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Effects of Surfactant on Geotechnical Characteristics of Silty Soil
(Kesan SurfaktanTerhadap Ciri Geoteknik Tanah Berlodak)

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ABSTRACT

Surfactants are often used as a cleaning agent for restoration of oil-contaminated soil. However the effect of surfactant on the geotechnical properties of soil is not clearly understood. In this study, the effects of surfactant on silty soil were investigated for consistency index, compaction, permeability and shear strength. Sodium dodecyl sulfate (SDS) was used in this study to prepare the surfactant-treated soil. Our results showed that the soil with added surfactant exhibited a decrease in liquid and plastic limit values. Maximum dry densities increased and optimum moisture contents decreased as contents of added surfactant were increased. The presence of surfactant assists the soil to achieve maximum density at lower water content. The addition of surfactant decreased the permeability of soil from 6.29×10^{-4} to 1.15×10^{-4} ms^{-1}. The shear strength of soil with added surfactant was examined using the undrained unconsolidated triaxial tests. The results showed that the undrained shear strength, C_u was significantly affected, decreased from 319 kPa to 50 kPa for soil with 20% of added surfactant. The results of this study showed that the presence of surfactant in soil can modify the mechanical behaviour of the soil.

Keywords: Consistency index; geotechnical properties; residual soil; shear strength; surfactant

ABSTRAK

Surfaktan sering digunakan sebagai agen pembersih bagi membaik pulih tanah tercemar minyak. Walaupun begitu kesan surfaktan terhadap sifat geoteknik tanah tidak jelas. Dalam kertas ini, kesan surfaktan tehadap tanah berlodak dikaji berdasarkan indeks ketekalan, pemadatan, ketelapan dan kekuatan ricih. Natrium dodesil sulfat (SDS) telah digunakan dalam kajian ini untuk menyediakan tanah terawat surfaktan. Keputusan menunjukkan tanah yang ditambah surfaktan mempamerkan penurunan nilai-nilai had cecair dan plastik. Ketumpatan kering maksimum meningkat dan kandungan lembapan optimum menurun dengan peningkatan kandungan surfaktan. Kehadiran surfaktan membantu tanah untuk mencapai ketumpatan maksimum pada kandungan air yang lebih rendah. Penambahan surfaktan menurunkan ketelapan tanah daripada 6.29×10^{-4} ke 1.15×10^{-4} ms^{-1}. Kekuatan ricih tanah yang ditambah surfaktan diuji menggunakan ujian tiga paksi tidak terkukuh tidak bersalir. Keputusan menunjukkan kekuatan ricih tidak bersalir, C_u adalah jelas dipengaruhi, menyusut daripada 319 kPa ke 50 kPa bagi tanah ditambah 20% surfaktan. Keputusan kajian ini menunjukkan bahawa kehadiran surfaktan dalam tanah boleh mengubah kelakuan mekanik tanah.

Kata kunci: Cirian geoteknik; indeks ketekalan; kekuatan ricih; tanah baki

INTRODUCTION

The exposure of hydrocarbon into soil and aquatic environments is probably due to human errors such as underground storage leakage, accidental collides and spill. The degree of hydrocarbon contamination is controlled by many factors such as distance from source, types of hydrocarbon components, initial concentration and types of medium of pathway (Rahman et al. 2010). Oil spillage may be responsible to severe environmental damages and remediation procedures should be taken to restore soil quality (Hudson et al. 2009). Removal of oil from contaminated soil and groundwater is difficult due to its low solubilities and high interfacial tensions (Lee et al. 2002). Remediation of contaminated soil using soil washing technique is widely used with advanced additives to enhance the washing efficiency (Lee et al. 2004; Salehian et al. 2012).

Lacking of landfill sites for disposal and cost of excavation, remediation of oil-contaminated has been commonly carried out using surfactant. Surfactants may be the primary action to remove large amounts of oil from the soil matrix followed by other remediation techniques such as bioremediation (Hudson et al. 2009). The usage of surfactant in remediation of the subsurface saturated zone has been well-acknowledged and received much attention (Oostrom et al. 1999; Ramsburg & Pennell 2002). Application of surfactant in remediation of LNPLs and oil-contaminated sites has been widely adopted and has shown satisfying results (Cheah et al. 1998; Ducreux et al. 1997; Rothmel et al. 1998). Many works related to the remediation option of soil cleaning using surfactant have been carried in order to decontamination of soil contaminated with hydrocarbon compounds (Iturbe et al.

2004; Kuhlman & Greenfield 1999; Torres et al. 2007; Yeh & Young 2003). Yeh and Young (2003) studied the effects of soil textures in terms of cationic exchange capacity (CEC) and soil organic matter (SOM) values on cleaning procedures using surfactant.

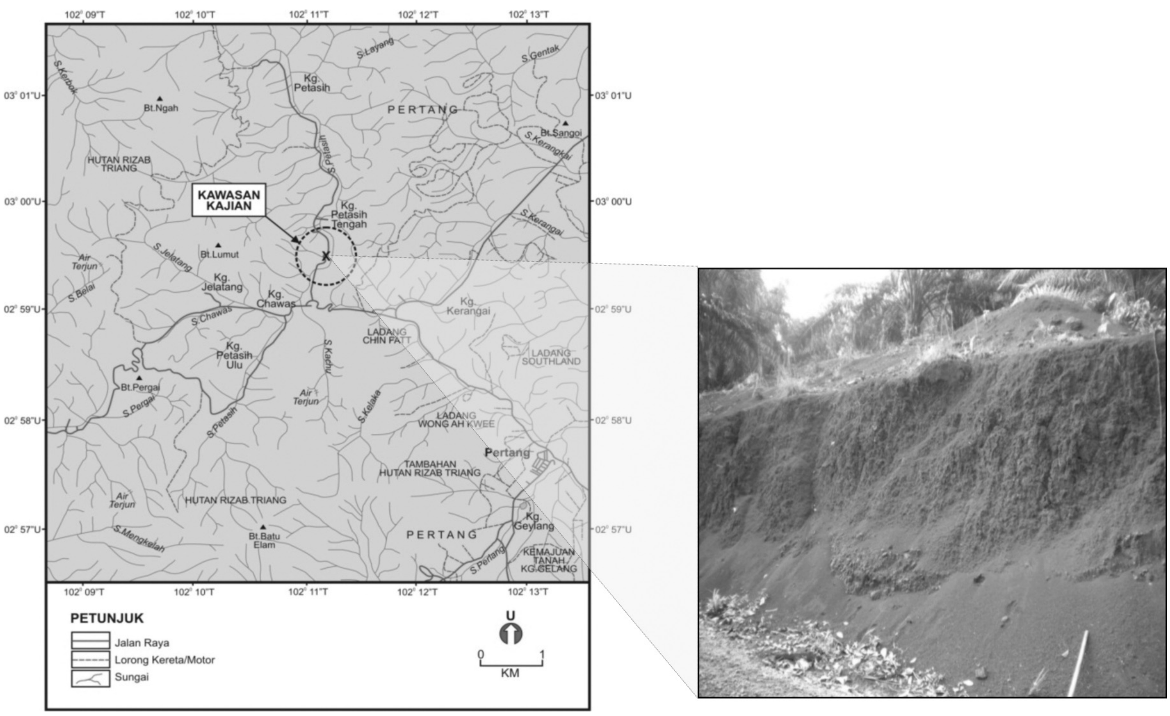
Surfactant molecules compose long hydrocarbon chain of hydrophobic (or tail) and hydrophilic (head) sections. It is a compound that can increase the contaminant of NAPL (Non-Aqueous Phase Liquid) solubility in the water phase through micellar solubilisation. This later improves the NAPL mobilization as a resultant of the reduction in interfacial reduction (Harwell et al. 1999, Martell & Gélinas 1996). In petroleum industry, surfactant solution has been used to increase the oil recovery in reservoir (Hudson et al. 2009). Torres et al. (2007) found that the higher the particle size, the lower the washing removal rate. The efficient removal of oil from soil is the combined effects of particle size and total concentration of petroleum hydrocarbon. Introduction of surfactant for cleaning of oil-contaminated soil may alter the mechanical behaviour of such treated soil. An application of chemicals probably alters the original geotechnical properties of soils (Hueckel et al. 1997; Sai & Anderson 1991; Uppot & Stephenson 1989). Acar et al. (1985) examined the liquid limit of bentonite with different chemical dielectric constants. Several studies on the effects of low dielectric constant on diffuse double layers and hydraulic conductivity were also performed (Anderson et al. 1985; Broderick & Daniel 1990; Li et al. 1996; Lo et al. 1997; Parker et al. 1986). Many of the organic compounds with low dielectric constant (less than 40) have a tendency to shrink the diffuse double layers and decrease their repulsive forces, causing flocculation of clay particles and to dehydrate interlayer zones of expandable clays which subsequently became gritty or granular (Bowders & Daniel 1987; Park et al. 2006). As a result, the liquid limit decreases while hydraulic conductivity increases with the decrease in dielectric constants of organic compounds. Park et al. (2006) performed a comprehensive study of the effects of surfactant and electrolyte solution on kaolinite clay soil. They studied the interactions between clay soils-surfactant-naphthalene (as pollutant) by performing the Atterberg limits tests, pH, viscosity, surface tension, compaction, unconfined strength, hydraulic conductivity tests and isotherm equilibrium tests in the laboratory.

The aim of this study was to investigate the role of added surfactant on geotechnical properties of treated soil. The geotechnical properties of soil with added surfactant were studied by performing Atterberg limit tests, compaction, permeability tests and shear strength in the laboratory.

MATERIALS AND METHODS

SAMPLE COLLECTION AND PREPARATION

The base soil used in this study was residual soil of ultrabasic rock (serpentinite) origin that was collected from Petaseh, Negeri Sembilan, located at 3°1′10.34″N and 102°10′44.39″E (Figure 1(a)). This soil is reddish brown due to high content of iron oxide (Figure 1(b)).



(a) (b)

FIGURE 1. (a) Sampling site for base soil used in this study and (b) outcrop of residual soil developed from ultrabasic rock

Anionic surfactant used in this study is sodium dodecyl sulfate (SDS). SDS is easily biodegradable by soil and/or aquatic microorganism (Lee et al. 2002). Basic properties of SDS are summarized in Table 1 (Park et al. 2006).

Preparation of treated soil was performed by mixing the surfactant thoroughly with soil at percentages of 0, 5, 10 and 20% of dried weight of base soil. The treated soil was then kept in airtight plastic container for three days to homogenise the mixture.

DETERMINATION OF BASE SOIL CHARACTERISTICS

The base soils were tested and analysed for index properties and classified as per unified classification scheme. The analyses include particle size distribution, x-ray diffraction (XRD) and x-ray fluorescence (XRF) analysis, specific gravity, pH, consistency index (liquid and plastic limits), compaction, permeability and undrained shear strength.

Particle size distribution was carried out based on dry sieving and pipette techniques. The presence of minerals was determined through XRD analysis. The XRF analysis was adopted to determine the presence of elements in the base soil. Prior to this analysis, the powdered soils samples were prepared in pellet forms. A pycnometer bottle method was applied to determine the soil specific gravity.

CHARACTERISATION OF TREATED SOIL

Four sets of treated soils were prepared and analysed for consistency index, compaction, permeability and undrained shear strength. Each set of treated soils consisted of 5, 10 and 20% of surfactant contents. After curing period, the consistency index and compaction tests were carried out at different contents of added surfactant (Table 4).

The consistency index of liquid limit was determined by using the Casagrande cup techniques. Soil sample was placed in Casagrande cup and groove of 13 mm wide was made down to its centre. The metal cup then was repeatedly dropped until the groove closes and the number of blows was recorded. The representative moisture content at liquid limit is equivalent to 25 blows. The plastic limit was defined by rolling 3 mm diameter of soil thread or it started to crumble.

The standard Proctor 2.5 kg (or BS light) compaction effort was used to determine the values of maximum dry density, $\rho_{dry\ max}$ and optimum water content, w_{opt}. For each surfactant content, about 2.5 kg of contaminated soil was used to perform the test. The soil samples were compacted with 2.5 kg rammer at high of 30 cm into three uniform thickness in a standard cylinder mould. Twenty five blows were applied on to each layer. Then samples were collected and oven dried to determine the moisture content. A similar procedure was repeated for samples with higher moisture contents. The compaction curves delineated from the dry density and moisture content values would be used to determine the values of $\rho_{dry\ max}$ and w_{opt} for each fraction of surfactant-treated soil.

The permeability of treated soils was determined by a falling head permeameter method. Soil samples were prepared using a standard compaction test mould. The unconsolidated undrained tests for treated soils were performed for each percentage of added surfactant. For each test of particular added surfactant content, three samples were prepared at a maximum dry density, $\rho_{dry\ max}$ and optimum moisture content, w_{opt} of standard Proctor tests. Therefore, nine samples were prepared in standard compaction mould. The samples were sealed and tested after 3 days of curing period. Prior to shearing, confining stresses of 140, 280 and 420 kPa were imposed to the samples under cell pressure, σ_3. Samples were sheared at constant strain rate of 1.00 $mmmin^{-1}$. Shearing of the samples was performed until the samples failed.

Standard methods adopted in order to determine the base soil characteristics and geotechnical characterisations for the treated soil were referred to the British Standard Institution 1377 (1990a; 1990b; 1990c; 1990d) Part 2, 4, 5 and 7.

RESULTS AND DISCUSSION

GENERAL CHARACTERISTICS OF BASE SOIL

The results of the basic characteristics for the base soil used in this study are shown in Table 2. The residual soil developed from the ultrabasic rock showed higher fraction of fine particles of silt and clay compared with that of coarse fraction. Clay and silt particles represented by 47% and 38%, respectively and were classified as silty clay. Higher fraction of fine particles in ultrabasic residual soil is associated with its mineralogy (Keong 2002). Feldspar minerals are abundant in ultrabasic rocks which tends to weather to clay minerals. It has been widely recognised that the decomposition of ultrabasic igneous rock associated

TABLE 1. Basic properties of SDS

Properties/Product name	Sodium dodecyl sulfate (SDS)
Molecular formula	$CH_3(CH_2)_{11}SO_4Na$
Molecular weight	288
Viscosity[a]	1.45
CMC[b] (g/L)	2.3-2.37

[a]Based on ultra filtration through YM1 membrane (Amicon, Inc., Beverly, MA, USA)
[b]Measured at 10 CMC by Brookfield Viscometer®

TABLE 2. Basic characteristics of base soil used in this study

Parameters	Unit	Results
Sand	%	15
Silt	%	38
Clay	%	47
pH		5.86
Specific gravity, G_s		2.8
XRF analysis	$mgkg^{-1}$	
Ni		176-597
Cr		748-9270
Mn		526-943
Co		127-151
Ba		205-257
XRD analysis	2θ=24.9°	Kaolinite
	2θ=33.1°	Hematite
	2θ=21.4°	Goethite
Liquid limit, w_L	%	60
Plastic limit, w_P	%	38
Plasticity index, I_P	%	22
MDD, $\rho_{max\ dry}$	gcm^{-3}	1.52
OMC, w_{opt}	%	26.1
Permeability, k	ms^{-1}	6.29×10^{-4}
Shear strength, C_u	kPa	466-582

Notes: MDD – maximum dry density; OMC – optimum moisture content

with the formation of residual soils containing mainly of montmorillonite (Bagchi et al. 1996; Garnier et al. 2009; Van der Merwe 1964).

Specific gravity of the soil was 2.8 and the pH was 5.8. It has darker reddish brown colour and contains Ni, Ba and Co. Ni and Cr in ultrabasic soil are commonly found in high content (Alloway 1990; Brook 1987; Sahibin et al. 2009). XRD analysis showed the presence of hematite, kaolinite and goethite. The peak matched well for hematite located at 2θ angle of 33.1° with peak intensity of 59.5 Cps and spacing, *d* of 2.701 (Figure 2(a)). Kaolinite and goethite minerals were indicated by peaks at 2θ angles of 24.9° and 21.4°, respectively. The SEM images of the treated soil showed interaction between the soil particles and surfactants. Bulbous lighter shape of surfactant particles are seen located and attached with the flaky clay minerals (Figure 2(b)). Liquid and plastic limits were 60% and 38%, respectively.

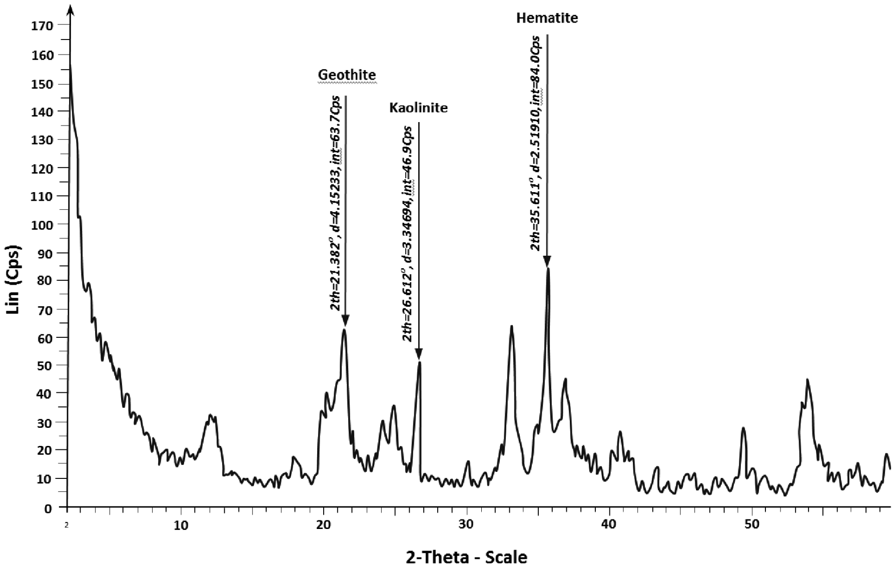
The maximum dry density, $\rho_{max\ dry}$ and optimum moisture content, w_{opt} were 1.52 gcm^{-3} and 26.1% while permeability, *k* value was $6.29 \times 10^{-4} ms^{-1}$. Shear strength coefficient of undrained unconfined, C_u gave values ranged between 466 kPa and 582 kPa.

GEOTECHNICAL CHARACTERISTICS OF TREATED SOIL

Atterberg Limit The results of Atterberg limit value are shown in Table 3 and graphically plotted in Figure 3. The untreated soil showed liquid limit, w_L and plastic limit, w_P values of 60% and 38%, respectively. The w_L values decreased from 60% to 42% with surfactant contents of 5% which then gradually dropped from 42% to 32% at surfactant content of 20% (Figure 3). The values plotted on Casagrande plasticity chart indicated that the treated soils shifted toward a lower plasticity with the increase in surfactant contents (Figure 4). A similar trend was also shown for the values of w_P with increasing contents of surfactant. The value of w_P dropped from 38% to 25% at surfactant contents of 20%. The values of w_P apparently dropped to 30% at 5% of surfactant content but then slightly decreased to 27% and 25% at 10% and 20% of added surfactant. Generally, the occurrence of surfactant has altered the liquid and plastic limits of the treated soil. This condition is a result of the mantling of the charged clay particles by the presence of surfactant. Thus, lessens the chances of water interaction with clay as water acts as binding agent between clay particles. Therefore, removal of water-clay interaction has led to the modification of the plasticity characteristics of the treated soil. Park et al. (2006) observed a similar effect of surfactant on the liquid and plastic limits of kaolinite.

COMPACTION BEHAVIOUR

The results of the compaction tests on treated soil are shown in Table 5. Generally, soil compaction with the presence of surfactant helps soil achieve maximum density with the lower water content. Figure 5(a) shows the compaction curves for different contents of added surfactant. The tests indicated that the addition of surfactants increased the maximum dry density, ρ_{dmax} and decreased the optimum moisture content, w_{opt}. The values of ρ_{dmax} and w_{opt} of untreated soil (0% of surfactant) were 1.52 gcm^{-3} and



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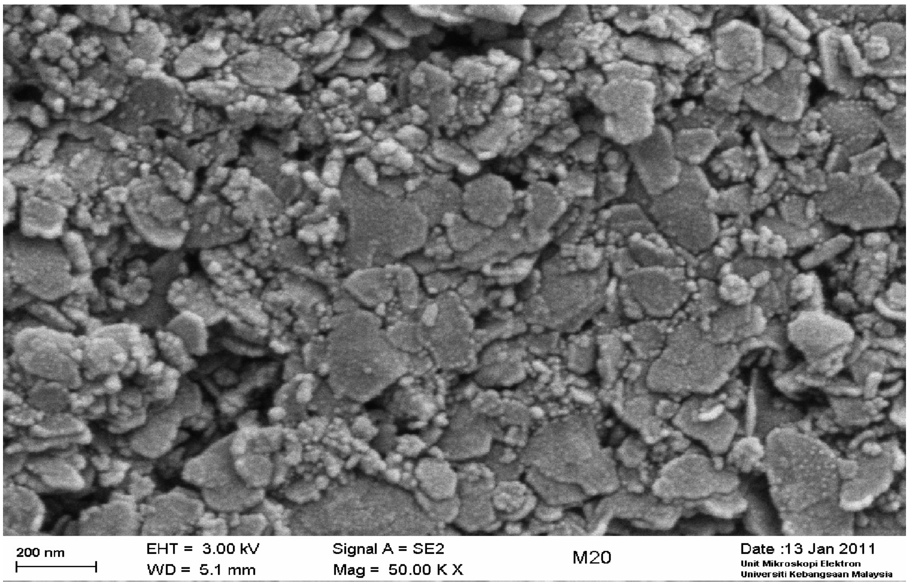

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FIGURE 2. (a) XRD analysis of base soil and (b) SEM observation of base soil treated with surfactant

TABLE 3. Atterberg limit values for surfactant-treated soil

SDS content (%)	Liquid limit, w_L (%)	Plastic limit, w_P (%)	Plasticity index, I_P (%)
0	60	38	22
5	42	30	12
10	37	27	10
20	32	25	7

26.13%, respectively. It is shown that the addition of surfactant has increased the ρ_{dmax} and contrary with the w_{opt} values. The results suggested that compaction occurred with the presence of surfactant assisting soil to achieve maximum density at lower water content compared with that of untreated soil. Surfactant has reduced the surface tension allowing water to move freely in pores and saturate soil with less water (Henry & Smith 2003; Oostindie et al. 2011; Parks et al. 2006). The increasing surfactant content coated the soil particles with thick film causing lubrication. This in turn cause particles to re-orientate to a denser packing (Parks et al. 2006).

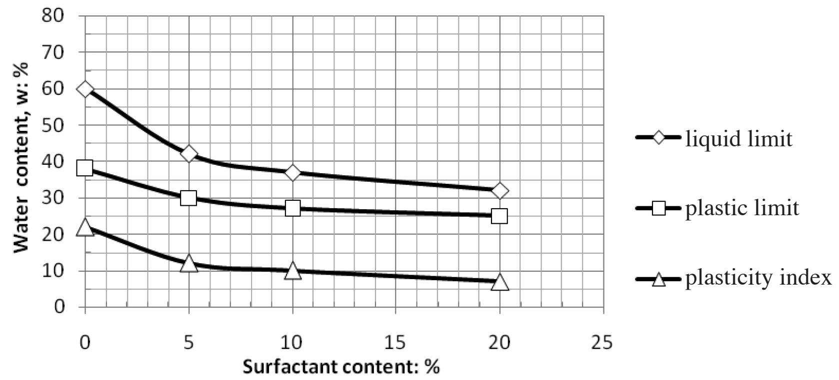
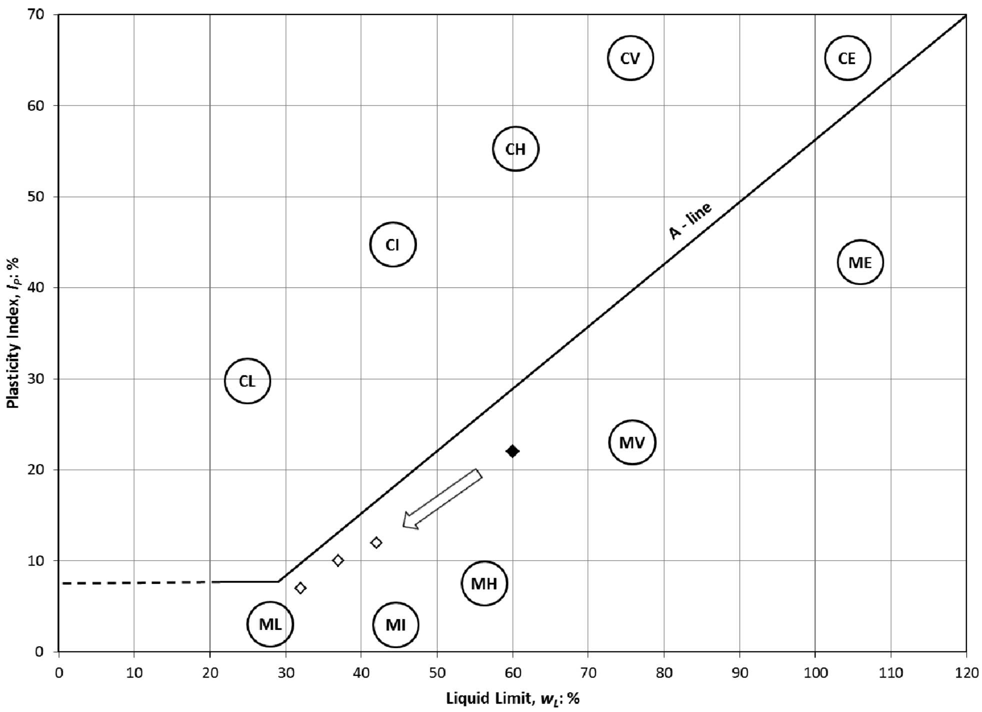


FIGURE 3. Atterberg limit values against surfactant contents



Notes: Fine materials: C=clay; M=silt. Plasticity: L=low; I=intermediate; H=high; V=very high; E=extremely high

FIGURE 4. Plasticity chart of the untreated soil (black symbol) and the surfactant-treated soil (blank symbol). Arrow shows the direction of increasing surfactant content

TABLE 4. Compaction characteristics of the treated soil with different contents of surfactant

Surfactant Content (%)	MDD ρ_{dmax}(gcm^{-3})	OMC $w_{opt(}$%)
0	1.52	26.13
5	1.53	24.17
10	1.54	22.01
20	1.56	18.70

MDD – maximum dry density; OMC – optimum moisture content

EFFECT ON PERMEABILITY

The effect of surfactant content on permeability, *k* is shown in Figure 6. For untreated soil (0% surfactant), the *k* value was 6.29×10^{-4} ms^{-1}. An addition of surfactant contents to the base soil has caused the *k* values to drop from 6.29×10^{-4} ms^{-1} to 3.12×10^{-4}ms^{-1} with 5% of surfactant content. The drawdown of *k* values continued to 2.67×10^{-4} ms^{-1} and 1.15×10^{-}4 ms^{-1} with the surfactant contents of 10% and

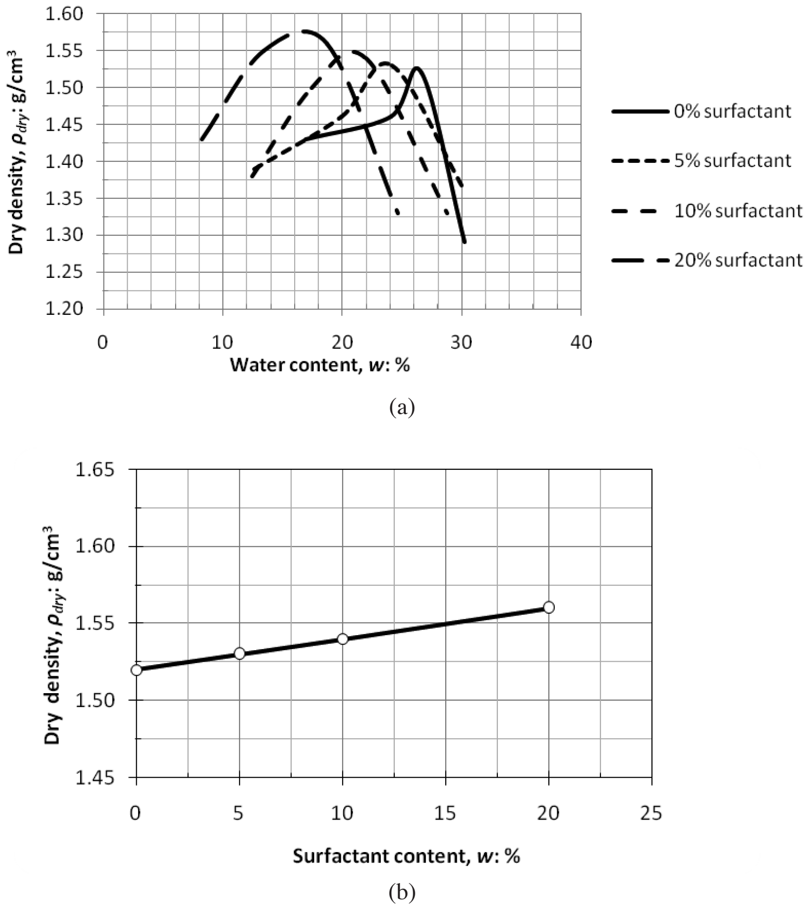


FIGURE 5. (a) Compaction curves for the treated soil with surfactant contents and (b) effect of surfactant on MDD values

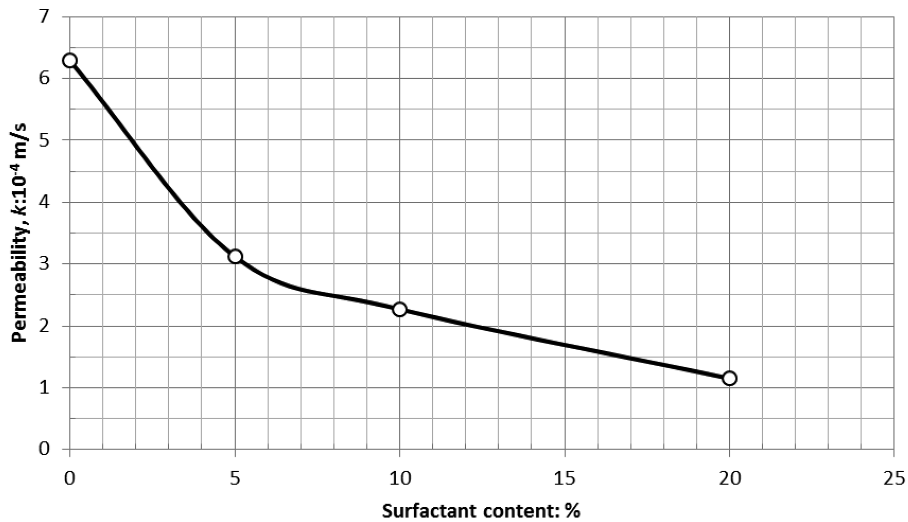
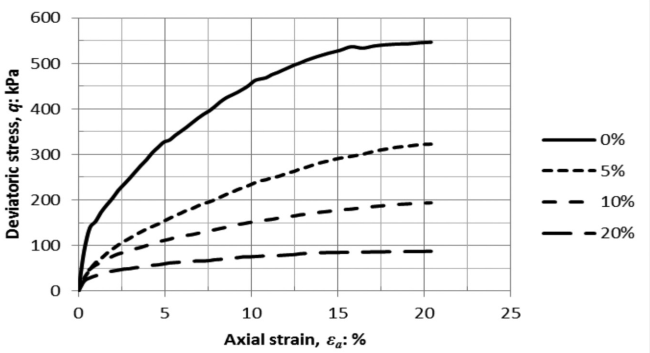


FIGURE 6. Permeability of treated soil with increasing surfactant contents

20%, respectively. It is clearly indicated that the increase in added content of surfactant is responsible in reduction of k value of surfactant-treated soil. The drop in k value was quite high at 5% of surfactant content if compared with that of 10% and 20% of added surfactant which can be best represented by a linear line as shown in Figure 6. The decrease of the permeability might be related to blockage of micro cavities by movement of tiny particles when these soil particles were activated by surfactant. The hydrophilic tails in surfactant has a tendency to bind with

TABLE 5. The maximum deviatoric stresses (q_{max}) and applied confining stresses (σ_3) for the treated soil with different surfactant contents

Surfactant content (%)	Minor principle stress, σ_3 (kPa)	Dev. stress, $q=\sigma_1-\sigma_3$ (kPa)	Major principle stress, σ_1 (kPa)	Shear strength C_u (kPa)
0	140	546.6	686.6	319
	280	673.0	953.0	
	520	696.5	1216.5	
5	140	322.6	462.6	190
	280	372.4	652.4	
	520	445.1	965.1	
10	140	193.7	333.7	106
	280	200.1	480.1	
	520	239.3	759.3	
20	140	87.1	227.1	50
	280	103.3	383.3	
	520	108.2	628.2	



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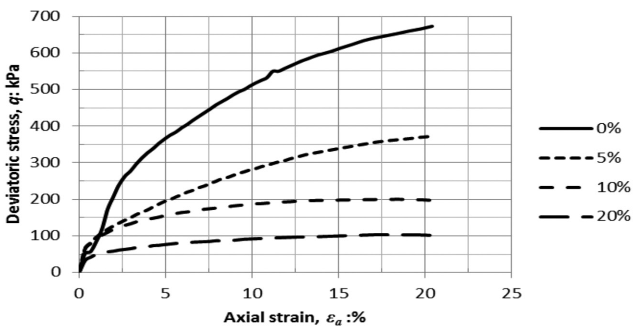

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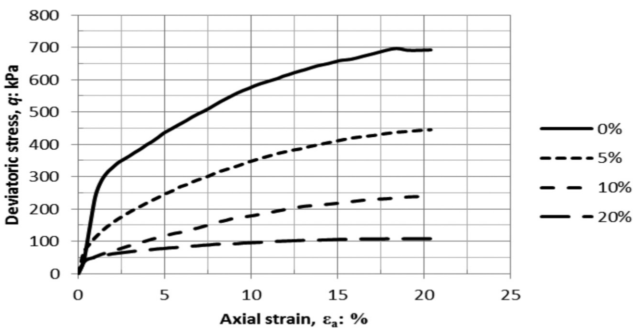

(c)

FIGURE 7. Shear-strain of treated soil with surfactant contents at confining stresses of (a) 140kPa, (b) 280kPa and (c) 520kPa

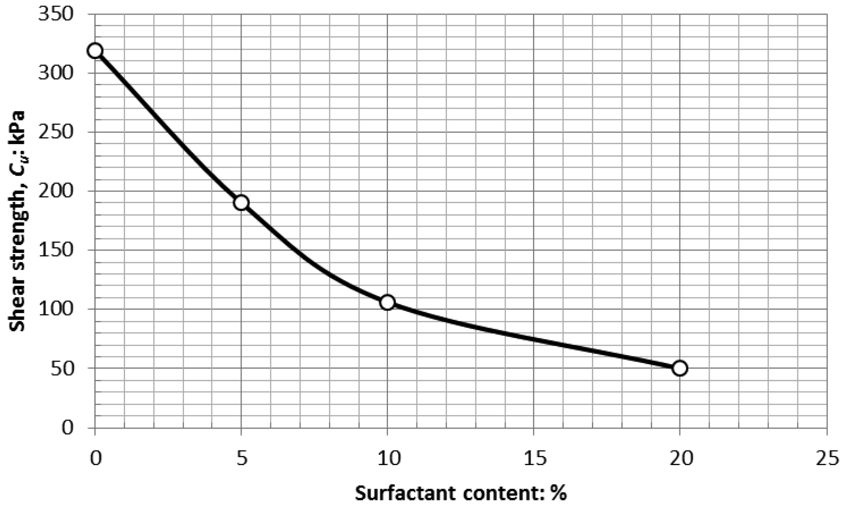

FIGURE 8. Effect of surfactant contents on shear strength of treated soil

water, thus time required for water to pass through pores will increase along with the presence of surfactant (Parks et al. 2006). Other studies showed that the permeability could decrease due to higher viscosity of surfactant than water (Anderson et al. 1985; Broderick & Daniel 1990). Parks et al. (2006) also added that no flocculation effect and the increase in k value by SDS used in the study were observed. From SEM observation, surfactant tends to associated with soil particles and filled gap between pores, thus decreasing the permeability of the treated soil.

SHEAR STRENGTH

The results of the undrained tests and stress-strain curves were shown in Table 5 and Figure 7. The undrained shear strength, C_u extracted from Mohr's circle, assuming that fiction angle, ϕ_u equal to null (Craig 1995). Most of the tests showed stress-dependant behaviour and failure of soil samples mostly associated with bulging mode of failure. Samples showed an initial drastic linear increase in deviatoric stress, q up to axial strain between 1% and 2% (Figure 7). Upon further shearing, the samples showed an increase in q but at lower increment up to the peak values prior to failure of the samples.

The effect of surfactant on treated soils is shown in Figure 8. The shear strength, C_u values dropped from 319 kPa for untreated soil (0% surfactant) to 50 kPa for soil treated with 20% of surfactant (Table 5). Parks et al. (2006) also found that additional SDS decreased the undrained shear strength, C_u of elastic modulus, E of kaolinite mixture compared with that of kaolinite remoulded with water. The drawdown values of C_u would be due to coating of soil particles by surfactant, reducing the particle friction due to lubrication effect.

CONCLUSION

Base soil used in this study is characterised by clay and silt fractions as well as a high content of Cr and Mn. This study indicated that the addition of surfactant in soil can modify the mechanical characteristics of soil. Surfactant in treated soil reduced liquid and plastic limits, permeability and shear strength. The presence of surfactant assists soil to achieve maximum density at lower water content. The reduction in shear strength due to the presence of surfactant can be the disadvantage criteria in construction or foundation materials. Therefore, recycling contaminated soil treated with surfactant for construction purposes should be avoided, however if the permeability of compacted soil might reach to recommended value, it can be used as landfill liner.

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