on the effect of contaminated soil on permeability was done by first soaking the samples separately in two different kinds of oil namely palm oil and engine oil for a few hours. Then the sample was placed in the permeability container. The concept of the set-up of the test follows the direct instructions as given in Head [9].

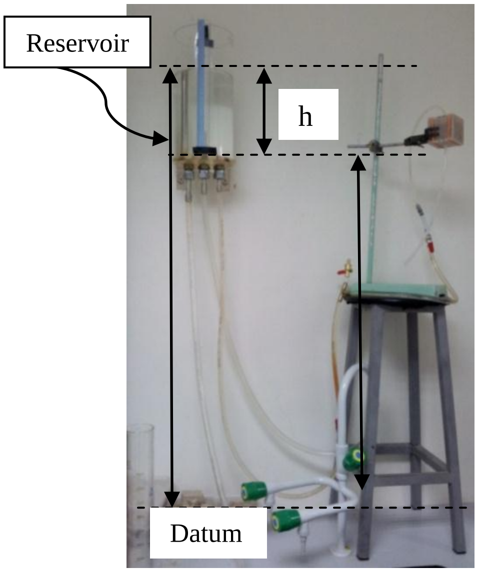

Fig. 5: Apparatus of constant head test

A fully automated motorised direct shear apparatus was then used to determine the shear strength of the soil with testing method in accordance with BS 1377:1990: Part 7[6]. The direct shear test was done with normal stresses of 25, 50 and 100 kPa under dry conditions and also fully saturated with water and with engine oil as shown in Fig 7.

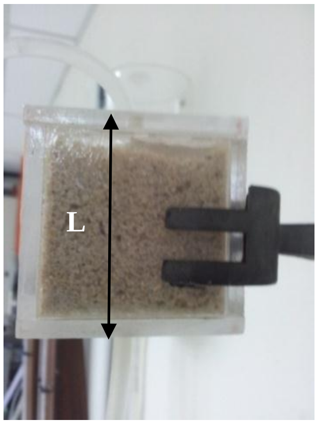

Fig. 6: Specially designed container

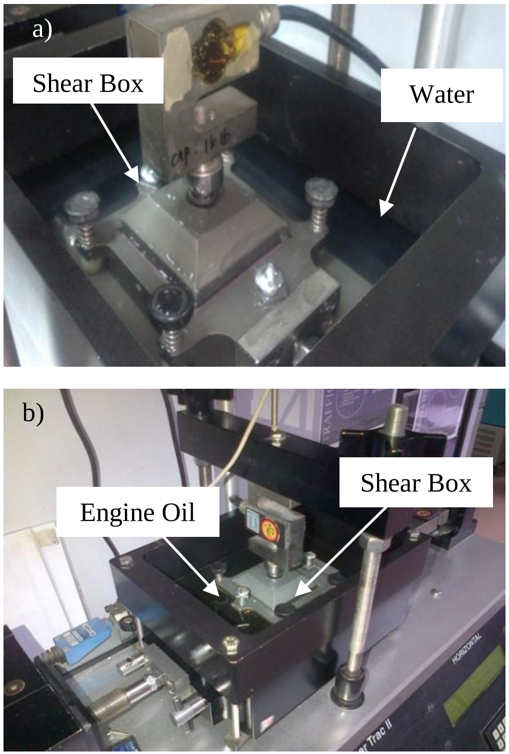

Fig. 7: The direct shear apparatus where the sample is being saturated with a) water and b) engine oil

Fully saturated conditions were achieved by pouring either water or the contaminated fluid directly into the shear box carriage before a test is commenced. As the sample is being sheared under its respective conditions, the shear strength parameter of cohesion and angle of friction was determined. All the samples were prepared under dense condition with relative density of approximately (D_r) 0.85 and above.

3. Results and Analysis

A constant head test was used to determine the permeability of the samples of different grading and particle shapes tested under clean and contaminated conditions. The results of the tests are summarised in Table 2. Figs. 7 and 8 show the difference in the hydraulic conductivity (k) of dense and loose samples under clean and contaminated conditions.

It was found that the contaminated samples that were soaked in palm oil showed lower permeability characteristics as compared to clean sands. However, samples that were soaked in engine oil were more permeable than the sand samples that were soaked in palm oil and also that of clean sands. As a result, engine oil tends to increase the permeability of the soil. This is due to the difference in viscosity between the two oils, where the viscosity of palm oil at 20°C is 69 cP which is lower than that of the engine oil which has a viscosity of 125 cP.

It can be seen that for loose sand samples that were pre-soaked with engine oil, the increase in the hydraulic conductivity (k) is not as great as that of the dense samples. Engine oil tends to permit water to flow readily through the sand samples even in its dense conditions. It was also observed that the gap graded sands have a better permeability characteristics than the well graded sand due to the finer sized particles that fill the void between the larger particles which prohibit free drainage of the liquid molecules.

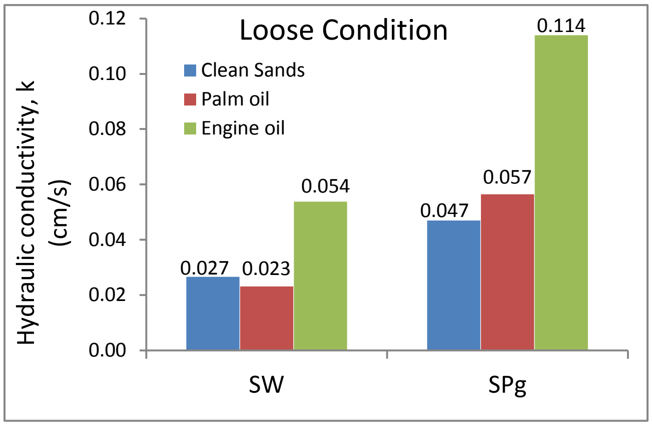

Fig. 8: Comparison of k of the loose sand samples under different conditions

Table 2: Summary of the results from the constant head test

Condition		L (cm)	Q/t (cm^3/s)	h (cm)	h/L	k (cm/s)
Clean Sands	**SW**					
	loose	5	0.917	6.9	1.38	0.0266
	dense	5	0.092	14.4	2.88	0.0013
	SPg					
	loose	5	1.458	6.2	1.24	0.047
	dense	5	1.000	13.9	2.78	0.014
Contaminated with Palm Oil	**SW**					
	loose	5	0.833	7.2	1.44	0.0213
	dense	5	0.057	12.8	2.56	0.00089
	SPg					
	loose	5	1.750	6.2	1.24	0.0565
	dense	5	0.267	11.7	2.34	0.0046
Contaminated with Engine Oil	**SW**					
	loose	5	3.417	12.7	2.54	0.0538
	dense	5	3.167	7.7	1.54	0.0823
	SPg					
	loose	5	5.083	8.9	1.78	0.114
	dense	5	2.667	14.2	2.84	0.0376

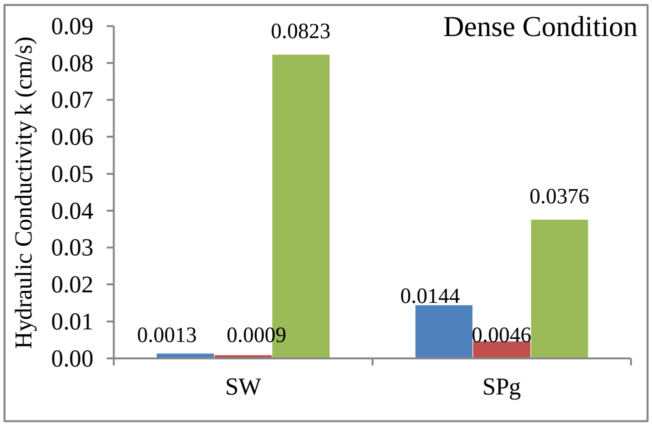

Fig. 9: Comparison of k of the dense sand samples under different conditions

The direct shear test was performed on each of the samples under several conditions, dry and saturated with water and also with engine oil. As the soil sample is being sheared at its respective normal stress, the critical stress is being recorded in this study as it is an important parameter in the design and interpretation of shear results. According to Hamidi et. al. [10], the critical shear strength is the shear strength of a soil mass that continuously deforms at constant volume, constant shear stress and at a constant rate of shear strain.

In this state, the relative density does not have any effect on the outcome of the critical state angle of friction and it is depend exclusively on the initial normal stress on the sample. It is evident from Figs. 10 and 11, where the critical shear stress and the normal stress is plotted to obtain the critical friction angle and its cohesion value from the failure envelope. It is also noted that a small amount of cohesion exists even for the dry sands, which however in its nature do not exhibit cohesion at all. This can be explained by Bolton [11],[12] that dilatancy plays a vital role in the characteristics of the failure envelope which would be the main reason for the existence of cohesion. The data obtained from the graphs are then summarised and presented in Tables 3 and 4.

The data show that the friction angle decreases as liquid is present in the soil medium. In this case, Fig. 12 presents that the contaminated sand for both the SW and SPg sand soaked with engine oil showed the lowest friction angle values of 27.4° and 22.2° respectively as compared to the sand samples that were saturated with water which has friction angle values of 31.6° and 31.3° degrees for SW and SPg sand respectively and values of 39 and 35.68 for dry sands. It was also observed that SW sand showed slightly higher friction angle values than SPg samples. The decrease in friction angle was at least 8° degrees from the dry sands that which were contaminated with oil.

The build up of cohesion is also very apparent for the sand samples that were soaked with engine oil. Fig. 13 shows the cohesion value for SW sand increased from 2.78 (dry state), 5.02 kPa (saturated in water) and increased further to 22.26 kPa when saturated in engine oil. Observations with the SPg sand were similar with cohesion increasing from 1.18 kPa (dry condition), 3.64 kPa when saturated with water and 19.21 after soaking it in engine oil.

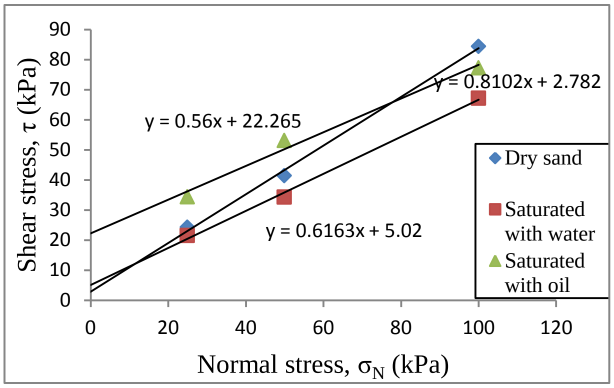

Fig. 10: The failure envelope of the critical shear stress for the SW sand

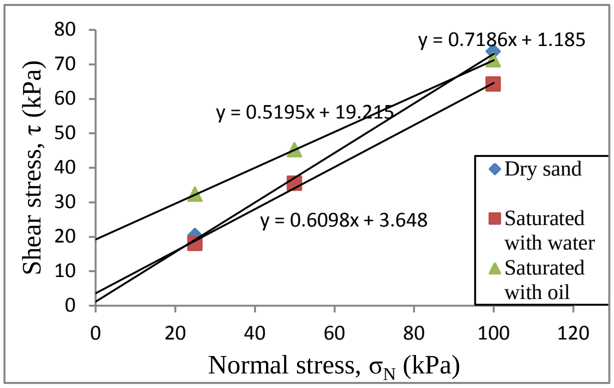

Fig. 11: The failure envelope of the critical shear stress for the SPg sand

Table 3: Summary of the friction angle and cohesion for SW sand under different conditions

Condition	Normal Stress (kPa)	Critical shear stress (kPa)	Friction angle Ø (degrees)	Cohesion c (kPa)
Dry	25	24.287	39	2.782
	50	41.42		
	100	84.43		
Saturated with water	25	21.46	31.63	5.02
	50	34.29		
	100	67.17		
Saturated with oil	25	34.37	29.25	22.26
	50	53.11		
	100	77.32		

Table 4: Summary of the friction angle and cohesion for SPg sand under different conditions

Condition	Normal Stress (kPa)	Critical shear stress (kPa)	Friction angle (degrees)	Cohesion (kPa)
Dry	25	20.32	35.68	1.185
	50	35.36		
	100	73.63		
Saturated with water	25	18.02	31.34	3.648
	50	35.45		
	100	64.194		
Saturated with oil	25	35.25	27.43	19.21
	50	75.12		
	100	111.19		

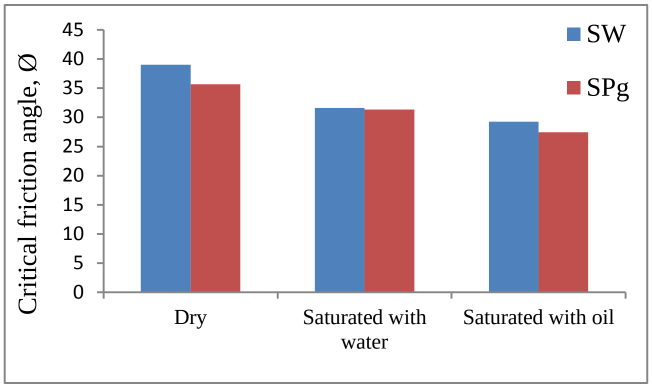

Fig. 12: The change in the critical friction of the samples under different testing conditions

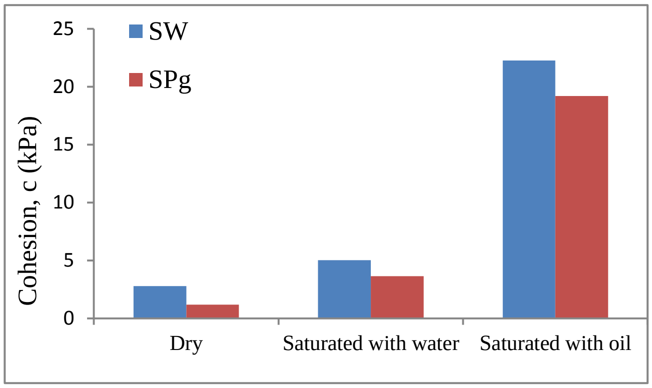

Fig. 13: The change in the cohesion values of the samples under different testing conditions

4. Conclusions and Findings

The study used sand samples with two different morphological characteristics with two distinct grading classifications and slightly different shape parameters. The well graded sand (SW) is distinguished to have a wide distribution of particle size as compared to the gap graded sand (SPg) where there is an excess or deficiency of certain particle sizes with at least one particle size missing. The shape parameter of the samples shows that SPg have slightly higher sphericity and roundness values than the SW samples. This study showed that a difference in particle morphology has a favourable effect on the permeability and strength characteristics.

It is well established in the Kozeny-Carmen equation expressed in eq. 2 that the hydraulic conductivity (k) is dependent on the shape factor (C), specific surface area per unit volume of particles (S_s), tortuosity of flow channels (T), unit weight of water (γ_w), the viscosity of permeant (η) and the void ratio (e). The equation clearly signifies that the shapes of the sand particles and the void ratio are one of the main parameters that affects the hydraulic conductivity (k). The equation does take the contaminants in the soil into account for the determination of (k).

$$k = \frac{1}{C_s\, S^2\, T^2}\,\frac{\gamma_w}{\eta}\,\frac{e^3}{1+e} \qquad (2)$$

Accordingly, the permeability test results for the samples soaked in palm oil and engine oil showed that the viscosity of the contaminant liquid played a vital role in the permeability of the soil. Viscosity of engine oil is higher than palm oil at 20ºc (125 cP and 69 cP respectively). Therefore it can be said that the more viscous the contaminant, the higher the infiltration is and vice versa. This is most probably due to the mixture between the more viscous oil and the sand which tends to "grip" the particles together. When the sample is permeated with water, the voids in the mixture are being pushed aside and eventually form a "path" that makes it easier to infiltrate through the sample. Both scenarios of dense and loose sample show similar observations, however the hydraulic conductivity increase was more apparent in the dense sample with engine oil.

The shear strength of the sand samples was also affected when contaminated with engine oil. The critical friction angle tends to decrease to about 19% as water is allowed to saturate the sample, but the values decreased to a further 26% when saturated with engine oil. This is particularly caused by the engine oil molecules that surrounds the sand particles which reduces the inter-particle friction. The cohesion parameter however increased significantly with the presence of engine oil to more than about 700% from the dry sand samples. This significant increase is due to the high viscosity of the liquid tend to hold the particles together. The study has raised a comprehensive awareness to minimise problems or unwarranted construction risk that is caused by oil contamination.

5. Acknowledgement

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