EFFECT OF CRUDE OIL PRODUCTS ON THE GEOTECHNICAL PROPERTIES OF SANDY SOIL

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EFFECT OF CRUDE OIL PRODUCTS ON THE GEOTECHNICAL PROPERTIES OF SANDY SOIL

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ABSTRACT

Different regions around the world are encountering oil pollution due to many reasons such as leakage of oil due to tanker accidents, transportation on land and sea, and during the process of oil drilling. This oil spill would have a negative effect on the environment and on the ecological life and it may also change the geotechnical properties of the soil. Recently, the effects of crude oil on soil contamination have received serious attention from many researchers. Most of these researchers studied the effect of crude oil itself without taking into consideration its products. Added to that, most of these outcomes have shown contradiction in their results due the addition of crude oil to the soil. Some results showed an increase in the maximum dry density while other results indicated a decrease. Similar trend was noticed in the shear strength of soil as well. The aim of this research is to investigate the effect of crude oil products (kerosene and diesel) on some of the geotechnical properties of sand. In order to achieve the goal of this research, three different types of sandy soils were selected based on their grain size distribution. The initial physical properties of the selected soils such as optimum moisture content, maximum dry density, and shear strength, angle of internal friction, grain size distribution, and permeability were determined. A number of samples were prepared by mixing the soil with different percentages of crude oil products (kerosene and diesel) and their effects were studied by conducting different experiments such as the proctor compaction test, direct shear test and the permeability test. The results indicated that as the percentage of crude oil products increased, the angle of internal friction of the sand would decrease. An apparent cohesion was found and increased gradually as diesel and kerosene were added to the soil. The maximum increase was noticed at 8 percent of crude oil product being added. When more than 8 percent was added, less increase in cohesion was noticed. At low normal stress, as the percentage of crude oil products in soil increased, the shear strength would increase up to a certain percent and then it decreases. At high normal stress, as the percentage of crude oil products in soil increased, the shear strength would decrease. The results indicated a decrease in permeability of all soil samples due to the addition of diesel and kerosene. From this analysis, the behavior of soil can be understood due to contamination of poorly graded sand by crude oil products (diesel and kerosene). Mathematical correlations that predict different properties of sandy soils such as shear strength, friction angle, cohesion and permeability with reasonable accuracy were estimated by regression analysis. The significantly high coefficients of correlation values indicate that the approximation concept used for the analysis performed well for the soil samples. Coefficient of curvature, coefficient of uniformity, specific gravity, normal stress and percentage of diesel/ kerosene were used as independent variables during the analysis of the models.

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k – Coefficient of permeability, cm/s
Q – Flow rate, cm^3
L – Length between the two outlets of the manometer (h1-h2), cm
A – Cross sectional area of flow, cm^2
t – Time, sec
h – Height, cm
SS – Shear strength in kPa
φ – Angle of internal friction in degrees
C – Cohesion
k – Permeability in cm/s
NS – Normal stress in kPa
C_c – Coefficient of curvature
C_u – Coefficient of uniformity
G_S – Specific gravity
D – Percentage of diesel
Kr – Percentage of kerosene
M_p – Weight of empty pycnometer, g
M_x – Weight of soil, g
M_{pw} – Weight of pycnometer + water, g
M_{pws} – Weight of pycnometer + water + soil, g
T_i – Initial Temperature, °C
T_f – Final Temperature, °C
K– Conversion factor

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CHAPTER 1 INTRODUCTION

1.1 Problem Statement

Laboratory testing programs and researches have been carried out from different parts of the world to study the effect of different chemicals and wastes of the geotechnical properties of soil. Some wastes for example have been added to the soil to improve its physical properties such as reducing settlement and increasing its shear strength and some can be used in soil stabilization. On the other hand, some new researches have shown that some of these wastes can have a negative impact on soil properties and on the environment. Therefore, it is important to study the soil behavior due to the addition of different contaminant to the soil in order to reduce the problems associated with this and to avoid any future troubles.

The gulf region contains a large amount of oil reserve and there are thousands of gas stations built in their areas. Therefore, there are many incidents that may occur unintentionally which may cause thousands of tons of oil to leak out. Oil spill may be caused due to many reasons such as transportation on land and on sea, tanker ship accidents and due to drilling of oil processes. This pollution may affect the air, the land and the water. Land contamination by oil spill would be harmful to both environments as well as to buildings and structures resting on soil by changing its geotechnical properties. Moreover, throughout the past twenty years, many accidents have occurred that caused not only crude oil to leak into the water but even diesel and kerosene. Crude oil contains materials that may last for years and are very difficult to be cleaned. Thus the effect of crude oil products on the geotechnical properties of the soil such as shear strength parameters and permeability should be studied.

In this research, the geotechnical behavior of soil due to the addition of crude oil products (kerosene and diesel) were studied. Three different sandy soils were selected based on their sieve size gradation and were mixed separately with different percentage of crude oil products. The results obtained from this research will encounter and help us in understanding the behavior of the soil due to crude oil products contamination.

1.2 Thesis Objectives

This study seeks further investigation for evaluating the soil properties contaminated by crude oil products such as kerosene and diesel. The aim is to develop a better understanding of the behavior of the soil exposed to oil product contamination resulting in changing its physical properties. The outcome of this study might be guidance for designers and researchers to improve their understanding of the soil behavior in the addition of crude oil products. The primary objectives of this study are:

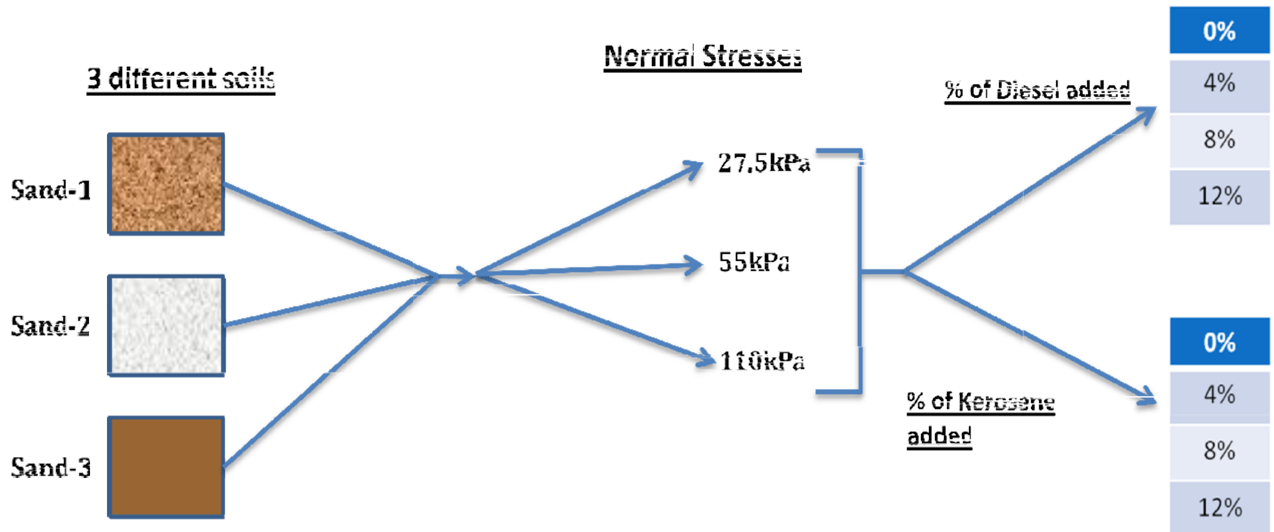
1) To investigate the effect of the addition of different percentages of crude oil products on different soil geotechnical properties.
2) To conduct direct shear test on three types of soil contaminated with crude oil products (kerosene and diesel) to study their effect on the shear strength values.
3) To conduct the constant head permeability test on three types of soil contaminated with crude oil products (kerosene and diesel) to study their effect on the coefficient of permeability.
4) To provide a comprehensive idea of soil behavior contaminated with crude oil products from the data collected and analyzed the above.
5) From the results determined, different models of shear strength, friction angle, cohesion and permeability of sandy soil would be analyzed using multiple regression analysis and a list of equations would be determined.
6) To provide guidance and information to engineers and researchers.

1.3 Structure of the thesis

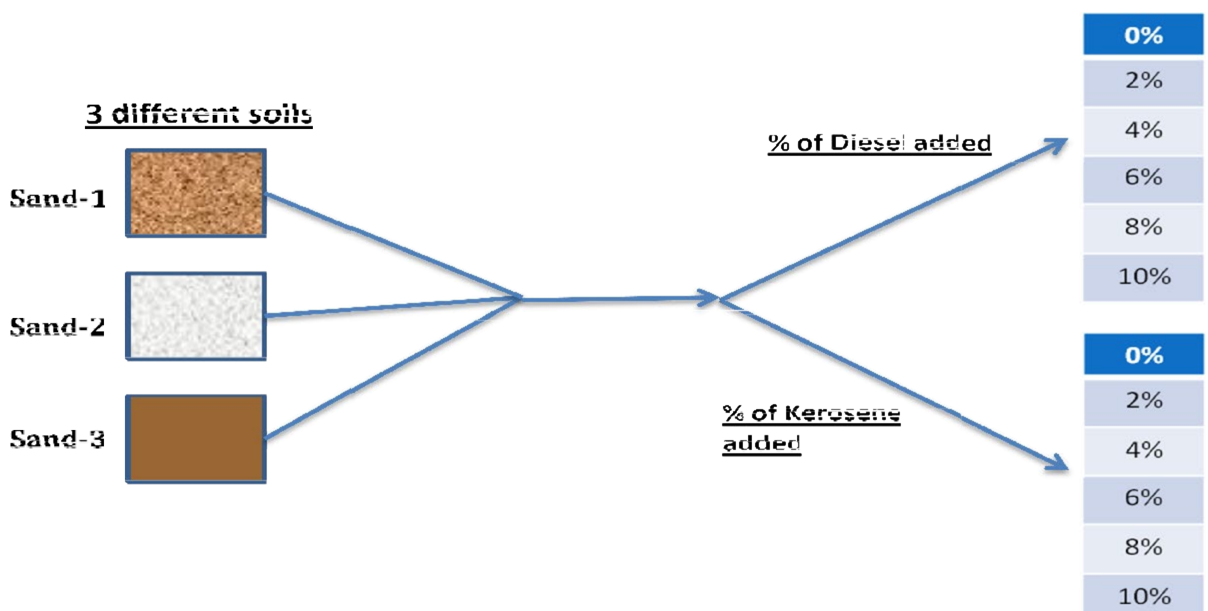
1. Soil Classification:

2. Proctor Compaction Test:

3. Direct Shear Test:



4. Permeability Test:



5. Analysis of the Results:

CHAPTER 2 LITERATURE REVIEW

2.1 General

As the world demand for oil products is increasing, the possibility of leakage of oil would also increase. This leakage associated with many problems to both environment and soil properties. Many researchers have proposed different methods to clean the soil from crude oil products and to reduce its negative impact on the environment. One of these methods is to change the soil, or use the contaminated soil as a base material or topping material for car parks or roads. Others were to clean the soil by different methods such as biological methods, washing methods and absorption methods [1].

The knowledge of geotechnical contaminated soil is still under investigations. There is not much research that studies the effect of crude oil products on the geotechnical properties of soil. Recently, some researchers studied the effect of crude oil contamination on clayey and sandy soil [2]. Three different types of soil – silty sand, poorly graded and lean clay – were used in their work and were mixed separately with 2%, 4%, 8%, 12%, and 16% by dry weight of crude oil. The results have shown that an increase in the crude oil content would result in a decrease in the maximum dry density and the optimum moisture content of the soil. The rate of reduction for maximum dry density was faster for the silty sand and clay than for the sandy soil. The oil contamination has caused a reduction in the strength and the permeability of the soil samples. They found that as oil has a hydrophobia property, it would prevent the contact of water with soil particles. As a result, as the oil content is increased, the capillary tension would decrease. The cohesion in the poorly graded soil didn't show any district path with the addition of oil. It only showed low cohesion which was explained as the result of viscosity and inherent cohesion of oil. It was also noticed that the effect of the oil content on permeability decrease with the increase in soil porosity. The decrease in hydraulic conductivity was a result of the trapped oil that occupies the pore spaces of the soil; the pore volume of the soil would decrease and this would result in a decrease in permeability. Since hydrocarbon compounds have low solubility in water, the normal procedure for permeability was used in their study.

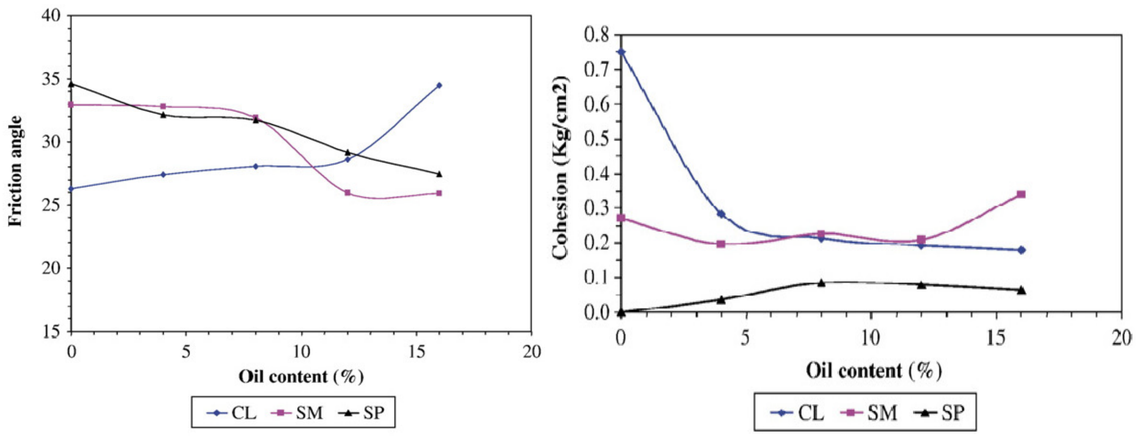


FIGURE 2.1 Influence of oil content on shear strength parameters of soil samples [2].

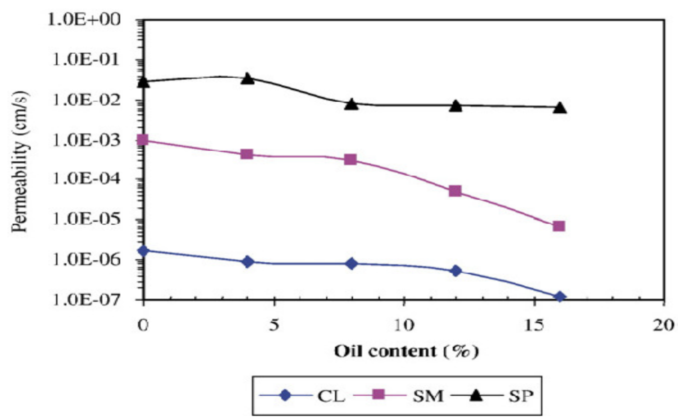


FIGURE 2.2 Influence of oil content on permeability coefficient of soil samples [2].

Moreover, another studied the geotechnical behavior of oil –contaminated fine-grained soil [3]. They showed in their research that an increase in maximum dry density was noticed at low optimum moisture content for clay when it was contaminated by crude oil. The shear strength of the contaminated soil was found to be higher than the uncontaminated soil at high confining pressure. The increase in the strength of the clay mixed with oil was due to the agglomeration of the particles in the presence of oil. The agglomeration has caused a reduction in the specific surface area which was observed in the oil contaminated clay and this caused the contaminated soil to behave like a cohesionless material during the strength testing.

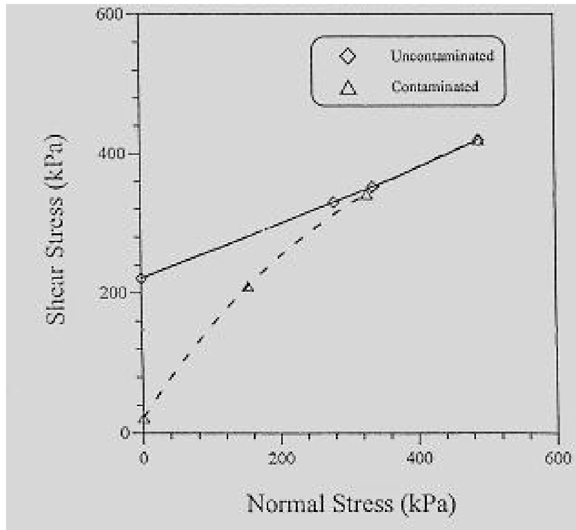
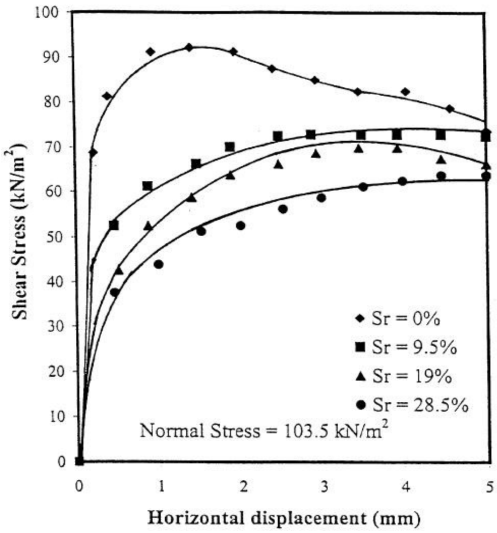


FIGURE 2.3 Mohr-Coulomb Envelopes for Uncontaminated and Contaminated Clay [3].

Purj (2000) studied the effect of oil contamination on the compaction characteristics, shear strength, one dimensional compression and hydraulic conductivity of sand [4]. It was found that when crude oil was used as a pore fluid, the maximum dry unit weight of sand was about 6 percent higher when compared with water as the pore fluid. This was explained as oil is more effective in reducing the friction between the soil particles resulting in a reduction in the spacing between the soil grains. Therefore an increase in the dry unit weight for a given compaction effort would be found. The peak shear strength, the angle of internal friction and the hydraulic conductivity was found to decrease as the percentage of oil saturation increased. Tests were conducted at different relative density of compaction of 40%, 65%, and 80%. It was noticed that for a known amount of oil saturation the decrease in the angle of internal friction was more pronounced for samples at a higher relative density. This would be effect the stability of onshore and offshore structures and slopes. For the permeability test, three types of motor oils with different viscosities as well as crude oil were used. The hydraulic conductivity was seen to decrease with the increase in the degree of oil saturation, with the increase in the relative density of the sand and with the increase in the viscosity of the oil contaminant.



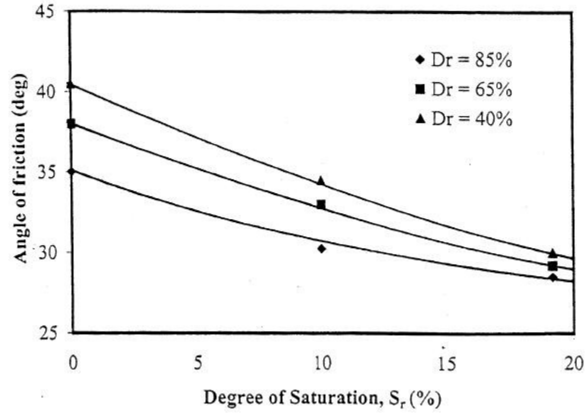


FIGURE 2.4 Typical plot of shear stress vs. horizontal displacement [4].

FIGURE 2.5 Angle of internal friction vs. degree of oil saturation [4].

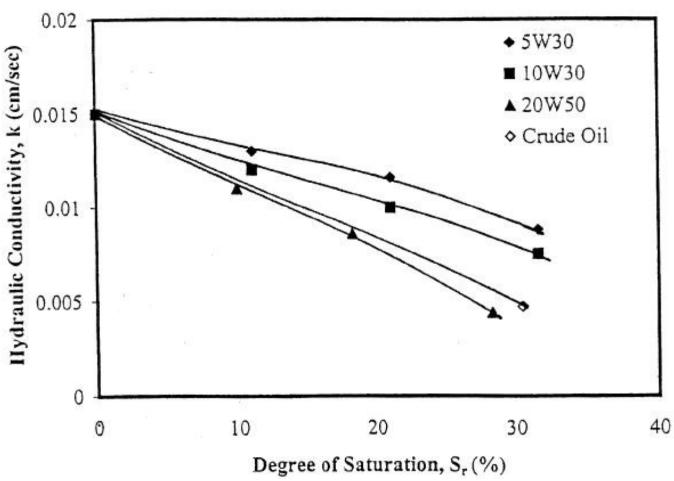
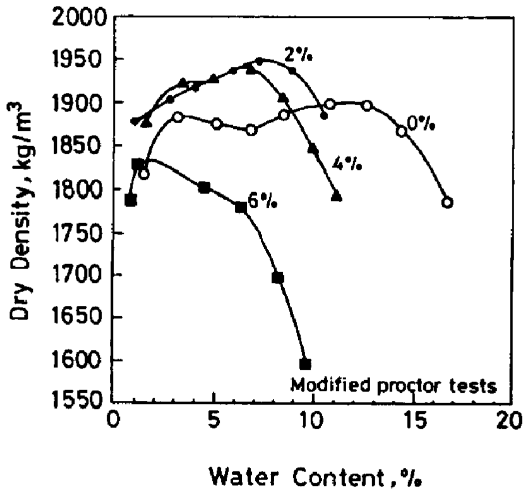


FIGURE 2.6 Hydraulic conductivity vs. degree of saturation for Dr = 85% [4].

Three oil sand materials were tested for their shear strength properties using triaxial compression and direct shear test [5]. Results obtained using the triaxial test showed that the angle of internal friction equal to zero which suggested that the sample behaved cohesive in nature and no interparticle contacts in oil-sand samples. While the direct shear test showed an increase in the friction angle and a lower cohesive values. The results also showed a higher friction angle values for the oil sand sample at 20 degree Celsius than at 30 degree Celsius. The results of the shear strength obtained would be useful in calculating the bearing capacity of oil sand material under trucks and shovels in the field.

The behavior of three fine grained soils and a granular soil with the addition of glycerol, propanol and acetone have been studied [6]. The three chemical were mixed with water to prepare the required amount of pore fluid. It was shown using the unconfined compression test that the shear strength and stress strain behavior of clay decreased by contamination and a marginal reduction for the silty soil was observed. The stress strain behavior has shown softening with the increase in the concentration of the pore fluids. The reduction that was observed in the shear strength and the stress strain behavior in the low and high plastic clays was due to the reduction in the frictional contacts at the particle contacts. This was also believed to be caused by a change in mineral pore fluid mineral interactions.

Ghaly (2001) showed in his research that the angle of internal friction of the sand decreases as the percentage of the oil increased [7]. The effect of crude oil on the geotechnical properties of Kuwaiti sand was studied by Al Sanad et al (1995) [8]. They showed in their research that the compressibility of the sand has increased due to the addition of crude oil. They found that the compaction characteristics have improved due to the addition of oil up to 4% by weight. The coefficient of permeability has decreased by 20% and the angle of internal friction decreased when oil was added. Most of the papers that studied the behavior of granular soil due to addition of crude oil have shown that the compaction curve tends to decrease first then it increases to the maximum value. It was concluded that the compaction curve tends to improve as the percentage of crude oil added increase.



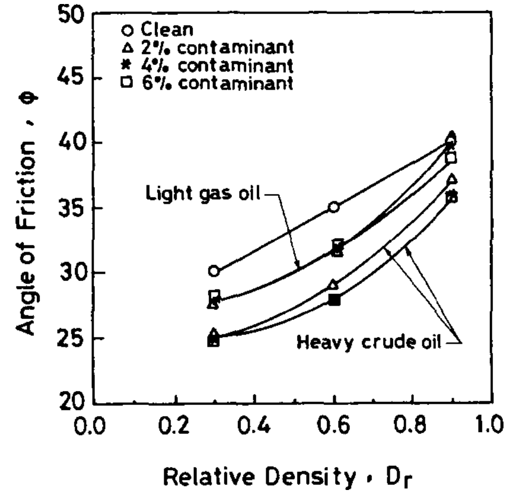


FIGURE 2.7 Compaction curves for samples with different Oil content [8].

FIGURE 2.8 Relationship between Relative Density and Friction Angle for Heavy Crude Oil and Light Gas Oil [8].

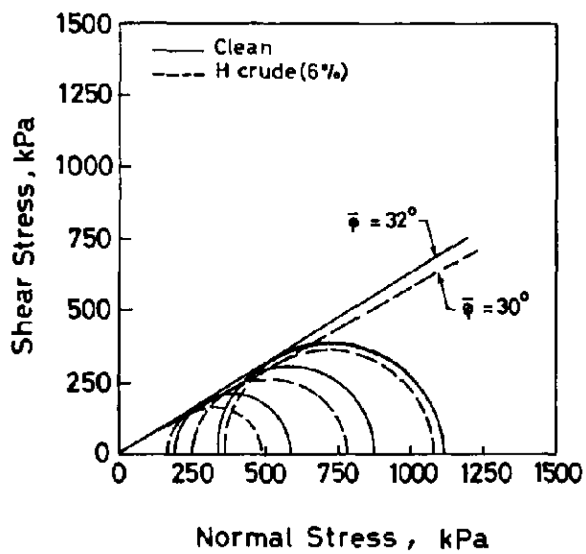


FIGURE 2.9 Failure Envelope for clean and contaminated specimens [8].

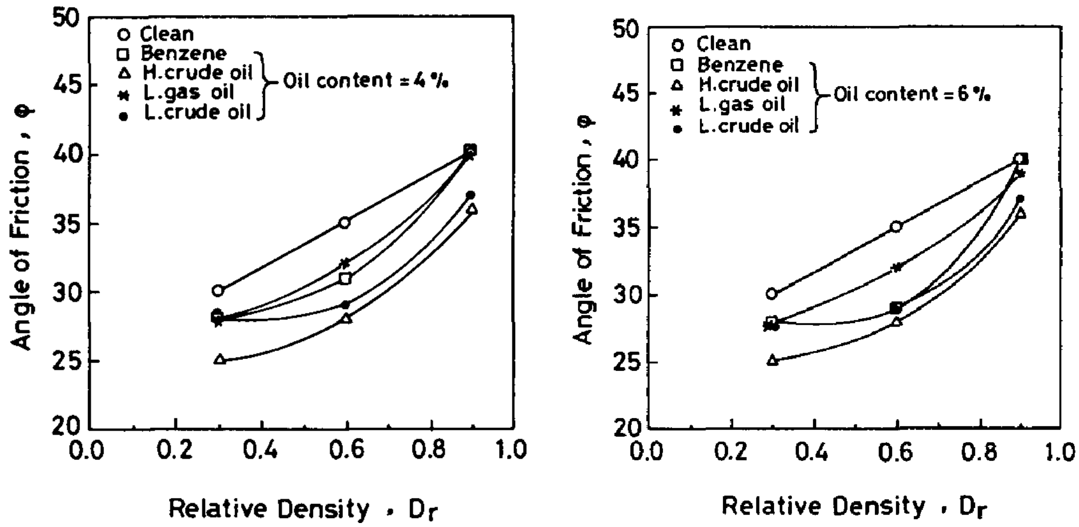
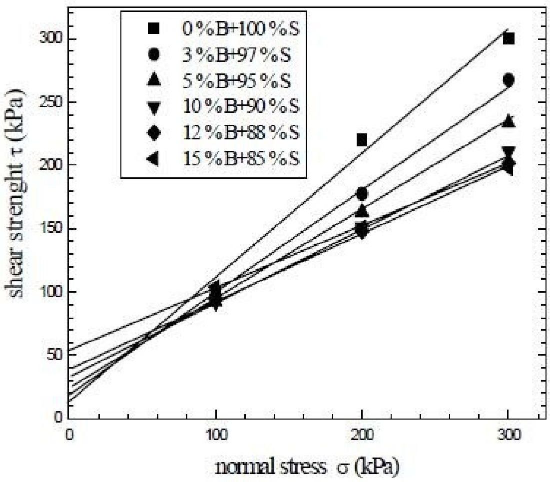


FIGURE 2.10 Relationship between Relative Density and Friction Angle for Clean and Contaminated Sand (Oil Content = 4%, 6%) [8].

Shin et. al (2002) concluded that the contaminated soil with oil posses a lower angle of internal friction than clean sand [9]. The stress strain behavior of loose and dense sand with saturated oil and water were studied [10]. They found that contaminated sand with oil will reduce the angle of internal friction and increases the volumetric strain. Many other studies of the effect of crude oil on different soil properties are still under investigation. The results would be beneficial for the geotechnical and structural engineers.

On the other hand, the soil shear strength could be increased or decreased when mixed with non soil material. Many materials have been added to the soil to increase the shear strength and to stabilize the soil such as lime, fly ash, industrial wastes, cement, fibers and hay [11,12,13,14]. Added to that, Gueddouda et al.(2008) studied the effect of the addition of a small amount of bentonite on sandy soil [15]. They concluded that the maximum dry unit weight, permeability and angle of internal friction decreased while the cohesion increased due to the addition of bentonite.



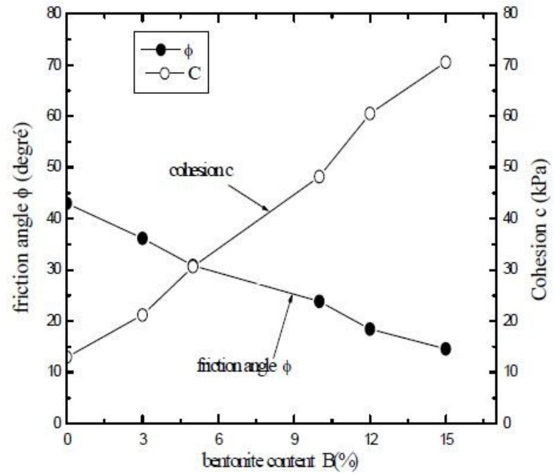


FIGURE 2.11 Mohr-coulomb failure envelopes obtained from direct shear tests of s/b mixtures [15].

FIGURE 2.12 shear strength parameters vs. Bentonite content of s/b mixtures [15].

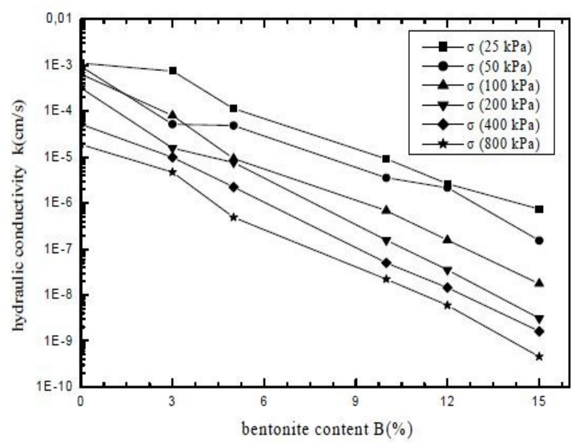


FIGURE 2.13 Hydraulic conductivity vs Bentonite content of s/b mixtures [15].

Kalkan (2009) studies the effect of silica fume on the geotechnical properties of finely grained soil exposed to freeze and thaw[16]. The main goal of his research was to reduce the effects of thawing and freezing cycle on the strength and permeability. He concluded that the silica fume decreased the liquid limit, plasticity index, maximum dry unit weight, permeability and increased the plastic limit, optimum moisture content, unconfined compressive strength. He found that the cause for the increase in optimum moisture content is due to the change in the surface area of composite samples and the reason for the decrease in dry density is due to the addition of high quantity of silica fume with low density where the voids of the composite samples were filled. Added to that, the permeability effect was significantly observed when silica fume content reached 25 percent, after that it has a less effect. The reason for this decrease in permeability was because the addition of high amount of silica fume to the finely grained soil particle would fill the void and cause a chemical reaction in the composite sample [16].

Sariosseiri et al. (2009) studied the effect of cement treatment on the geotechnical properties of some fine and coarse grained soils [17]. Cement was added in different percentages of 2.5, 5, 7.5 and 10 percent of the dry weight of the soil. Different laboratory test were conducted on the soil and an improvement in the drying rate, workability, unconfined compressive strength and shear strength were shown. The optimum moisture content increased and the maximum dry unit weight decreased when cement was added. It was noticed that the unconfined compressive strength increased significantly when treated with cement contents greater than 5 percent. It was seen that the addition of small percent of cement have improved the unconfined compressive strength of one soil type. Added to that, the other two other types of soil have nearly the same gradation but have shown a variation in their unconfined compressive strength [17].

Ene et al. (2009) studied the effect of pyroclastic dust on the geotechnical properties of expansive soil [18]. The soil was mixed with varying amount of pyroclastic rock dust. An increase in the pyroclastic dust proportion resulted in an increase in the maximum dry density, optimum moisture content, shear strength and CBR. On the other hand, plasticity and linear shrinkage have decreased. The increase in the maximum dry density and optimum moisture content was seen upto 8% of pyroclastic dust was added and then it decreased. This increase was due to the higher density of the dust particles when compared with the clay particles and due to the reaction between the clay minerals present in the soil and the calcium oxide present in the pyroclastic dust [18]. As to Al Rawi and Award (1981), they claimed that the increase in the shear strength was the result of the increased production of gelatinous cementing agents with lime, which takes a large amount of void space and makes it harder [19]. Ola (1977) on the other hand, claims that the increase in strength was due to the bonding agents with cement particles to produce large aggregates which makes the soil behaves as a coarse-grained and becomes strongly bonded. Their results have proved that the pyroclastic dust binds the clay particles together and fill the voids. This increases soil aggregation and reduces the water absorption which improves the swelling properties and workability of the soil [20].

Indrawan et al. (2006) studied the effect of coarse grained materials on the hydraulic properties and shrinkage characteristics of residual soil [21]. Residual soil was mixed with different percentages of gravelly sand and medium sand. The permeability was seen to be increasing as coarse grained mixture increased. Raharjo et al. (2008) studied the effect of coarse grained material on the hydraulic conductivity and shear strength on top soil [22]. Different granite content was mixed with top soil and the results have shown that several parameters of the soil water characteristics have changed. The air entry value, the residual matric suction and the volumetric water content of the top soil mixture was seen to decrease with the increase in the granite chips content. The angle of internal friction and permeability has also increased with an increase in granite chip content whereas the rate of increase of the shear strength relative to increase in matric suction has decreased.

TABLE 2.1 A summary of some of the papers results that were conducted on soils by the addition of different contaminants:

Paper Author	soil type	contaminant added	maximum dry density	optimum moisture content	shear strength	Angle of friction	Cohesion	permeability
Khamehchiyan , 2007, Iran	silty sand	crude oil	decrease	decrease	-	decrease	no district path	decrease
	poorly graded sand	crude oil	decrease	decrease	-	decrease	no district path	decrease
	lean clay	crude oil	decrease	decrease	-	increase	decrease	decrease
Rehman, 2007, KSA	clay	crude oil	increase	decrease	increase	-	-	-
Ratnaweera, Meegoda	high plastic clay, low plastic clay, clayey silt, silty sand	glycerol	increase	increase	decrease	-	-	-
		propanol	increase	increase	decrease	-	-	-
		acetone			little decrease	-	-	-
Purj, 2000, Illinois	sand	crude oil			decrease	decrease	-	decrease
		5W30			-	-		decrease
		10W30			-	-		decrease
		20W30			-	-		decrease
Al-sanad, 1995	sand	Heavy crude	increase up to 4%	decrease		decrease	no cohesion	decrease
		light crude	-	-		decrease	no cohesion	decrease
		gas oil	-	-		decrease	no cohesion	decrease
Gueddouda, 2008, Algeria	sandy soil	bentonite	decrease	decrease	-	decrease	increase	decrease

The properties of some of the crude oil and chemicals that were used by other researchers are shown in the tables below:

TABLE 2.2 Summary of some of the Crude oil properties studied by other researchers: **[1]**

	Crude oil
viscosity (cp)	20.52
Specific gravity at 60 °F	0.8605
APA gravity at 60 °F	32.75
R.V.P (kPa)	75.9
Salt content (lb/1000 bbl)	10
Pour point °C	-18

TABLE 2.3 Summary of four types of oil properties studied by other researchers: [8]

	Benzene	Al Ritga heavy crude oil	Rawdatain Light crude oil	Al zoor gas oil
viscosity (cp)	1.74	224.3	34.3	7.9
Density (g/cc)	0.781	0.925	0.876	0.848
APA gravity at 60 °F	64.87	21	29.65	37.5
Specific gravity	0.722	0.925	0.877	0.836
Flash point (°C)	N/A	51.5	41.5	79

TABLE 2.4 Summary of water and three chemicals properties studied by other researchers: [6]

	Water	Glycerol	Propanol	Acetone
Unit Weight (kN/m^3)	9.8	12.4	7.9	7.7
Absolute viscosity (cp)	0.89	1490	1.9	0.316
Dielectric constant	78	42.5	20.1	20.7
Conductivity (mohs/cm)	$5X10^3$	N/A	N/A	N/A

2.2 Crude Oil Products

2.2.1 Leakage of Crude Oil Products

Many environmental and ecological problems are caused by oil spills. These problems may be caused accidentally or intentionally due to many different reasons in order to gain human own objectives. This pollution may affect the air, the land and the water. Land contamination by oil spill would be harmful to both environments as well as to buildings and structures resting on soil by changing its geotechnical properties which may lead to loss of bearing capacity and increase settlement in the foundation resulting in distress of loaded soil.

Recently, many researchers have been studying the effect of crude oil on the geotechnical properties of soil and their effect on the engineering applications. The gulf region is known to contain a large amount of oil and there is a chance of oil spill occurring accidentally. Oil spill may be caused due to many reasons such as transportation on land and on sea, tanker ship accidents and due to drilling of oil processes. Tanker ships accidents have caused crude oil to spill which resulted in damaging the natural ecosystems in different area such as Alaska, Galapagos Islands and France. Another example of this spill was in Kuwait during the gulf war. These accidents resulted in dumping hundreds of tons of crude oil in the open land.

The United Arab Emirates have faced some environmental disasters due to leakage of oil into its water and spreading to its coastal. On March 31- 1994, a collision in the United Arab Emirates occurred between a Panamanian-flagged supertanker Seki with the UAE tanker Baynunah causing 15,900 tons of crude oil to leak into the Arabian Sea. The oil slick polluted several beaches and threatened more than 40 kilometers of coastline. On April 2001, a spill occurred when an Iraqi tanker Zainab suspected of smuggling around 1,300 tons of fuel oil from Iraq went into trouble in the international waters. A 12 kilometers radius of oil spill reached a reserved island about 70 miles off the coast of the Emirates of Sharjah in the United Arab Emirates. This spill was said to be the worst environmental disaster in the emirates in years [23].

During the last year, more than one accident of crude oil leakage occurred around the world causing the worst environmental disasters throughout history. On 24 Jan 2010, a collision occurred between an oil tanker and two barges resulted in a major crude oil spill in the port of Arthur, Texas causing 450,000 gallons of crude oil to spill into the port. This accident had a minimal effect on the environment since 46,000 gallons were recovered and 175,000 had evaporated[24]. The Deep Horizon oil spill that occurred recently in the Gulf of Mexico was known to be the largest marine oil spill in the history. On 20 April 2010, a drilling rig explosion occurring as a result of methane gas igniting and exploding. The explosion killed 11 and injured 17 others. The leak was stopped on July 15 2010 after releasing 185 million gallons of crude oil. Marine and wildlife habitats were greatly damaged as well as the tourism and fishing industries. Attempts were made to stops leakage of oil from spreading to the beaches and wetlands and some scientist have reported of immense of dissolved oil not visible on the surface [25].

TABLE 2.5 List of Largest Oil Spills that took place in the last fifty years **[26]**

Spill / Tanker	Location	Year	Tons of Crude Oil
Gulf War oil spill	Arabian Gulf	1991	1,360,000–1,500,000
Ixtoc I oil well	Gulf of Mexico	1979-1980	454,000–480,000
Atlantic Express	Trinidad and Tobago	1979	287,000
Fergana Valley	Uzbekistan	1992	285,000
Nowruz oil field	Persian Gulf	1983	260,000
ABT Summer	Angola	1991	260,000
Castillo de Bellver	Saldanha Bay, South Africa	1983	252,000
Amoco Cadiz	Brittany, France	1978	223,000
Amoco Haven tanker disaster	Mediterranean Sea near Italy	1991	144,000
Odyssey	Nova Scotia, Canada	1988	132,000
Sea Star	Gulf of Oman	1972	115,000
Torrey Canyon	Scilly Isles, UK	1967	80,000–119,000
Irenes Serenade	Navarino Bay, Greece	1989	100,000
Urquiola	A Coruña, Spain	1976	100,000
Exxon Valdez	Gulf of Alaska	1989	35,000

Moreover, throughout the past twenty years, many accidents have occurred that caused not only crude oil to leak into the water but even diesel and kerosene. Most of these incidents were due to collisions of oil tankers carrying diesel oil. The table below lists some of the accident that occurred during the past twenty years causing leakage of diesel.

TABLE 2.6 List of accidents that caused leakage of diesel: **[23]**

Country	**Year**	**Amount of diesel leaked**	**Reason of leakage**
Thailand	6-Mar-1994	105,670 gallons	Collision between a cargo ship and an oil tanker
Malaysia	2-Nov-2002	116 tones	A Kingstin registered vessel Double Brave sank when it collided with a barge being towed by a tug boat
Ecuador	16-Jan-2001	160,000 gallons	A boat was leaking oil into the ecological sensitive waters when carrying fuel near the Ecuador Galapagos Islands
Brazil	20-Mar-2001	315,000 gallons	leakage occurred after the world's largest offshore platform sank five days after a failed rescue effort
Malaysia	28-May-2001	67 tones of fuel including diesel	an oil tanker sunk after being crashed from behind by a super tanker
Malaysia	13-Jun-2001	18 tones	A tanker laden with a toxic chemical has capsized off
USA	8-Apr-2001	35,000 gallons	A fishing vessel sunk and leaked diesel fuel in Alaska after it struck a rock
Vietnam	7-Sep-2001	19,000 tones	A Vietnamese Petrolimex tanker was hit by a Liberian-registered oil tanker
Brazil	18-Nov-2004	N/A	A cargo ship exploded and broke in half at a port

Added to that, the accident that resulted in leakage of kerosene into the seas was few. On 28 October 1990, a large barrel carrying 31,000 barrels of kerosene struck a reef in the Hudson River spilling 163,800 gallons of fuel into the water which was classified as a major spill [25].

Crude oil contains materials that may last for years and are very difficult to be cleaned. Oil spills is very difficult to control and its effect on both the environment and the physical behaviors of soil should be studied.

FIGURE 2.14 Bunker oil pollution on Ocean Beach in San Francisco [27]

FIGURE 2.15 Orange oil stain left by tide [28]

FIGURE 2.16 Oiled beach Gulf Shores [28]

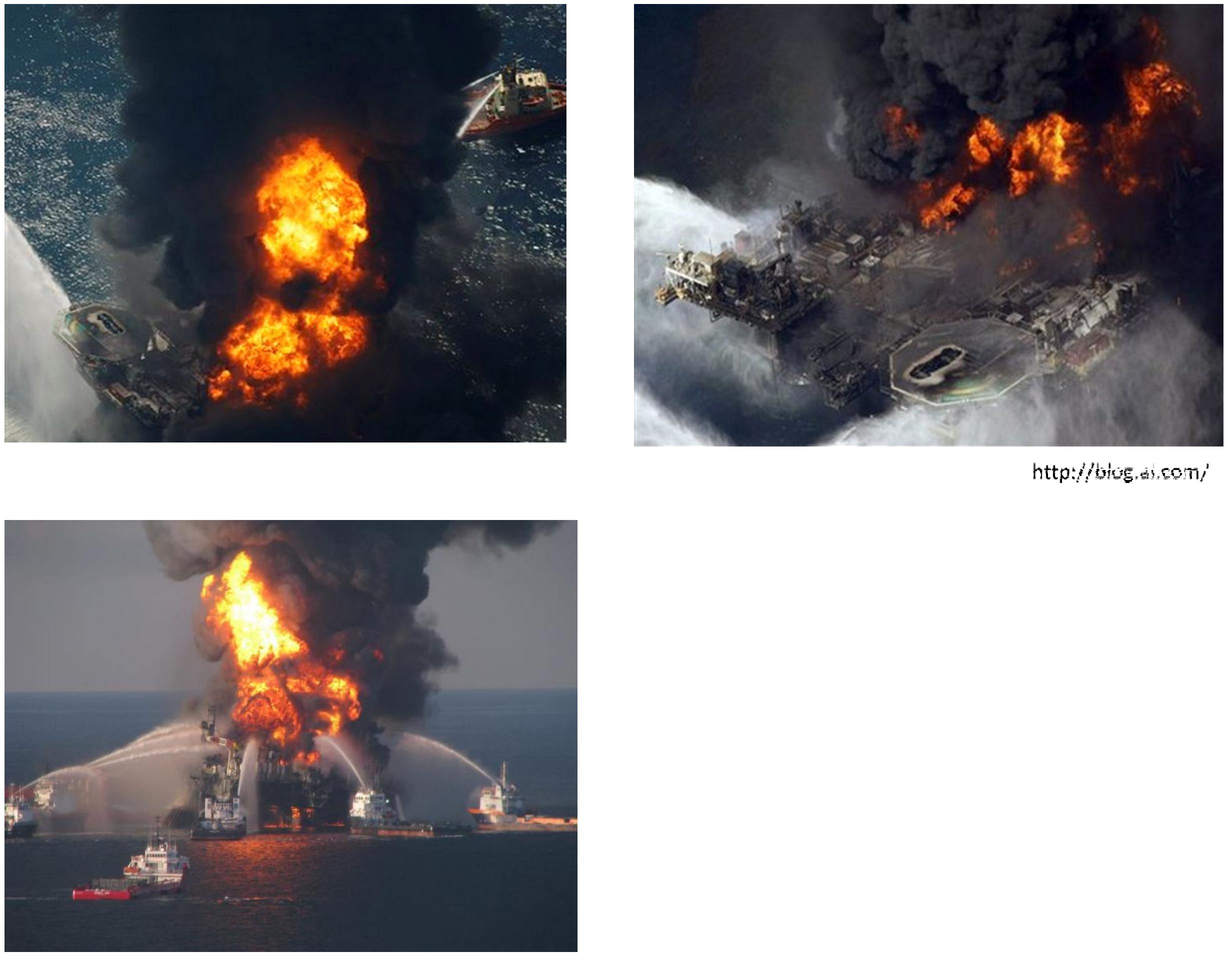


FIGURE 2.17 Coast Guard boat response crews battled the blazing remnants of the Deepwater Horizon offshore oil rig on April 21 [28]

2.2.2 Crude Oil Properties

Crude oil is a flammable liquid that occurs naturally, it consists of a complex mixture of hydrocarbons of different molecular weights, and other organic compounds. The appearance of the crude oil varies and depend on it composition. Tanker ships accidents have caused crude oil to spills which resulted in damaging the natural ecosystems in different area such as Alaska, Galapagos Islands and France. In this study, the effect of crude oil products – kerosene and diesel - on the geotechnical properties of granular sand was investigated. Different percentages of crude oil products were added to the soil and tested separately for direct shear and permeability tests.

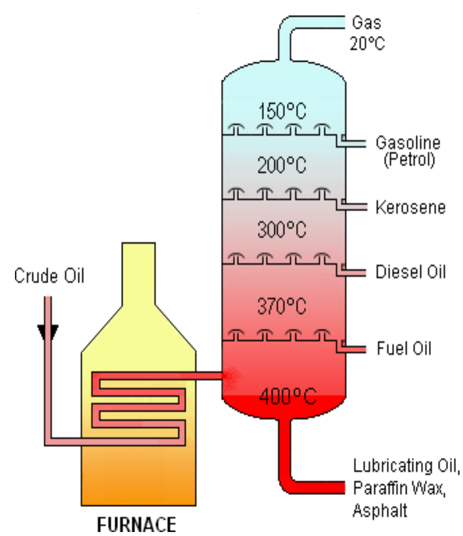


FIGURE 2.18 Fractional Distillation of crude oil [26]

Diesel is produced from fractional distillation of crude oil typically at 200–380°C. The density of diesel is about 0.85 kg/l and it has a high flash point greater than 55°C. Diesel is composed of about 75% saturated hydrocarbons, and 25% aromatic hydrocarbons. Diesel is used as a fuel for diesel engines [26].

Kerosene is a combustible hydrocarbon liquid. It is a thin, clear liquid formed from hydrocarbons which is immiscible in water. It is used in insecticide spays, in powering jet engine aircraft and in rockets and is most commonly used as a heating fuel. Kerosene is produced from crude oil by fractional distillation between 150 and 275 °C. The density of kerosene is between 0.78 and 0.81 g/cm3. And its flash point is between 37 and 65 °C. Kerosene is recovered from substances such as coal, oil shale and wood. It is a liquid mixture which is used as a fuel in internal combustion engines. Kerosene is composed of aliphatic hydrocarbons. Kerosene is different and less flammable than gasoline; it is a lubricant, not volatile, and it is extremely stable when stored. Kerosene could be stored in plastic containers since it expands and contract slightly with ambient temperatures [26].

2.3 SOIL CLASSIFICATION

2.3.1 General

Soil is natural body that consists of layers of minerals constituents which differs from its original material in its physical, chemical and mineralogical characteristics. Soil is composed of particles of broken rocks that were changed as a result of chemical and environmental processes such as weathering and erosion. Soil particles pack loosely creating a soil structure filled with pores spaces. Most soils have a density between 1 g/cm³ and 2 g/cm³ [29].

Most structures such as buildings, bridges and highways rests directly on soil and therefore analyzing the soil and designing the foundation is important for the structure to be safe from collapsing. Knowing the properties of the soil in the construction location is important since different construction sites may have different soil conditions and properties. Soil samples are collected from the construction location and sent to a soil laboratory to find their engineering properties.[30]

Soil classification systems divide the soil into groups and subgroups based on the common engineering properties. The most common classification systems that are used in soil classifications are the American Association of State and Transportation Officials (AASHTO) and the Unified Soil Classification System. According to the Unified Classification System, soil grain size can be divided into three separate size limits as shown below: [31]

TABLE 2.7 Soil separate size limits [31]

Classification	Grain Size
Gravel	75mm to 4.75mm
Sand	4.75mm to 0.075mm
Silt and Clay	< 0.075mm

Each of these types of classification for soil has different result when tested. Added to that, some experiments cannot be conducted to some type of soils. The American Society for Testing and Materials (ASTM) has given different definitions for various types of soils. They defined sand particle as particle of rock that would pass sieve No. 4 (4.75-mm) and is retained on sieve no. 200 (2.00-mm). Sand has been given three subdivisions: coarse, medium and fine [30] as shown in table 3.

TABLE 2.8 Soil particle-size ranges [31]

Component	Size Range
Cobbles	Above 3 inches
Gravel Coarse Fine	3 inches to No. 4 sieve 3 inches to 3/4 inch 3/4 inch to No. 4 sieve
Sand Coarse Medium Fine	No. 4 to No. 200 sieves No. 4 to No. 10 sieves No. 10 to No. 40 sieves No. 40 to No. 200 sieves
Fines (clay or silt)	Below No. 200 sieve (no minimum size)

Different procedures are used for identifying fine grained and coarse grained soil. Fine grained soils can be identified by using their dry strength, dilatancy, toughness, and plasticity. Soil particle can be described by their angularity, shape and color. Their angularity would tell us if the particle is angular, sub-angular, sub-rounded and rounded. The shape would describe if it is flat or elongated. The color would be important in identifying the organic soils. Other soil classifications are the odor, the moisture content, the HCL reaction, consistency, structure, range of particle size, maximum particle size, and hardness [30].

When 35 percent or less of the soil passes No. 200 (75-µm) sieve, it is known as granular material. In my researches, three different types of granular sand will be selected based on their grain size distribution. The soil in this research will be classified using the Unified Soil Classification System in ASTM D-2487.

2.3.2 Specific Gravity of the Soil

The specific gravity of a soil is required in many of the calculations in soil mechanics. Therefore knowing the specific gravity of a given soil would help us in knowing the minerals present in a specific soil. The specific gravity of soil is the ratio of the unit mass of solids in the soil to the unit mass of water. Most of the values of the specific gravity of soil fall in the range of 2.6 to 2.9.

$$G_s = \frac{M_s}{V_s \, p_w} \tag{2.1}$$

2.3.3 Sieve Size Analysis of the soil

The particle size distribution of the soil can be determined by two methods which are the sieve size analysis for particles sizes larger than 0.075 mm diameter and the hydrometer analysis for particles sizes smaller than 0.075 mm diameter. In this research, the sieve size analysis was used since the soil used has particle diameter size larger than 0.075 mm. The particle size distribution is used to determine four different parameters. These parameters are the effective size (D_{10}), the uniformity coefficient (C_u), the coefficient of gradation (C_c), and the sorting coefficient (S_0).

$$C_u = \frac{D_{60}}{D_{10}} \tag{2.2}$$

$$C = \frac{(\ _{30})^{2}}{0\ 60} \tag{2.3}$$

$$_0 = \frac{D}{D_2} \tag{2.4}$$

D60, D30, D10 are the particle diameters that correspond to certain percent passing of a given soil and they can be obtained from the grain size distribution curve. Using the Unified Soil Classification System, our soil can be classified. The particle size distribution curve shows not only the particle sizes but also the type of distribution of various particles. Poorly graded soils are those with a narrow range of particle sizes and well graded soils are those with a wide range.

The particle size distribution curve is used to determine the percentage of gravel, sand, silt and clay size particles present in the soil. It would also show the type of distribution of different particle sizes. Three different curves can be obtained from a particle distribution curves. The first is called the poorly graded soil were the soil grains are of the same size. The second is the well graded curve which has the coefficient of uniformity greater than 6 and coefficient of curvature between 1 and 3. That third curve is the gap graded and has a combination of two or more uniformly graded fractions.

2.4 Soil Compaction

The soil at some of the construction sites may not be suitable for supporting structure such as buildings, bridges, highways and dams. In some cases it may be very loose indicating a large elastic settlement. Therefore, we need to increase the density of the soil in order to increase its unit weight and shear strength. Increasing the density of the soil is desirable in earthwork construction and in building foundation. Compaction is a process of increasing the bulk density of the soil by removing the air from it. In order to determine the maximum dry density and the optimum moisture content of a given soil sample, two common tests can be used namely the Standard Proctor compaction test and the modified Proctor compaction test.

TABLE 2.9 Standard Proctor Compactor Specification [32,33]

	Standard Compaction test [32]	**Modified compaction test** [33]
Volume of Mold	0.0009438m^3	0.0009438m^3
Hammer	24.4 N	44.5 N
Height of fall	305 mm	457 mm
Compaction effort	600 kN-m/m^3	4*600 kN-m/m^3
No. of Soil layer in the mold	3	5
No. of blows for each layer	25	25

Compaction is the densification of the soil by removing the air from it and for doing this mechanical energy is required. The dry unit weight is the term used in the measuring compaction of a soil. When water is added to the soil, it acts as a softening agent and this allows the particles to slip and slide to densely packed positions. The dry unit weight first increases when the moisture content is increased. When the water content in the soil is equal to zero, the wet unit weight would be equal to the dry unit weight. Up to a certain amount of moisture content, any increase in moisture content would decrease the dry unit weight of the soil. The water content at which the maximum dry density is attained is known as the optimum moisture content.

This test determines the optimum amount of water to be mixed with soil in order to obtain maximum dry density for a given soil sample. For compaction of any particle soil in the field, the engineer can vary water content, amount of compaction and type of compaction. In

1933, Proctor have shown that there existed a unique relationship between the moisture content and the degree of dry density to which a soil can be compacted, and for that compacted energy applied on the soil there would a moisture content known as "optimum moisture content", by which the soil achieved its maximum dry density. Compaction would increase soil unit weight, which would produce three important effects. These are: an increase in shear strength, a decrease in future settlement and a decrease in permeability [30].

Moisture content has a great influence on the degree of compaction obtained. Aside from moisture content, there are other factors that affect compaction such as the soil type and the compaction effort. Soil type would include the grain size distribution, specific gravity of the soil, shape of the soil grain and the minerals present in the soil and these would affect the optimum moisture content and the maximum dry density. It is known that for sand, the dry unit weight has a general tendency to decrease first and then to increase to an optimum value with further increase in moisture content. This decrease at the beginning is due to the capillary tension effect. The capillary tension effect prevents the tendency of the soil particle to move around and be densely compacted.

Compaction curves that are obtained can be of different shapes. Lee and Suedkamp studied the compaction curves of 35 samples and came up with four shapes of compaction curves. These shapes are bell shaped, 1-1/2 peak, double peak, and odd shape. The 1-1/2 peak and the double peak are obtained from sands that have a liquid limit less than 30; this can be seen from the results obtained in this research.

The other thing that would influence the degree of compaction is the compaction effort. If we change the compaction effort per unit volume of soil, the wet unit weight curve would change. As the compaction effort increased, the maximum dry unit weight would also increase whereas the optimum moisture content would decrease to some extent. The degree of compaction is not proportional to the compaction effort.

Compaction in the field is usually done by rollers and mostly for most specifications, it is instructed to achieve a compacted dry unit weight of 90% to 95% of the maximum dry unit weight obtained in the laboratory.

2.5 Shear Strength

Shear strength of a soil is the maximum strength at which plastic deformation occurs due to an applied shear stress. Strength is the maximum stress that a material can sustain. If this stress exceeds the strength, the material would fail. Shear failure in a soil occurs when the shear stresses are large enough to let the particles roll and slide against each other. The shear strength would mainly depend on the interaction between the particles, not on their internal strength. These interactions can be divides into frictional and cohesive strength. Considering the shear strength in many of our geotechnical engineering problems is important. This includes: earth slopes, structural foundation, retaining wall, and tunnel lining and highway pavements.

Mohr (1990) presented a theory for rupture of materials that says a material fails because of a critical combination of normal stress and shearing stress. The Mohr-Coulomb failure criteria was presented in an equation as

$$r = c + cr \tan 0 \qquad (2.5)$$

The value of cohesion for sand and inorganic silt is 0. The shear strength parameter of a soil can be determined by two methods: the direct shear test and the triaxial test. The direct shear test is one of the oldest strength tests for soils. The shear strength of the soil sample can be determined using a displacement controlled direct shear apparatus. The horizontal displacement, vertical displacement and the shear force will be determined using direct shear machine. The experiment will be carried according to ASTM D-3080 specifications. The results would give us the angle of internal friction and the cohesion of the soil.

2.6 Permeability

Soil particles contain void spaces between them that allow water to pass through them. Knowing how much water flows thorough the soil per unit time would help us in the design of earth dams, and help us to determine the quantity of seepage under the structure and in dewatering the foundation before and after construction [31]. The table below shows the hydraulic conductivity for various soils:

TABLE 2.10 Range of the Hydraulic conductivity for various soils [31].

Type of soil	**Hydraulic conductivity, k (cm/sec)**
Medium to coarse gravel	Greater than 10^{-1}
Coarse to fine sand	10^{-1} to 10^{-3}
Fine sand, silty sand	10^{-3} to 10^{-5}
Silt, clayey silt, silty clay	10^{-4} to 10^{-6}
Clays	10^{-7} or less

The hydraulic conductivity can be determined by the constant head or the falling head method. The constant head is more suitable for granular soil while falling head test is used for low permeable soils such as silt and clay.

Studying the geotechnical properties of soil would help the geotechnical engineer to have a better knowledge of soil properties and how to deal with changes in its behavior. It may also help the structural engineer in his design process since it may affect the soil structure interaction in the soil and the foundation.

CHAPTER 3 EXPERIMENTAL WORK AND TESTED MATERIAL

3.1 Basic properties of soil sample and crude oil products

3.1.1 Soil Classification

In the first part of the research, classifying the soil was an important issue. In order to study the effect of crude oil products on sandy soil, it would be important to find soils with different gradations. Sieve size distribution was used to measure the gradation of the sand. The sieves are selected according to ASTM D-422 standard specifications. A known weight of the sample was passed through various known sieve sizes of 4.75mm, 2.36mm, 1.18mm, 0.6mm, 0.3mm, 0.212mm, 0.15mm, 0.106mm, and 0.075mm. The meshes were arranged in downward decreasing diameters. The sieves were vibrated for a period of time in order to make sure that each soil particle would attain it sieve correctly. The retained sand on each sieve was weighted using a balance and converted to a percentage of the total soil sample. The results were presented by semi-logarithmic plot known as particle size distribution curve. From this method the maximum soil diameter was found and we differentiated between the different soils samples according to their grain size distribution. This was done for the three different soils and they were classified using the Unified Soil Classification System.

FIGURE 3.1 Sieve used for a gradation and size test [34]

TABLE 3.1 Procedure for obtaining the percentage of soil passing different sizes of sieves:

Sieve No.	Sieve size (mm)	% passing		
		Sand-1	Sand-2	Sand-3
4	4.75	100	99.73	100
8	2.36	100	99.45	99.87
16	1.18	99.88	97.73	98.76
30	0.6	99.69	60.92	75.63
40	0.425	99.46	42.17	65.78
50	0.3	92.56	27.48	55.80
70	0.212	42.93	15.26	29.07
100	0.15	15.38	4.53	6.82
140	0.106	2.68	0.72	0.86
200	0.075	0.58	0.23	0.17

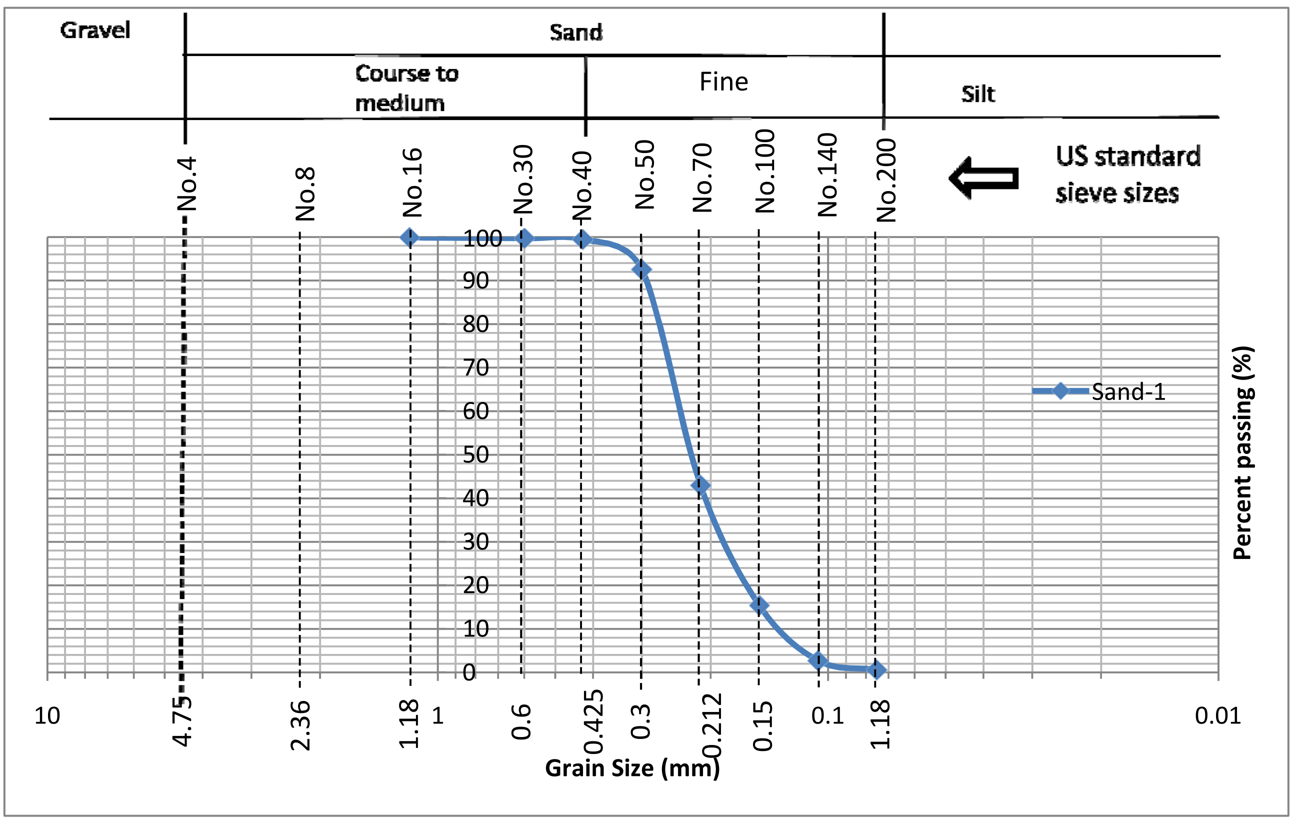


FIGURE 3.2 Sieve Size analysis for Sand-1

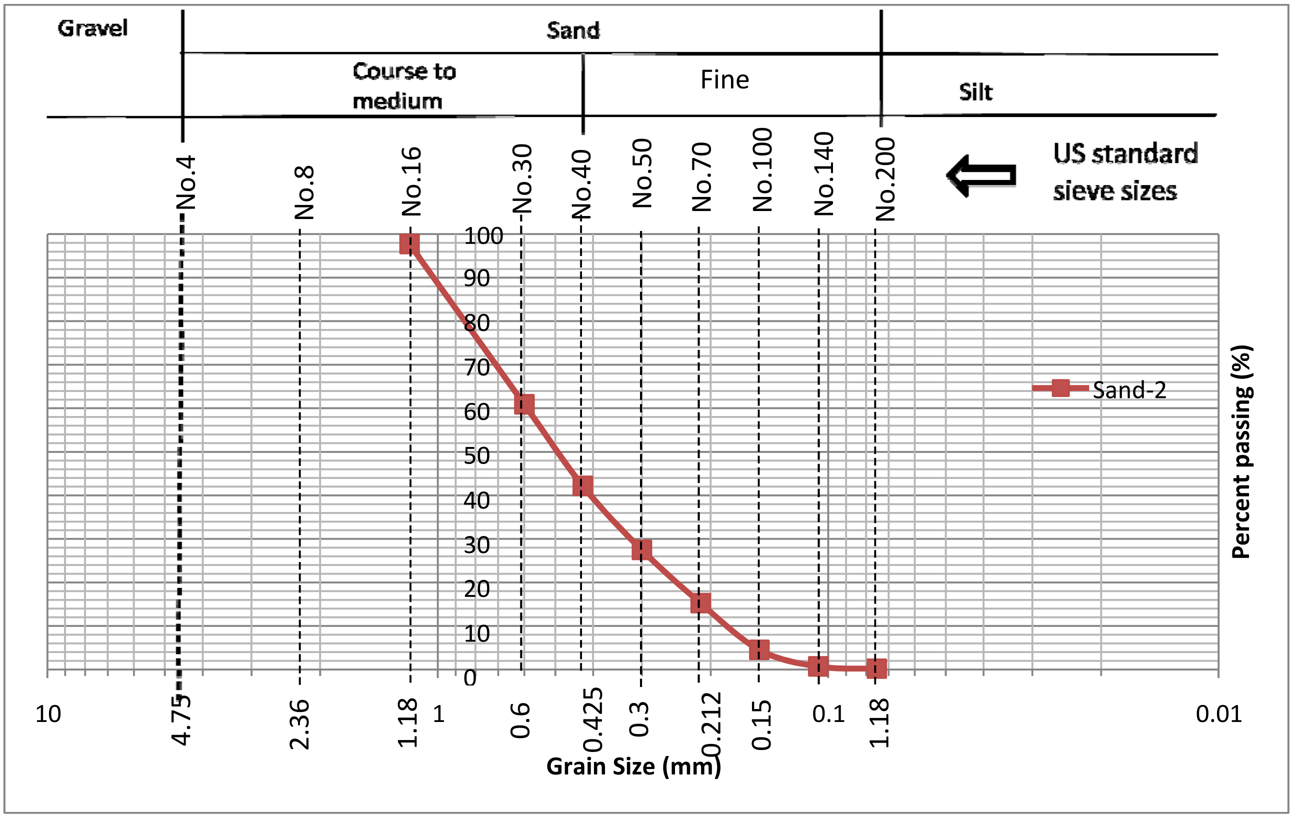


FIGURE 3.3 Sieve Size analysis for Sand-2

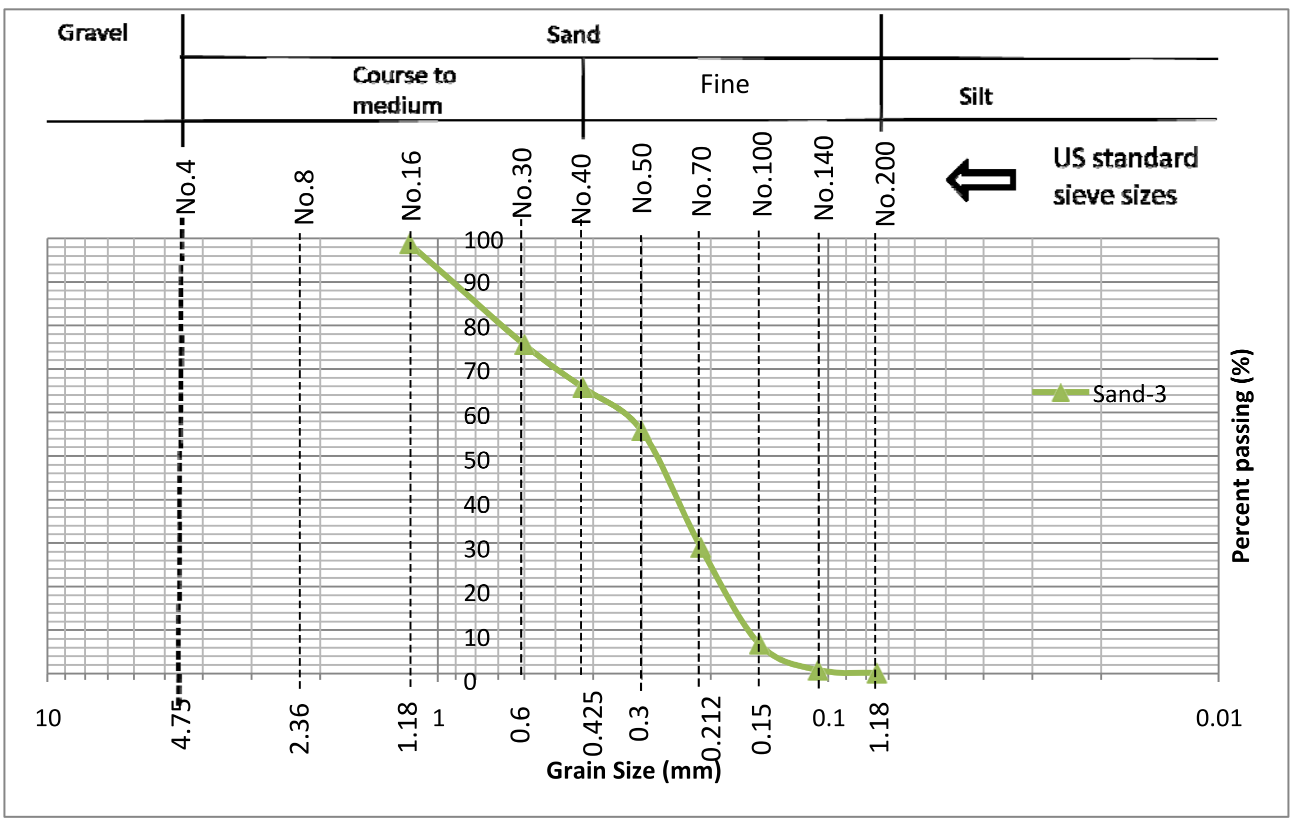


FIGURE 3.4 Sieve Size analysis for Sand-3

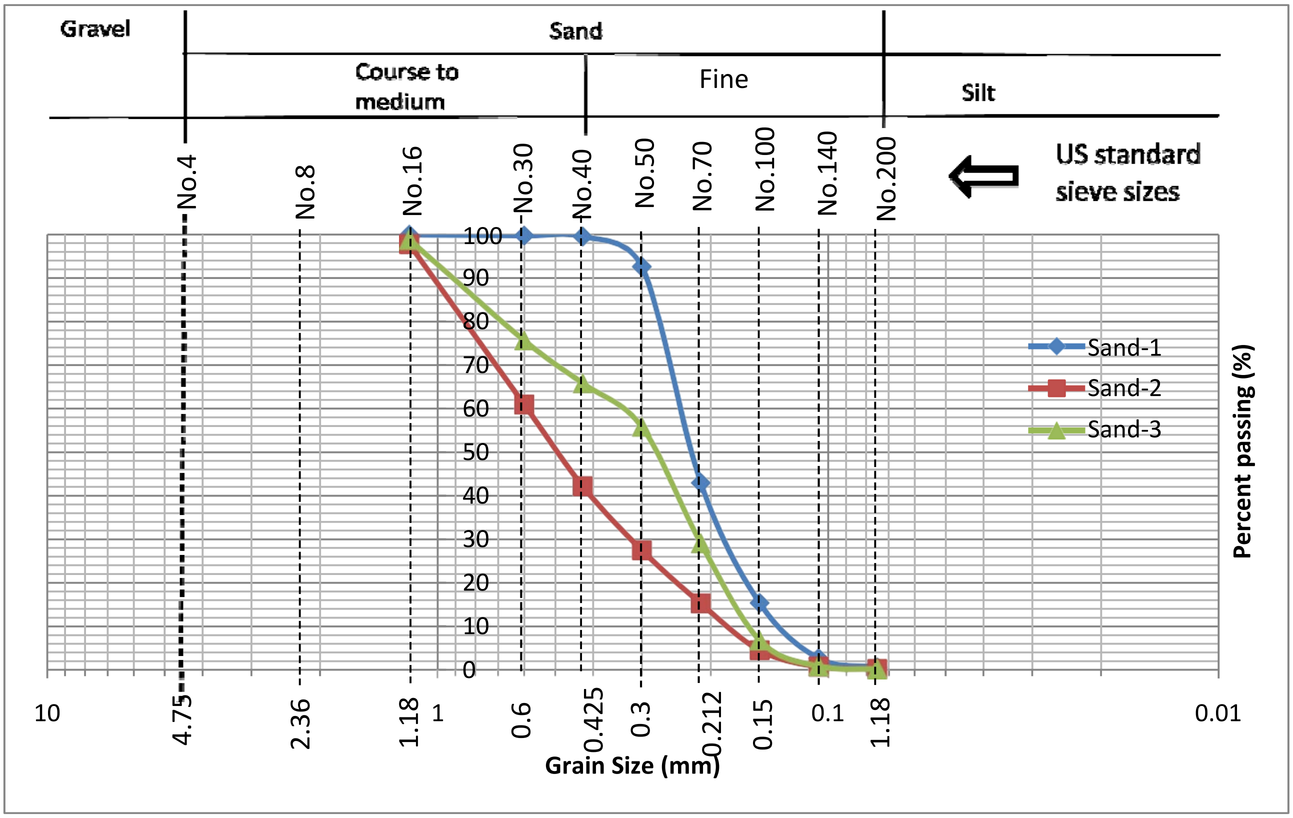


FIGURE 3.5 Sieve Size analysis for three different soils

From the Unified soil classification chart above, the three soil sample were classified step by step. Since 50% or more of the soil was retained on No. 200 sieve, it is a coarse grained soil. After that, we do the sieve analysis and check which has a greater percentage, the sand or the gravel. Since the percentage of sand is larger, we go to the next step which is finding the percentage of soil that pass the No. 200 sieve. Since less than 5% of the soil has passed the No.200 sieve, the soil is either well graded sand or poorly graded sand. To obtain our final result, we need to find the coefficient of gradation (C_c) and the uniformity coefficient (C_u) which should be obtained from using the grain size graph.

For well graded sand, the C_u must be >6 and the C_c must be > or = 1 and < or = 3 (SW)

For poorly graded sand, the C_u must be < or = 6 and/or the C_c is <1 or >3 (SP)

TABLE 3.2 Results obtained from the Sieve Size analysis test:

	Sand-1	Sand-2	Sand-3
D_{60}	0.25	0.6	0.33
D_{30}	0.19	0.32	0.22
D_{10}	0.15	0.19	0.17
C_u	1.67	3.16	1.94
C_c	0.96	0.90	0.86
Soil Classification	Poorly graded sand (SP)	Poorly graded sand (SP)	Poorly graded sand (SP)

From the values obtained it was noticed that all of the values of C_u were less than 6 and all the values of C_c were less than 1. Therefore, it was concluded that the three soil samples were poorly graded sands with different gradations.

3.1.2 Specific Gravity of the Soil

TABLE 3.3 Procedure for obtaining the specific gravity of the sands:

	Sand-1	Sand-2	Sand-3
weight of empty pycnometer (M_p), g	124.53	124.53	124.53
wt. of soil (M_x), g	100	100	100
wt. of pycnometer + water (M_{pw}), g	621.82	621.82	621.82
initial Temperature, °C	23.3	23.3	23.3
wt. of pycnometer + water + soil (M_{pws}), g	684.19	686.37	684.93
final Temperature, °C	23.7	23.5	23.5
density of water at T_x, g/cm³	0.99739	0.99745	0.99745
density of water at T_i, g/cm³	0.99751	0.99751	0.99751
Wt. of pycnometer + water (M_{pw}) at T_x, g	621.7602	621.7901	621.7901
K (conversion factor)	0.99915	0.9992	0.9992
Specific Gravity of soil (G_s)	2.66	2.82	2.71

$$M_{pw}(\text{at } T_x) = \frac{\text{density of water at } T_x}{\text{density of water at } T_i}[M_{pw}(\text{at } T_i) - M_p] + M_p \quad (3.1)$$

$$G_s = \frac{KM_s}{M_s + M_{pw}\,(\text{at } T_X) - M_{pws}} \quad (3.2)$$

The first step for calculating the specific gravity of the soil is to put the sample in a pycnometer, this is then filled with water and care is taken to eliminate air bubbles. Then we determine the mass of pycnometer when filled with water and soil and then we measure the temperature of the water and soil mixture. By knowing the temperature of the soil and water mixture, the mass of pycnometer when filled with water can be found from the calibration of the pycnometer. By determining all these date, the specific gravity of the soil was found for the three soil samples.

3.1.3 Crude Oil Products

In order to study the effect of crude oil products on the geotechnical properties of sandy soil, two crude oil products were chosen in this research. The crude oil products were diesel and kerosene.

The diesel that was used in this research was brought from the Emirates Petron station located in the United Arab Emirates. The basic properties of the diesel used are shown in TABLE 3.4.

TABLE 3.4 The basic properties of the diesel that was used in this study:

Property	LIMIT	Units
Appearance	Clear	-
Colour, ASTM	Max 2.0	-
Ash	Max 0.01	mass %
Calorific Value (Gross)	Report	Btu/lb
Carbon Residue (10%-MCRT)	Max 0.2	mass %
Acid Number, Strong Total	Max Nil Max 0.1	MgKOH/g MgKOH/g
Cetane Index	Min 52	-
Corrosion, copper strip	Max 1	-
Density at 15°C	Min 0.82 Max 0.845	°C
Disstillation, 90% recovery at	Max 357	°C
Flash point, PMCC	Min 65	°C
Pour Point	Report	°C
Cloud Point	Max +15	°C
Sediment and water	Max 0.05	vol %
Sulphur, Total	Max 500	mg/kg
Viscosity at 40°C	Min 2.0 Max 4.5	cSt
Total Aromatics	Min15 Max 25	mass %
Poly Aromatics Hydrocarbon (PAH)	Max 11	mass %
Lubricity (HFRR)	Max 460	microns
Oxidation Stability	Max 25	g/m^3

The kerosene that was used in this research was brought from the ADNOC Petron station located in the United Arab Emirates. The basic properties of the kerosene used are shown in TABLE 3.5.

TABLE 3.5 The basic properties of the kerosene that was used in this study:

Property	LIMIT	Results	Units
Acid Number, Strong	Max Nil	Nil	mgKOH/g
Appearance	Clear	Clear	-
Burning Test	Max 2.0	15	mg/Kg
Colour Saybolt	Min 25	28	-
Corrosion, Copper Strip	Max 1	1	-
Density at 15°C	Min 0.775 Max 0.83	0.79	Kg/l
Distillation vol recovered at	Max 200	176	°C
Distillation Final Boiling Point	Max 300	258	°C
Sulphur, Mercaptan	Max 0.003	0.0018	mass %
Flash Point, ABEL	Min 38	41	°C
Odour	Marketable	Marketable	-
Smoke Point	Min 25	26	mm
Sulphur, Total	Max 3000	100	ppm/wt
Viscosity		2.71	centistokes

3.1.4 Soil Compaction

In all research experiments, the maximum dry unit weight and the optimum moisture content was chosen to be the base conditions. Therefore, in order to determine these values, the standard proctor compaction test was used. Proctor (1933) developed this test in connection with the construction of earth fill dams in California. This test determines the optimum amount of water to be mixed with soil in order to obtain maximum compaction for a given soil sample. The standard sizes of the apparatus used for the test were based on ASTM D-698 using method-A.

Known water content was added to the soil and mixed thoroughly. The soil was placed into a compaction mold having a volume of 0.0009438 m^3. The soil was compacted in three layers with each layer being compacted by 25 blows with a 24.4 N hammer dropped from a height of 305 mm, subjecting the soil to a total compactive effort of about 600 kN-m/m^3. The wet unit weight of compaction was calculated as weight of the compacted soil over volume of the mold.

The resulting dry unit weight was determined by taking a sample from the compacted sand and it was left to dry in an oven for 24 hours. By knowing the moisture content, the dry unit weight was calculated by

$$y_d = \frac{y}{1+\frac{w(\%)}{100}} \tag{3.3}$$

The procedure was repeated for a number of water content to get a relation between the dry unit weight and water content. The data was plotted on a graph and from the compaction curve the maximum dry unit weight and the optimum water content was determined [35].

This was done for the three different soils and their and the values that were obtained are shown in TABLE 3.6.

TABLE 3.6 Results obtained from the Standard Proctor Compactor Test:

	Maximum Dry Unit Weight (kN/m^3)	Optimum Moisture Content
Sand-1	16.7	4%
Sand-2	15.6	16%
Sand-3	16.46	14%

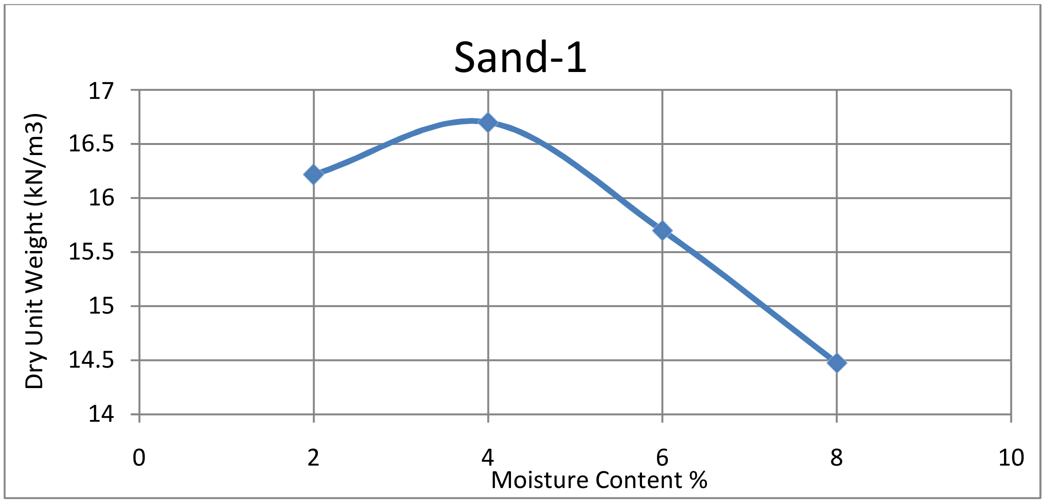


FIGURE 3.6 Compaction curve for Sand-1

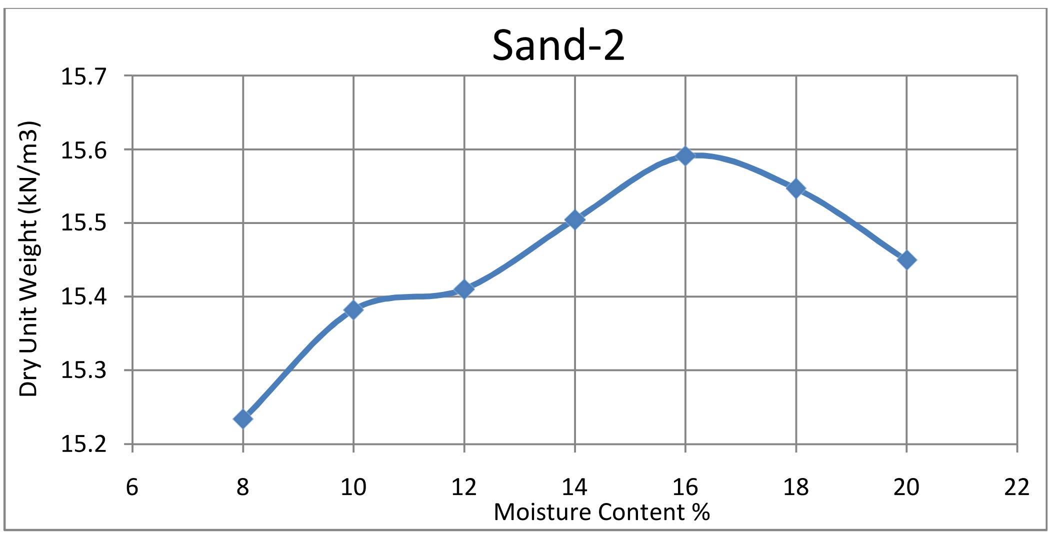


FIGURE 3.7 Compaction curve for Sand-2

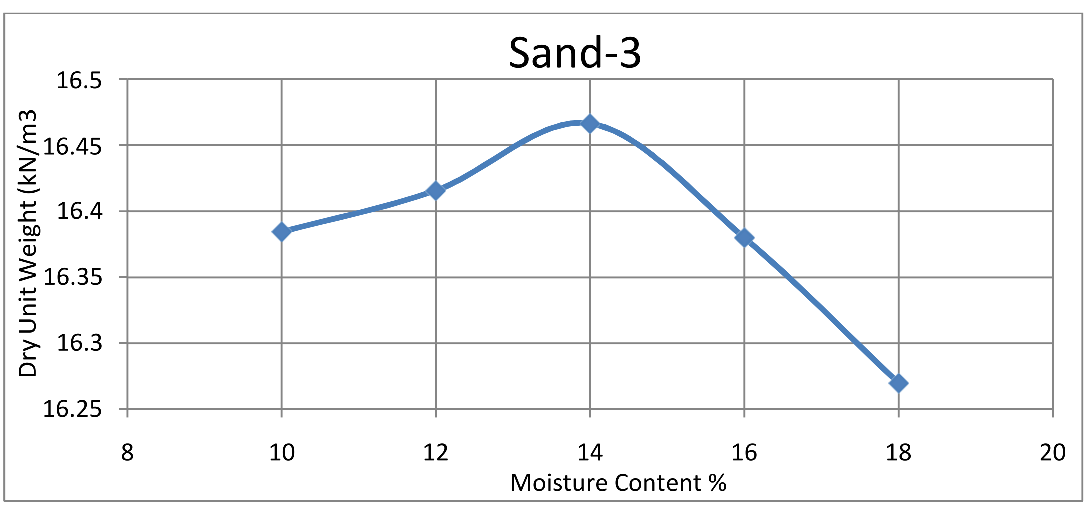


FIGURE 3.8 Compaction curve for Sand-3

Standard Compaction tests were carried out on the three soil samples. The results were plotted in the form of dry density versus water content.

The dry unit weight for sand-1 increases first when the moisture content is increased. Up to 4% moisture content and 16.7 kN/m³ dry unit weight, any increase in moisture content would decrease the dry unit weight of the soil. Sand-1 has the highest maximum dry unit weight among the three soil sample and has the widest range of change in dry unit weight with the addition of water.

Sand-2 has a maximum dry unit weight of 15.6 kN/m³ at 16 % optimum moisture content and sand-3 has a maximum dry unit weight of 16.46 kN/m³ at 14 % optimum moisture content. The dry unit weight for sand-2 and sand-3 has a general tendency to decrease first and then to increase to an optimum value with further increase in moisture content. This decrease at the beginning is due to the capillary tension effect. The capillary tension effect prevents the tendency of the soil particle to move around and be densely compacted. This effect is usually found in poorly graded sands. Added to that, sand-2 and sand 3 has a small range of change in dry unit weight with the addition of water.

3.2 Sample preparation

After particle size classification soil compaction, each soil sample was divided into thirteen parts and they were dried by oven. Then the samples were mixed with crude oil product (diesel and kerosene) in the amount of 0%, 2%, 4%, 6%, 8%, 10% and 12% by weight by the dry soil samples. The mixed samples were put in a closed container for a few days to allow for possible reaction between the soil and the crude oil products. Therefore, 39 mixed samples were prepared. These mixed soil samples were used during the direct shear and the permeability tests.

3.3 Program of laboratory testing

3.3.1 Shear Strength

The direct shear test is one of the oldest strength tests for soils. The shear strength of a soil is an important property since it controls the bearing capacity of the foundation system of a structure. In this experiment, the shear strength of the soil sample was determined using a displacement controlled direct shear apparatus found in the Geotechnical Engineering Lab in the American University of Sharjah. The horizontal displacement, vertical displacement and the shear force were determined using direct shear machine. The experiment was carried according to ASTM D-3080 standard specifications. The shear box was prepared as shown in TABLE 3.7. Then the sand was added in 3 layers and each layer was compressed using a compaction tool. The shear box was inserted into the machine and a normal stress was applied to it. A graph is drawn of shear stress versus the horizontal displacement. Each prepared soil sample was tested using normal stresses of 27.5, 55 and 110 kN/m^2 and from these three results a graph was drawn for the normal stress versus the shear stress. This gave us the angle of internal friction and the cohesion component [36].

This test was repeated for the three soil samples separately with different percentages of crude oil product (kerosene and diesel) of 0%, 4%, 8% and 12% by weight by the dry soil samples.

TABLE 3.7 Direct Shear Box Specifications used in the Research

Direct Shear Box specifications		
height	3.03	cm
width	6	cm
base	6.00	cm
volume	109.08	cm^3

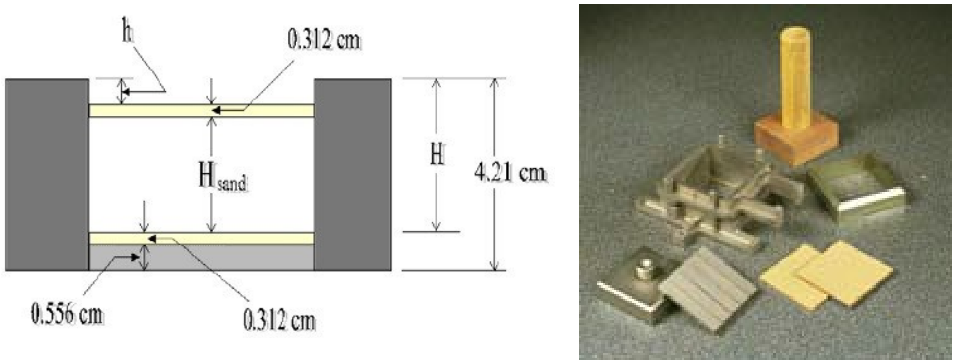


FIGURE 3.9 Shear box Dimensions [36]

FIGURE 3.10 Direct Shear Apparatus

In order to obtain our results on the maximum dry unit weight and on the optimum moisture content, the quantities shown in TABLE 3.8 were used during the experiments.

TABLE 3.8 Quantities that were required to be used for the direct shear test for diesel and kerosene:

	Sand-1	Sand-2	Sand-3
Water content (%)	4%	16%	14%
Dry unit weight (kN/m^3)	16.7	15.6	16.46
mass of soil required (g)	167.17	156.00	164.81
water required (mL)	6.69	24.96	23.07
4% oil (mL)	6.69	6.24	6.59
8% oil (mL)	13.37	12.48	13.18
12% oil (mL)	20.06	18.72	19.78

3.3.2 Permeability

Permeability of the soil is defined as easiness in which water flows through a specified soil. The pore sizes and their connectivity is what determine whether the soil has a high or low permeability. Water would flow easily through soil with large pore and slowly though soil with small pore. There are two tests to determine the coefficient of permeability in the laboratory. The constant head test and the falling head test. In this study, the constant head method was used since the soil is a granular. The experiment was carried according to ASTM D-2434 standard specifications. During the experiment, the prepared soil sample was added and compacted in three layers inside the apparatus. By knowing the volume of the apparatus, a known mass of the prepared soil sample was found from the soil dry unit weight. This soil was forced inside the apparatus to fill its volume and to get an equilibrium compaction for all the tests. Then the apparatus was connected to the two outlets of the manometer. Filter was added on each of the outlet in order to prevent the soil from flowing through the manometer. The cross sectional area and the length between the two outlets of the manometer was measured and was given as 7 cm. The experiment started by releasing the water inside the manometer and leaving it for one whole day until the heads on the manometer remain stable. After getting the constant conditions, the heads at the manometer and the time it takes to pass through the soil were recorded and the quantity of discharged water is measured. Recording and measuring the results was done three times for each test at different timings. From this the coefficient of permeability was determined. This test was carried out for the three soil sample separately with different percentages of crude oil products (kerosene and diesel) of 0%, 4%, 8% and 12% by weight by the dry soil samples.

$$= \frac{\quad}{Ath} \tag{3.4}$$

TABLE 3.9 Permeability Apparatus Specifications used in the Research

Permeability Apparatus specifications		
height	23	cm
Diameter	7.5	cm
Area	44.18	cm^2
volume	1016.11	cm^3

TABLE 3.10 Quantities that were required to be used for the Permeability test:

	Sand-1	Sand-2	Sand-3
water content (%)	4%	16%	14%
Dry unit weight (kN/m^3)	16.7	15.6	16.46
mass of soil required (g)	1730.22	1614.65	1705.80
water required (mL)	69.21	258.34	238.81
2% oil (mL)	34.60	32.29	34.12
4% oil (mL)	69.21	64.59	68.23
6% oil (mL)	103.81	96.88	102.35
8% oil (mL)	138.42	129.17	136.46
10% oil (mL)	173.02	161.47	170.58

FIGURE 3.11 Constant Head Permeability Cell and Apparatus [37]

FIGURE 3.12 Constant Head Apparatus [37]

CHAPTER 4 RESULTS

4.1 SHEAR STRENGTH

4.1.1 Sand-1

The results that are shown in the stress strain curve are the readings taken from the experiments that were conducted. From these results, the angle of internal friction, apparent cohesion and the shear strength of our soil samples were found.

From the results, it was seen that as the percentage of crude oil products increased, the angle of internal friction of the sand would decrease. A slightly greater decrease in the friction angle was noticed for the addition of kerosene than that with the addition of diesel. This reduction was because diesel and kerosene would act as a lubricant and would allow the soil particles to slip and slide against each other. Added to that crude oil products are more effective in reducing the friction between the soil particles resulting in a reduction in the spacing between the soil grains. As a result, the angle of internal friction of the soil samples would decrease.

An apparent cohesion was found and increased gradually as diesel and kerosene were added to the soil. The maximum increase was noticed at 8 percent of crude oil product being added and the value of cohesion was found to be around 5 kPa. When more than 8 percent was added, less increase in cohesion was noticed. The addition of crude oil products (diesel and kerosene) to the sand has shown a very close behavior on the graphs. The apparent cohesion of the sand was due to the capillary tension inside the voids. Added to that, having oil in soil prevents the water to contact the particles as a result of oil hydrophobia. Therefore, with oil inside soil, the capillary tension decreased and so the apparent cohesion of the soil increased. Moreover, this can also be explained as the result of viscosity and inherent cohesion of the crude oil products.

At low normal stress, as the percentage of crude oil products added to the soil is increased, the shear strength also increased. This increase in shear strength becomes less as more than 8 percent of crude oil product was added. The maximum increase in shear strength was noticed at 8 percent of crude oil product being added.

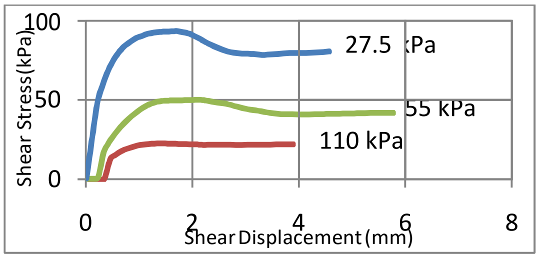
At high normal stress, as the percentage of crude oil products added to the soil is increased, the shear strength remained the same up to 8 percent being added and then it started to decrease.

It was noticed that as we increase the normal stress, the shear strength of the soil would show more noticeable reduction. This increase in shear strength at low normal stress despite the reduction in the angle of internal friction was due to the apparent cohesion that was noticed in the soil.

4.1.1.1 Stress-strain graphs for Sand-1

FIGURE 4.1 Stress-strain curves for Sand-1 with different % of diesel and kerosene added at different normal stresses of 27.5, 55 and 110 kPa

0%



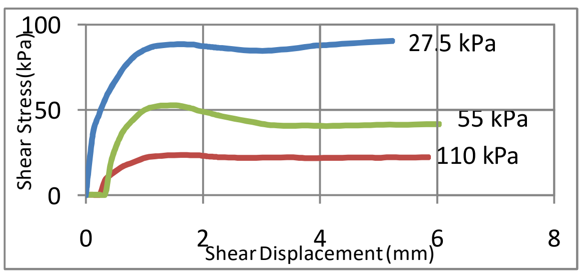
Normal stresses:

27.5 kPa

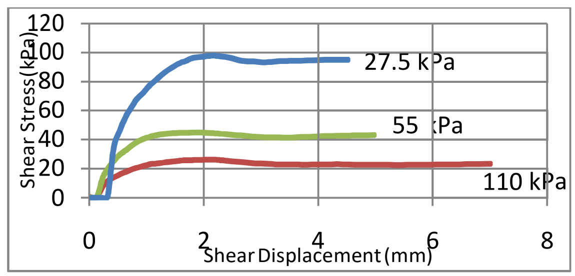
55 kPa

110 kPa

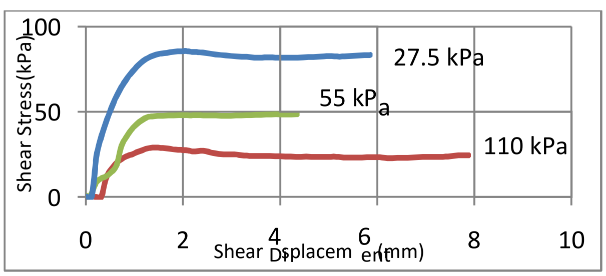
4% diesel



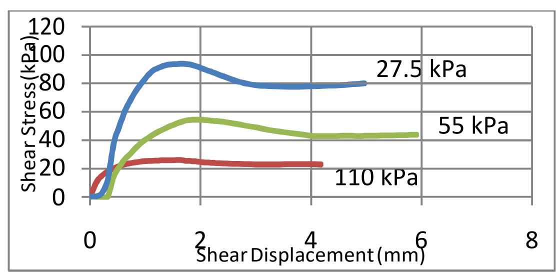
4% kerosene



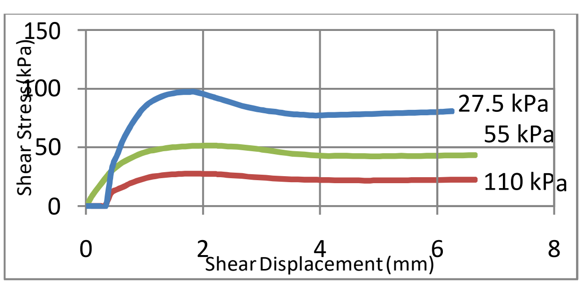
8% diesel



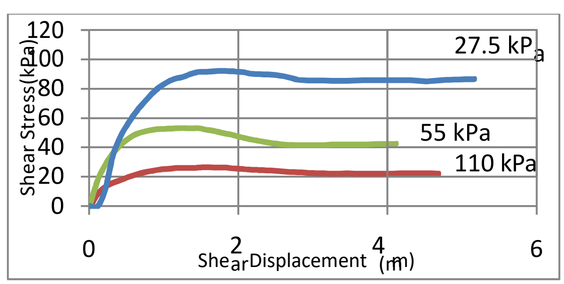
8% kerosene



12% diesel



12% kerosene



4.1.1.2 Direct shear on Sand-1 (with Diesel added)

TABLE 4.1 Shear Strength parameter results of Sand-1 with different percentages of Diesel added

	0%	4%	8%	12%
Cohesion (kPa)	0	2.5	5.15	4.6
Friction angle	36.24°	35.52°	35°	33.58°

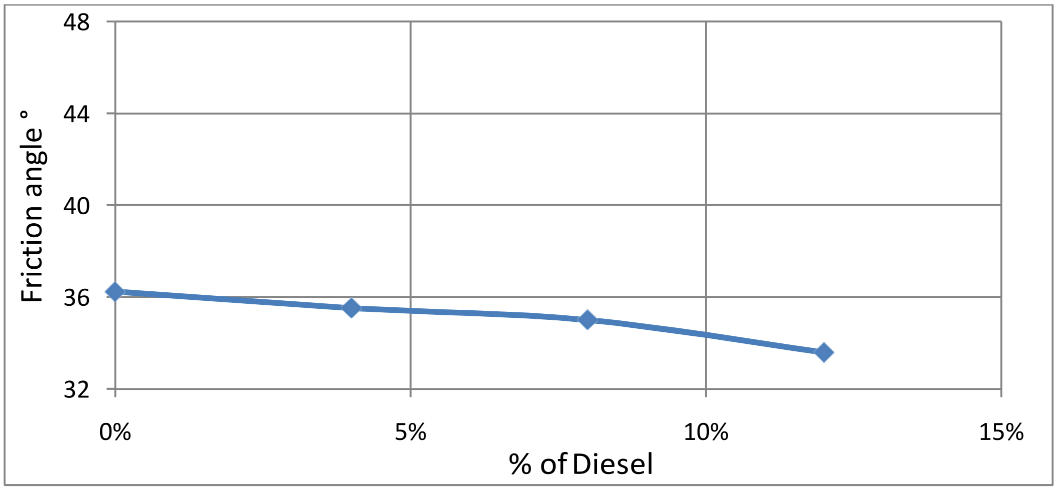


FIGURE 4.2 Effect of Diesel on the Friction Angle for Sand-1

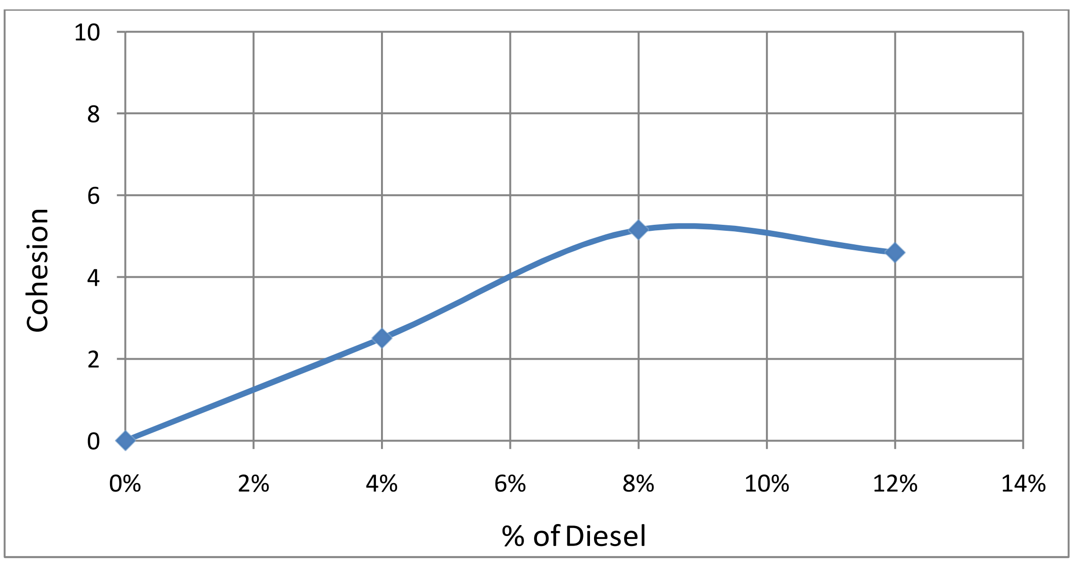
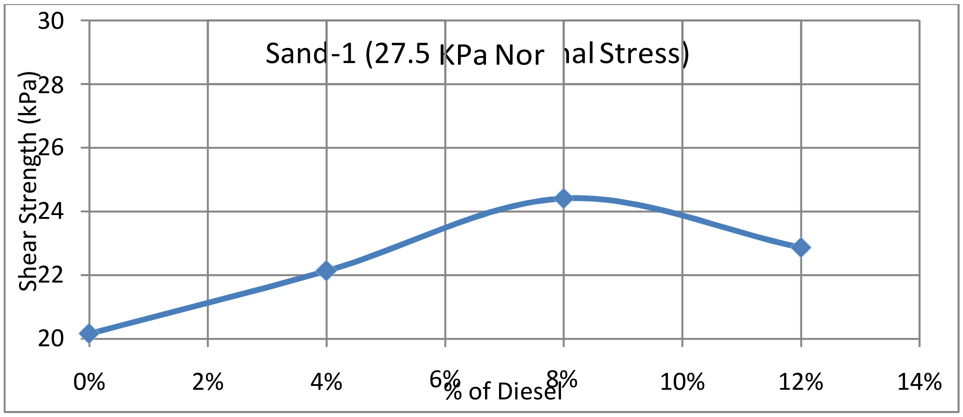
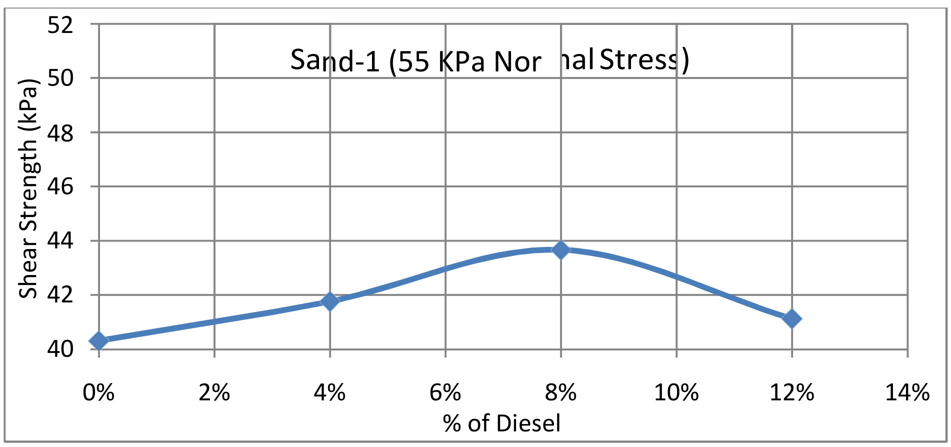


FIGURE 4.3 Effect of Diesel on the Cohesion for Sand-1

TABLE 4.2 Shear Strength results of Sand-1 with different % of Diesel added at different normal stresses

	Shear Strength (kPa)			
Normal Stress (kPa)	0%	4%	8%	12%
27.5	20.1575	22.13	24.4057	22.86
55	40.315	41.7601	43.6614	41.12
110	80.63	81.0202	82.1728	77.64





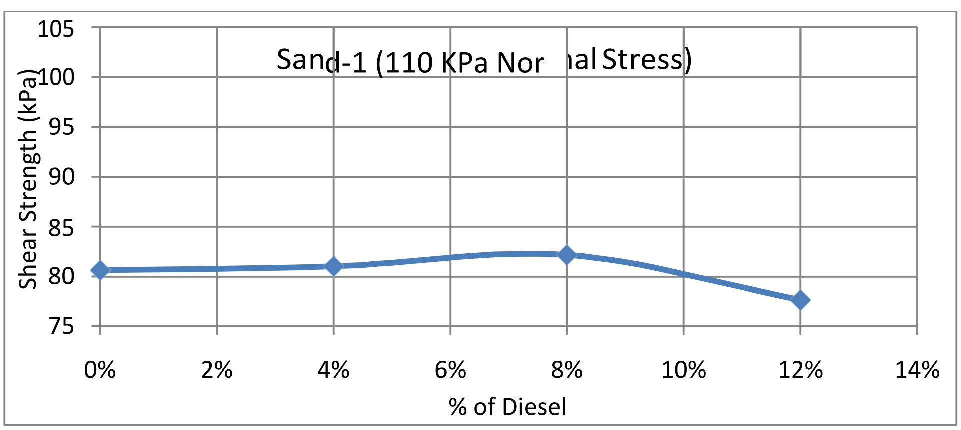


FIGURE 4.4 Effect of Diesel on Shear Strength for Sand-1 at different normal stresses

4.1.1.3 Direct shear on Sand-1 (with Kerosene added)

TABLE 4.3 Shear Strength parameter results of Sand-1 with different percentages of Kerosene added

	0%	4%	8%	12%
Cohesion (kPa)	0	3.35	5.45	4.05
Friction angle	36.24°	34.84°	33.38°	33.6°

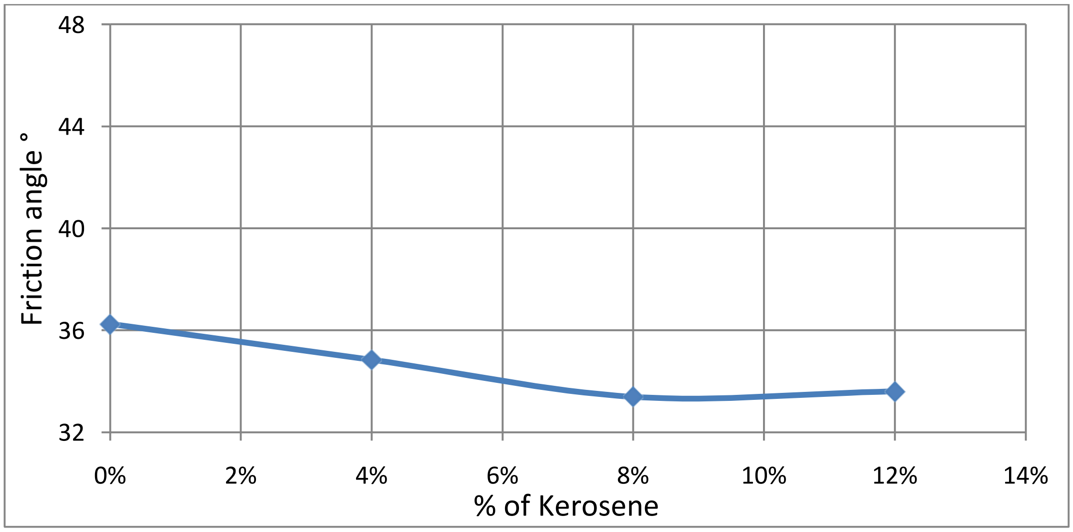


FIGURE 4.5 Effect of Kerosene on the Friction Angle for Sand-1

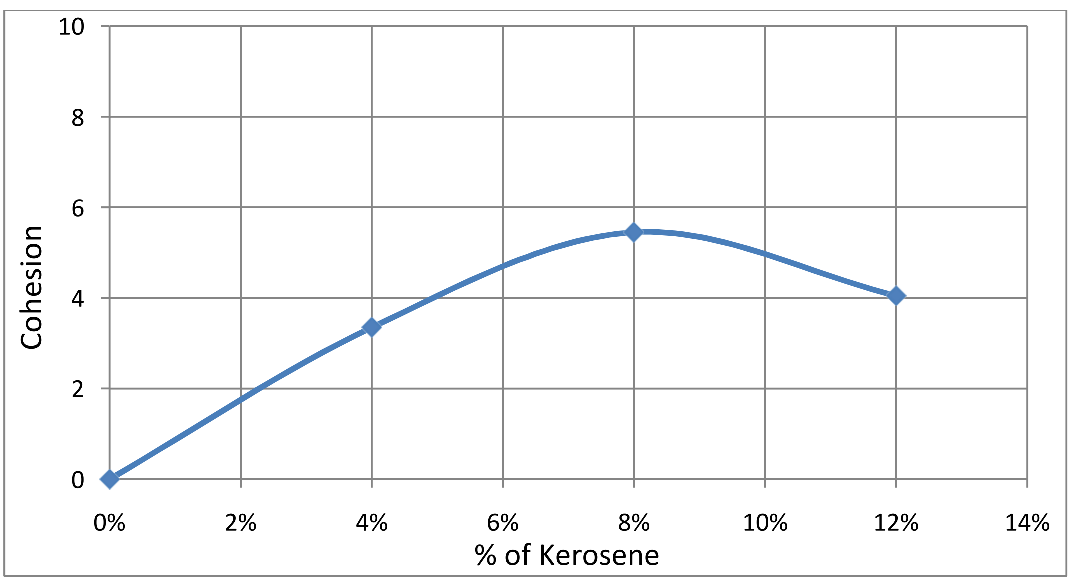


FIGURE 4.6 Effect of Kerosene on the Cohesion for Sand-1

TABLE 4.4 Shear Strength results of Sand-1 with different % of kerosene added at different normal stresses

	Shear Strength (kPa)			
Normal Stress (kPa)	0%	4%	8%	12%
27.5	20.1575	22.4915	23.5725	22.321
55	40.315	41.633	41.695	40.5919
110	80.63	79.9159	77.94	77.1338

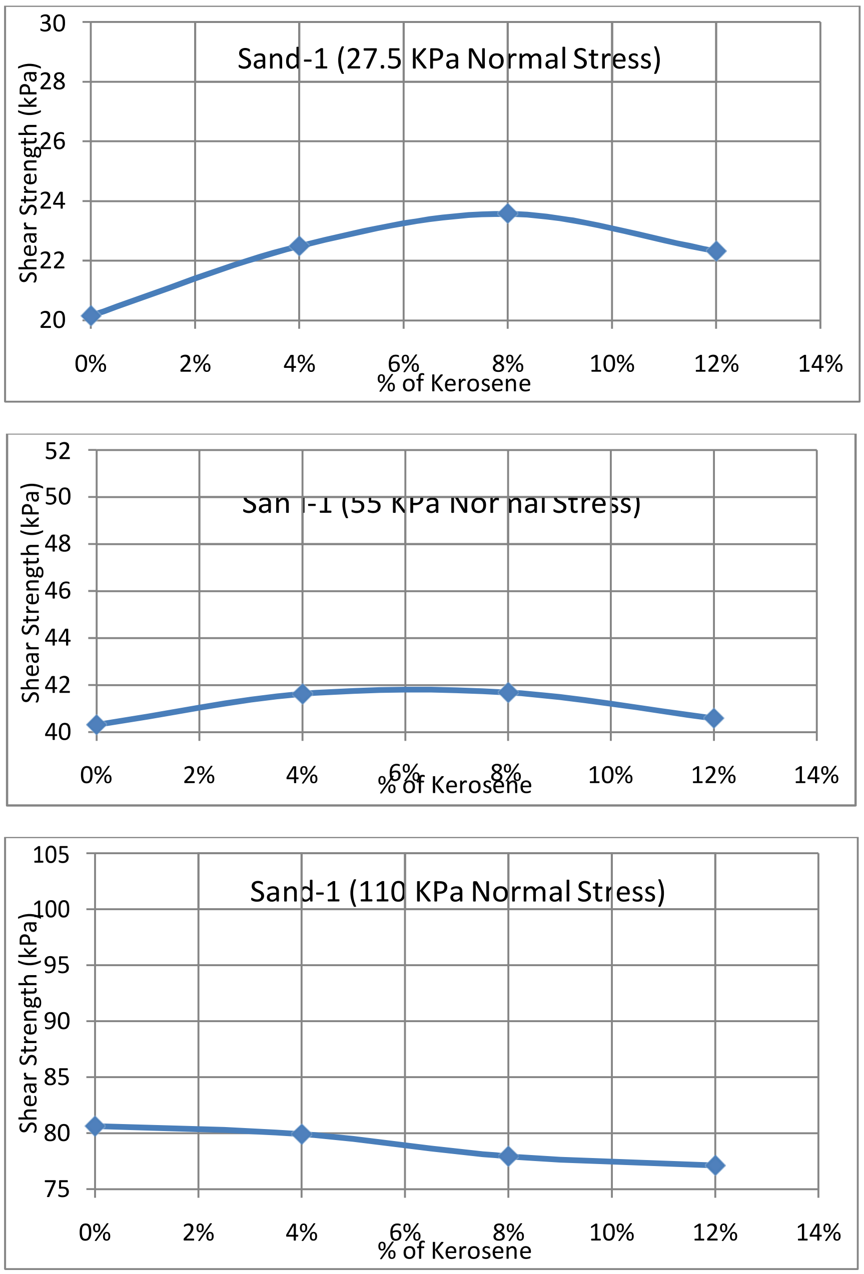


FIGURE 4.7 Effect of Kerosene on Shear Strength for Sand-1 at different normal stresses

4.1.2 Sand-2

The results that are shown in the stress strain curve are the readings taken from the experiments that were conducted. From these results, the angle of internal friction, apparent cohesion and the shear strength of our soil samples were found.

From the results, it was seen that as the percentage of crude oil products increased, the angle of internal friction of the sand would decrease. A slightly greater decrease in the friction angle was noticed for the addition of kerosene than that with the addition of diesel. This reduction was because diesel and kerosene would act as a lubricant and would allow the soil particles to slip and slide against each other. Added to that crude oil products are more effective in reducing the friction between the soil particles resulting in a reduction in the spacing between the soil grains. As a result, the angle of internal friction of the soil samples would decrease.

An apparent cohesion was found and increased gradually as diesel and kerosene were added to the soil. The maximum increase was noticed at 8 percent of crude oil product being added and the value of cohesion was found to be around 4 kPa. When more than 8 percent was added, less increase in cohesion was noticed. It was also seen that for the case of kerosene being added, the cohesion remained 0 when less than 4% of kerosene was added. The addition of crude oil products (diesel and kerosene) to the sand has shown a very close behavior on the graphs. The apparent cohesion of the sand was due to the capillary tension inside the voids. Added to that, having oil in soil prevents the water to contact the particles as a result of oil hydrophobia. Therefore, with oil inside soil, the capillary tension decreased and so the apparent cohesion of the soil increased. Moreover, this can also be explained as the result of viscosity and inherent cohesion of the crude oil products.

The increase of crude oil products percentage addition to the sand has shown a decrease in its shear strength. At high normal stress, the decrease in the shear strength was noticed clearly.

At low normal stress, as the percentage of crude oil products added to the soil is increased, the shear strength remained the same.

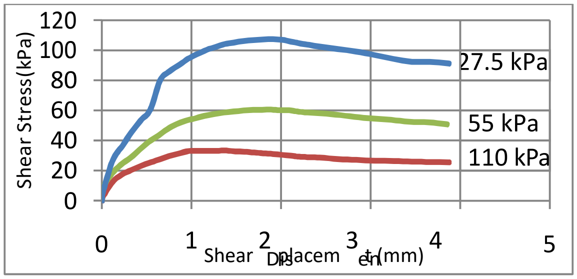
At high normal stress, as the percentage of crude oil products added to the soil is increased, the shear strength would decrease.

It was noticed that as we increase the normal stress, the shear strength of the soil would show more noticeable reduction. This stability in shear strength at low normal stress despite the reduction in the angle of internal friction was due to the apparent cohesion that was noticed in the soil.

4.1.2.1 Stress-strain graphs for Sand-2

FIGURE 4.8 Stress-strain curves for Sand-2 with different % of diesel and kerosene added at different normal stresses of 27.5, 55 and 110 kPa

<u>0%</u>



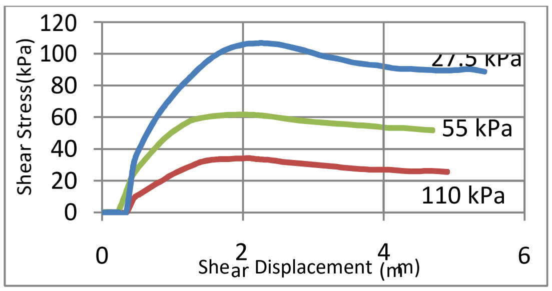
Normal stresses:

27.5 kPa

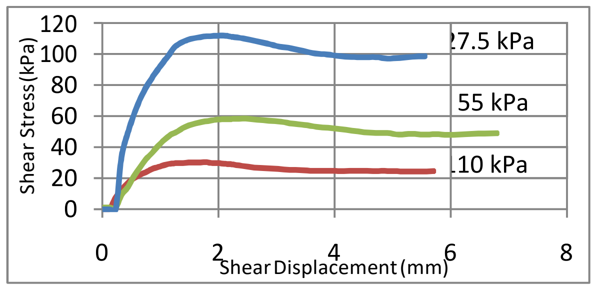
55 kPa

110 kPa

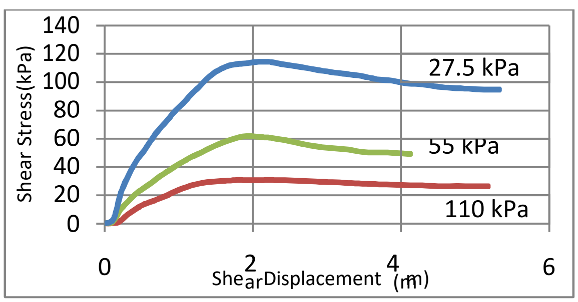
<u>4% diesel</u>



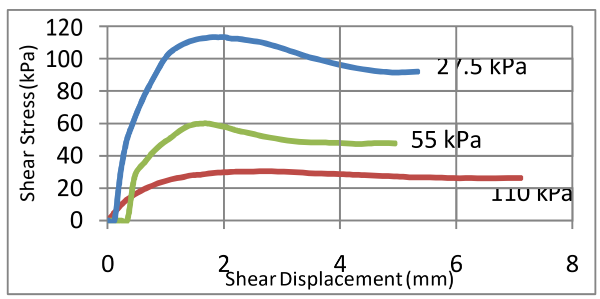
<u>4% kerosene</u>



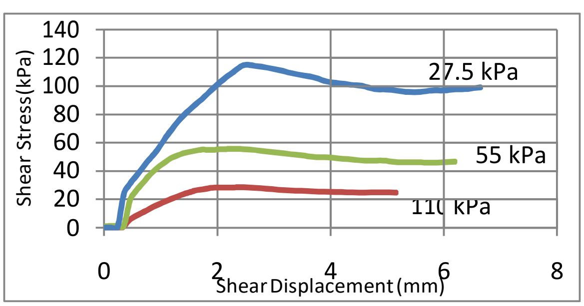
<u>8% diesel</u>



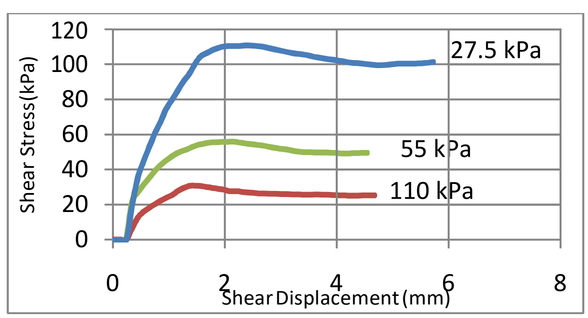
<u>8% kerosene</u>



<u>12% diesel</u>



<u>12% kerosene</u>



4.1.2.2 Direct shear on Sand-2 (with diesel added)

TABLE 4.5 Shear Strength parameter results of Sand-2 with different percentages of diesel added

	0%	4%	8%	12%
Cohesion (kPa)	0	3.2	4.05	2.6
Friction angle	42.614°	40.86°	39.522°	38.73°

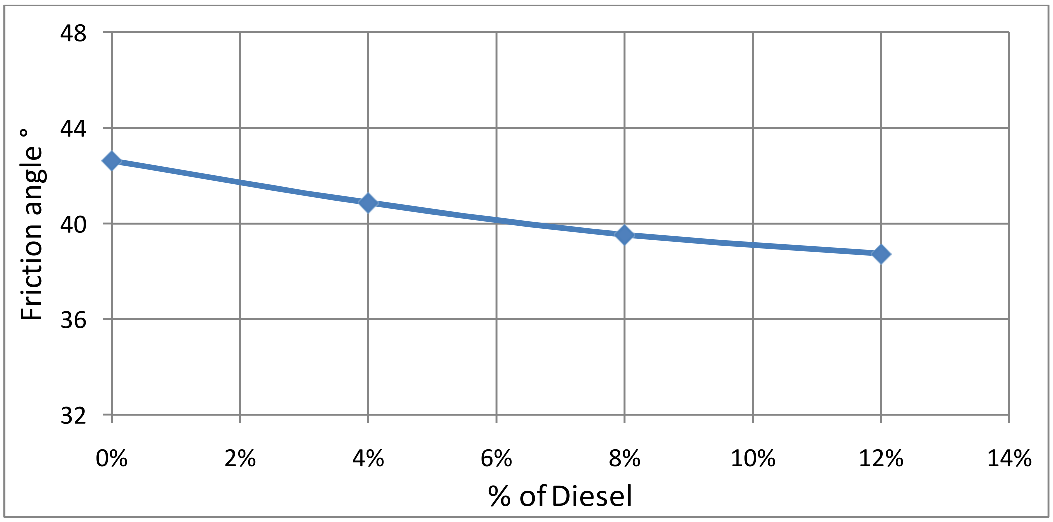


FIGURE 4.9 Effect of Diesel on Friction Angle for Sand-2

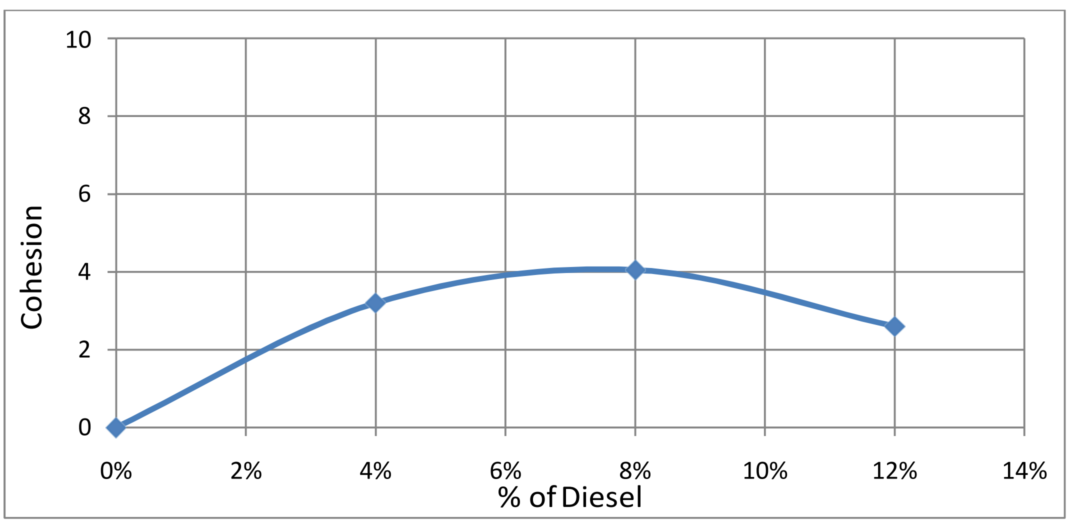


FIGURE 4.10 Effect of Diesel on Cohesion for Sand-2

TABLE 4.6 Shear Strength results of Sand-2 with different % of Diesel added at different normal stresses

	Shear Strength (kPa)			
Normal Stress (kPa)	0%	4%	8%	12%
27.5	25.3	26.9877	26.737	24.6553
55	50.5999	50.7753	49.424	46.7106
110	101.2	98.3507	94.798	90.8212

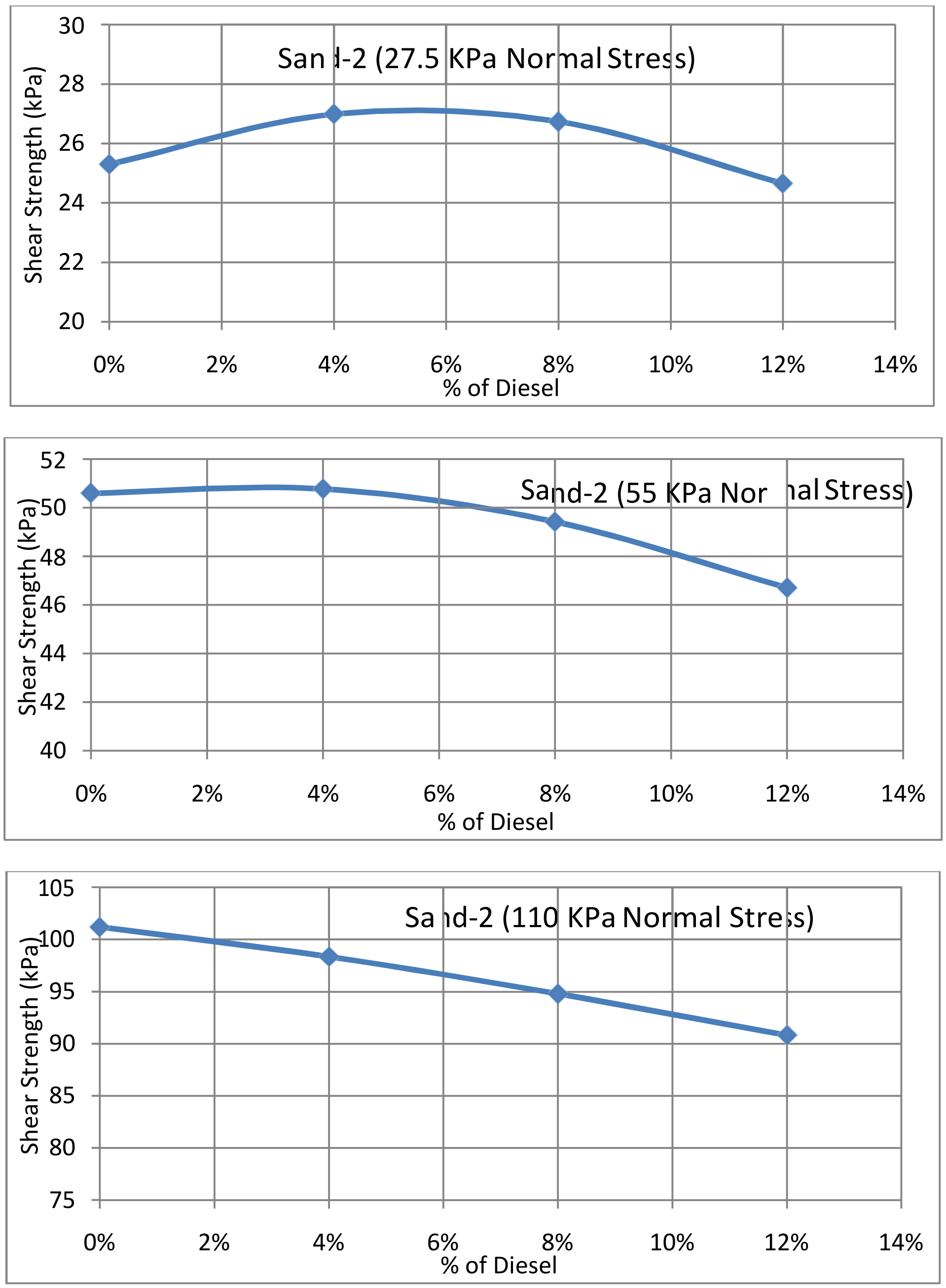


FIGURE 4.11 Effect of Diesel on Shear Strength for Sand-2 at different normal stresses

4.1.2.3 Direct shear on Sand-2 (with Kerosene added)

TABLE 4.7 Shear Strength parameter results of Sand-2 with different percentages of Kerosene added

	0%	4%	8%	12%
Cohesion (kPa)	0	0	4.25	4.9
Friction angle	42.614°	42.5°	38.344°	37.88°

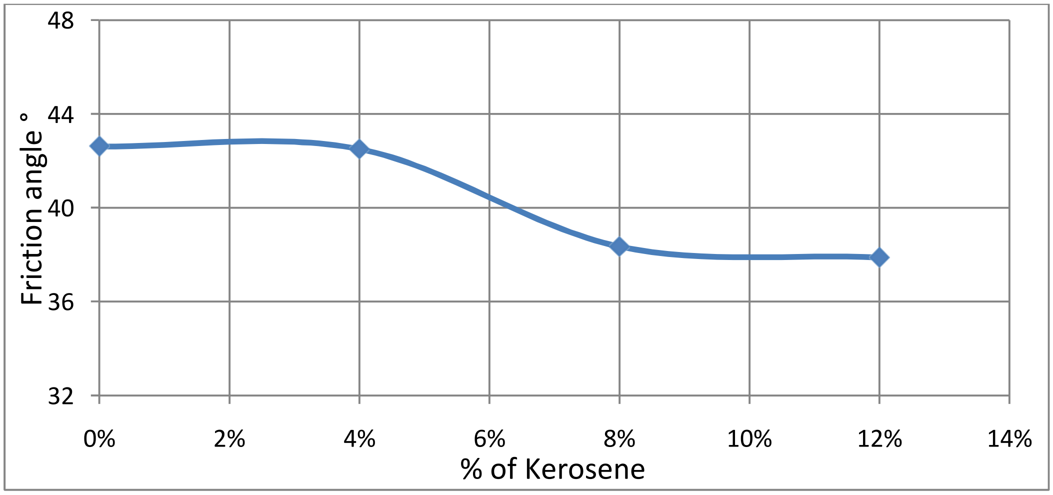


FIGURE 4.12 Effect of Kerosene on Friction Angle for Sand-2

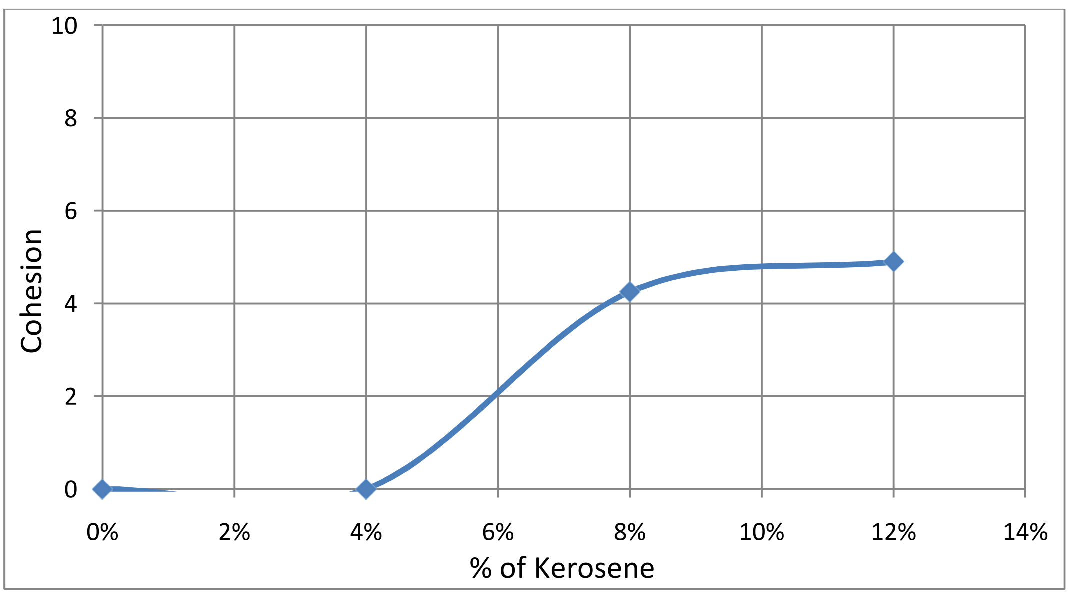
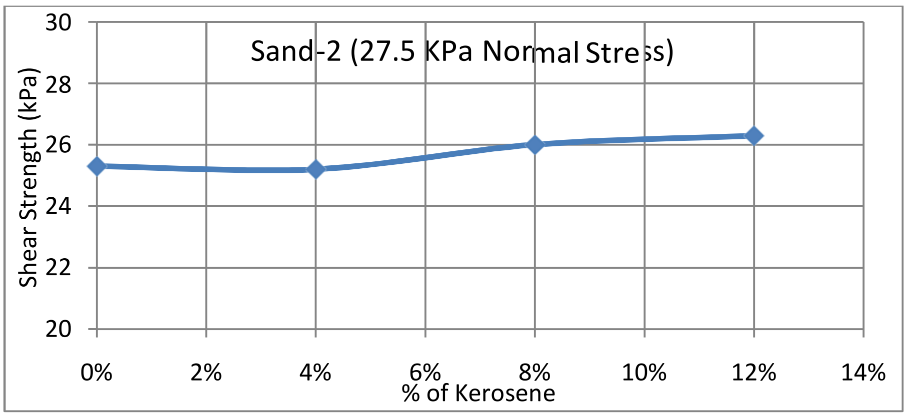
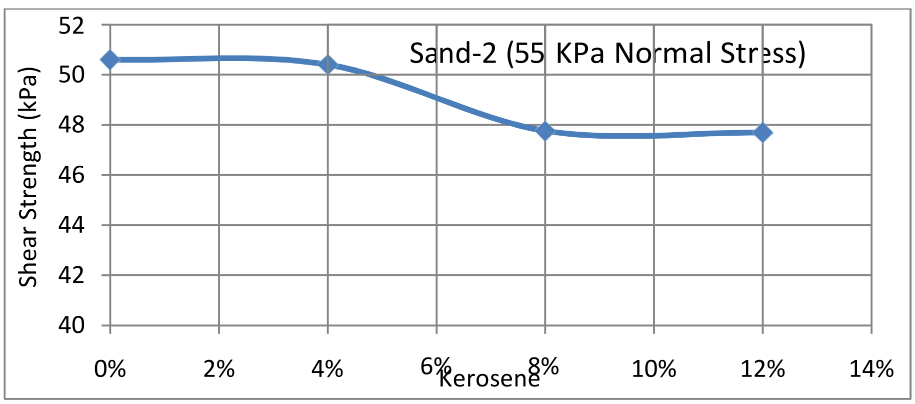


FIGURE 4.13 Effect of Kerosene on Cohesion for Sand-2

TABLE 4.8 Shear Strength results of Sand-2 with different % of Kerosene added at different normal stresses

	Shear Strength (kPa)			
Normal Stress (kPa)	0%	4%	8%	12%
27.5	25.3	25.1991	26.0025	26.2928
55	50.5999	50.3982	47.755	47.6855
110	101.2	100.796	91.26	90.471





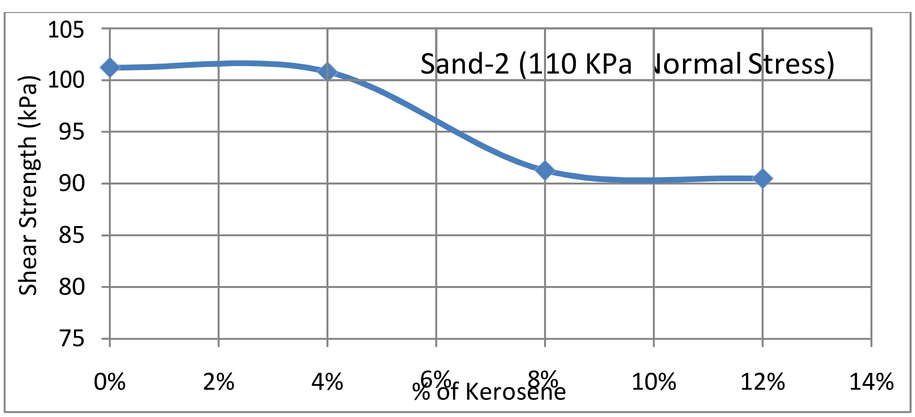


FIGURE 4.14 Effect of Kerosene on Shear Strength for Sand-2 at different normal stresses

4.1.3 Sand-3

The results that are shown in the stress strain curve are the readings taken from the experiments that were conducted. From these results, the angle of internal friction, apparent cohesion and the shear strength of our soil samples were found.

From the results, it was seen that as the percentage of crude oil products increased, the angle of internal friction of the sand would decrease. A slightly greater decrease in the friction angle was noticed for the addition of kerosene than that with the addition of diesel. This reduction was because diesel and kerosene would act as a lubricant and would allow the soil particles to slip and slide against each other. Added to that crude oil products are more effective in reducing the friction between the soil particles resulting in a reduction in the spacing between the soil grains. As a result, the angle of internal friction of the soil samples would decrease.

An apparent cohesion was found and increased gradually as diesel and kerosene were added to the soil. The maximum increase was noticed at 8 percent of crude oil product being added and the value of cohesion was found to be around 3.2 kPa when diesel was added and 5.65kPa when kerosene was added. When more than 8 percent was added, less increase in cohesion was noticed. The addition of crude oil products (diesel and kerosene) to the sand has shown a very close behavior on the graphs. The apparent cohesion of the sand was due to the capillary tension inside the voids. Added to that, having oil in soil prevents the water to contact the particles as a result of oil hydrophobia. Therefore, with oil inside soil, the capillary tension decreased and so the apparent cohesion of the soil increased. Moreover, this can also be explained as the result of viscosity and inherent cohesion of the crude oil products.

At low normal stress, as the percentage of crude oil products added to the soil is increased, the shear strength increases up to 4 percent and then it decreases. The maximum increase in shear strength was noticed at 4 percent of crude oil product being added.

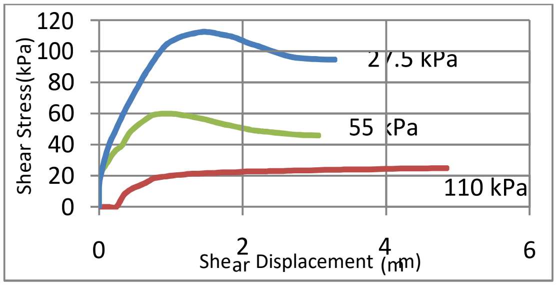
At high normal stress, as the percentage of crude oil products added to the soil is increased, the shear strength decrease.

It was noticed that as we increase the normal stress, the shear strength of the soil would show more noticeable reduction. This increase in shear strength at low normal stress despite the reduction in the angle of internal friction was due to the apparent cohesion that was noticed in the soil.

4.1.3.1 Stress-strain graphs for Sand-3

FIGURE 4.15 Stress-strain curves for Sand-3 with different % of diesel and kerosene added at different normal stresses of 27.5, 55 and 110 kPa

0%



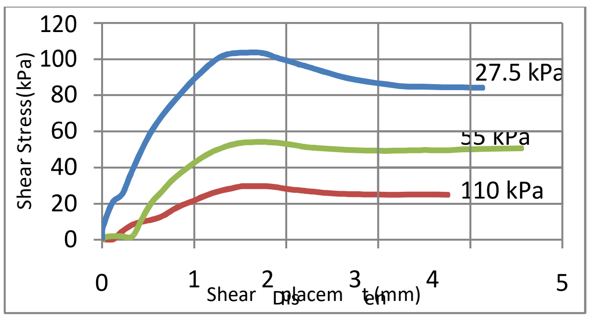
Normal stresses:

27.5 kPa

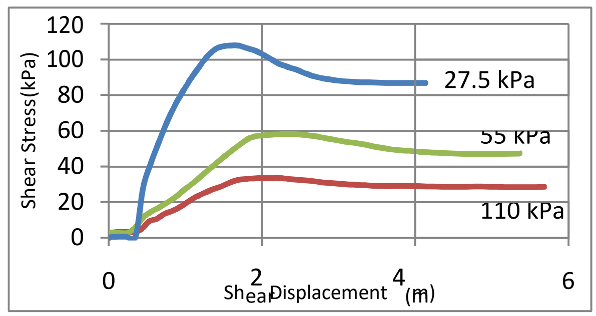
55 kPa

110 kPa

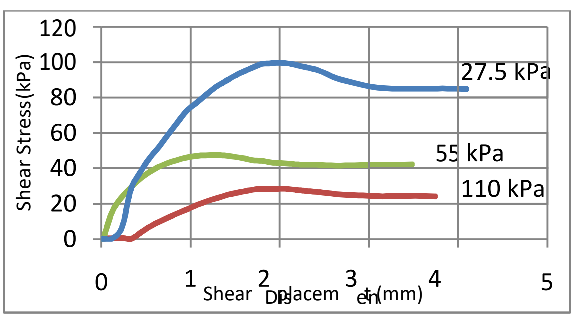
4% diesel



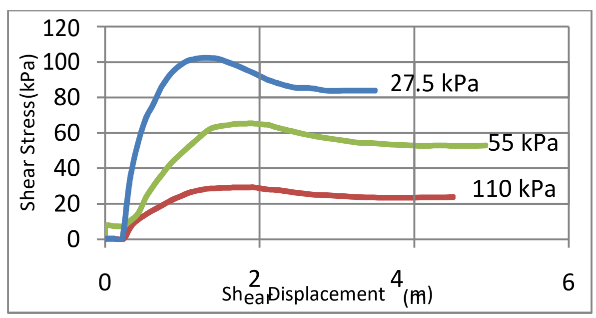
4% kerosene



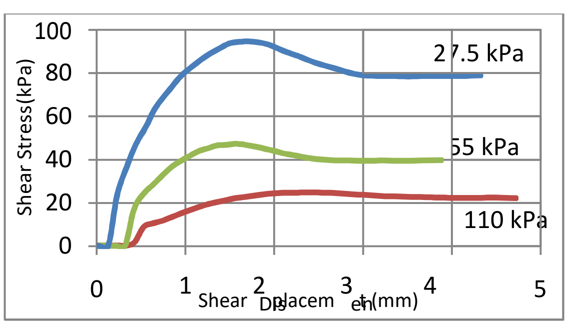
8% diesel



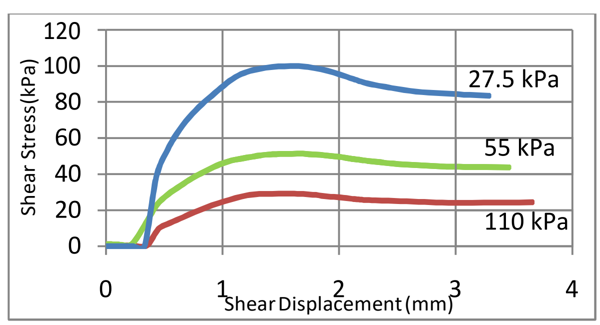
8% kerosene



12% diesel



12% kerosene



4.1.3.2 Direct shear on Sand-3 (with diesel added)

TABLE 4.9 Shear Strength parameter results of Sand-3 with different percentages of diesel added

	0%	4%	8%	12%
Cohesion (kPa)	0	2.9	3.2	2.8
Friction angle	40.49°	39.42°	36.1°	34.41°

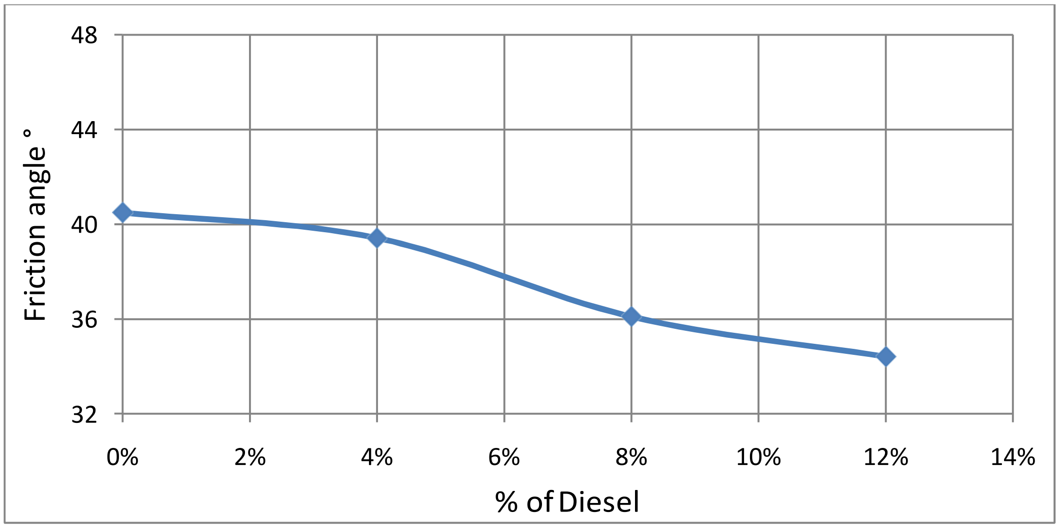


FIGURE 4.16 Effect of Diesel on Friction Angle for Sand-3

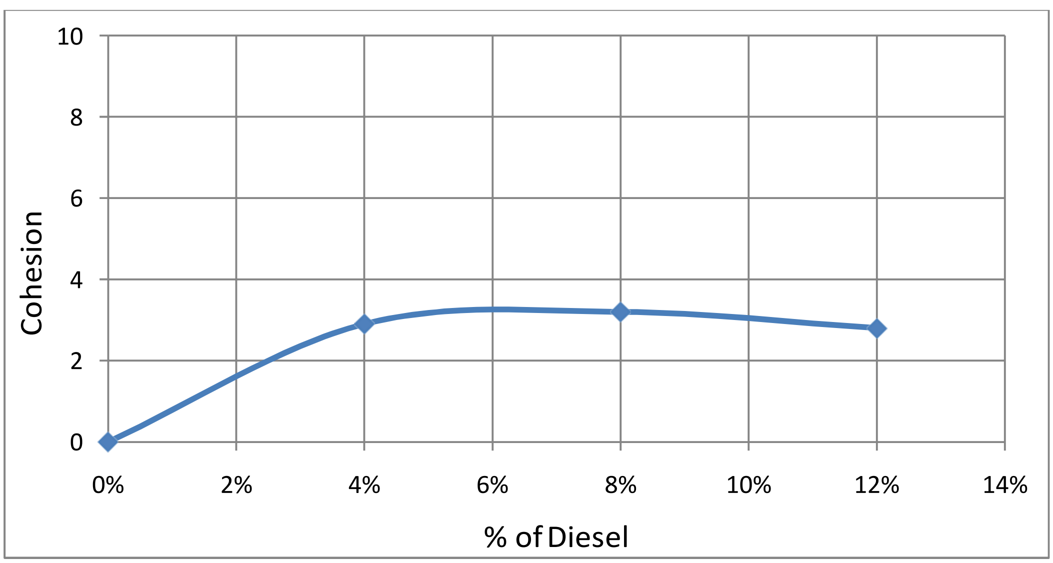


FIGURE 4.17 Effect of Diesel on Cohesion for Sand-3

TABLE 4.10 Shear Strength results of Sand-3 with different % of Diesel added at different normal stresses

	Shear Strength (kPa)			
Normal Stress (kPa)	0%	4%	8%	12%
27.5	23.485	25.5048	23.2533	21.6375
55	46.97	48.1097	43.3067	40.475
110	93.94	93.3193	83.4134	78.15

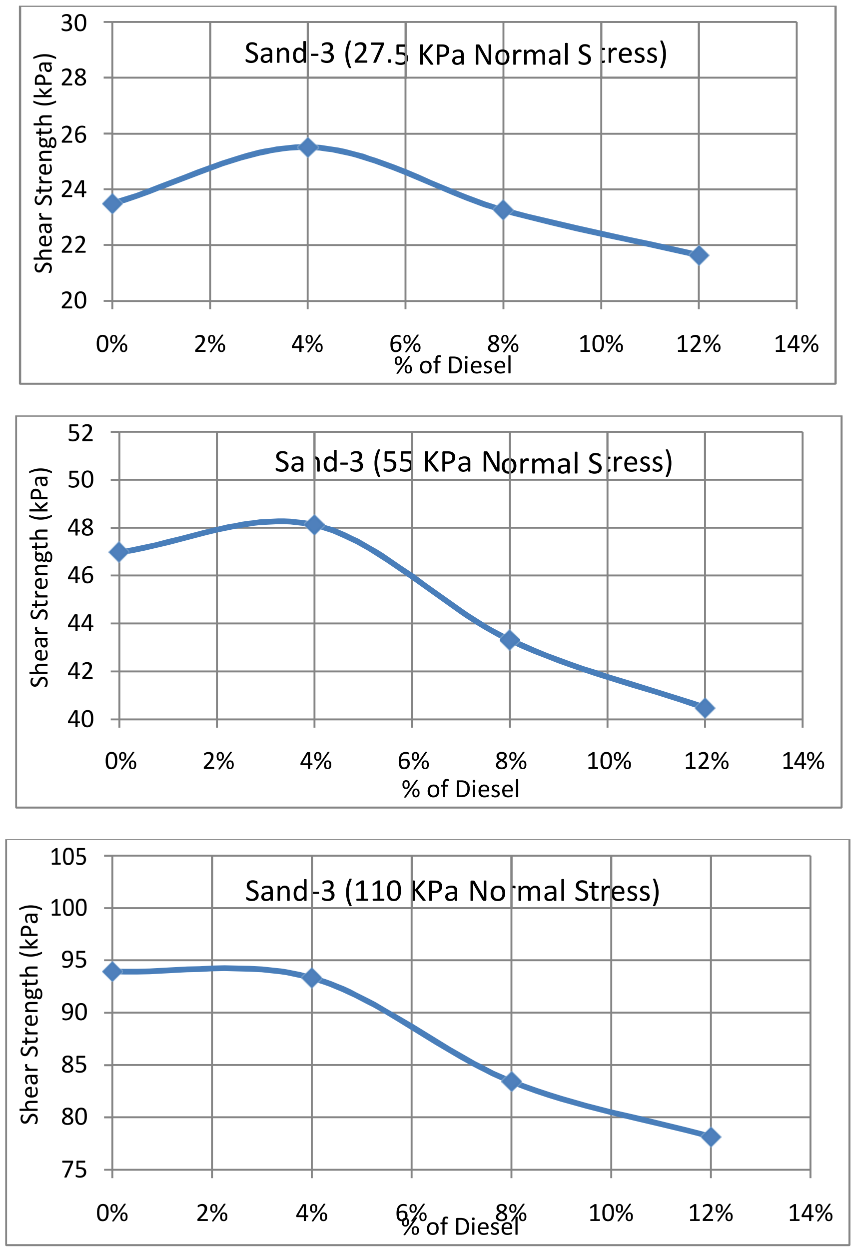


FIGURE 4.18 Effect of Diesel on Shear Strength for Sand-3 at different normal stresses

4.1.3.3 Direct shear on Sand-3 (with kerosene added)

TABLE 4.11 Shear Strength parameter results of Sand-3 with different percentages of Kerosene added

	0%	4%	8%	12%
Cohesion (kPa)	0	5.6	5.65	4
Friction angle	40.49°	37.44°	35.7°	35.6°

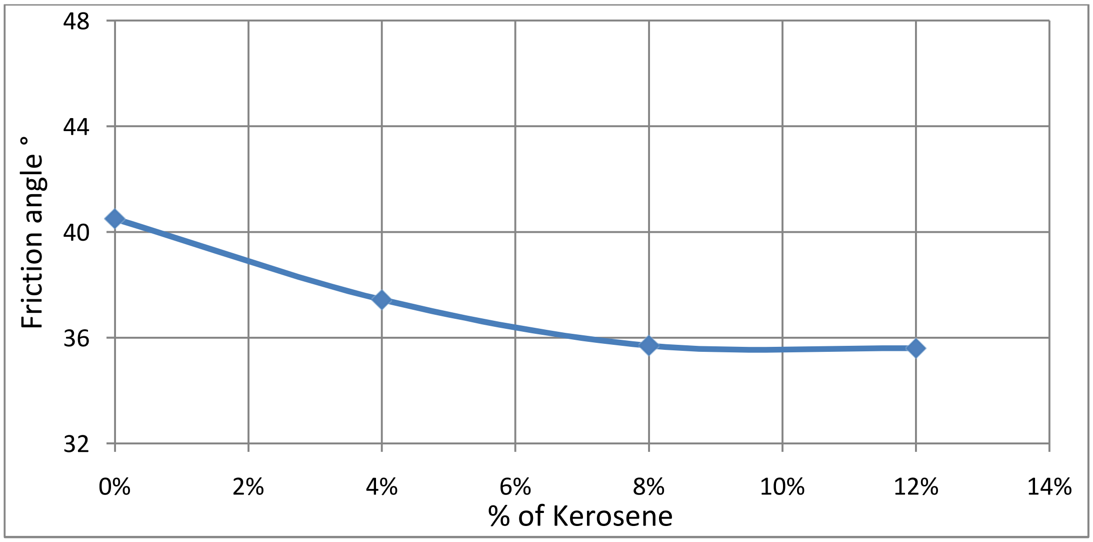


FIGURE 4.19 Effect of Kerosene on Friction Angle for Sand-3

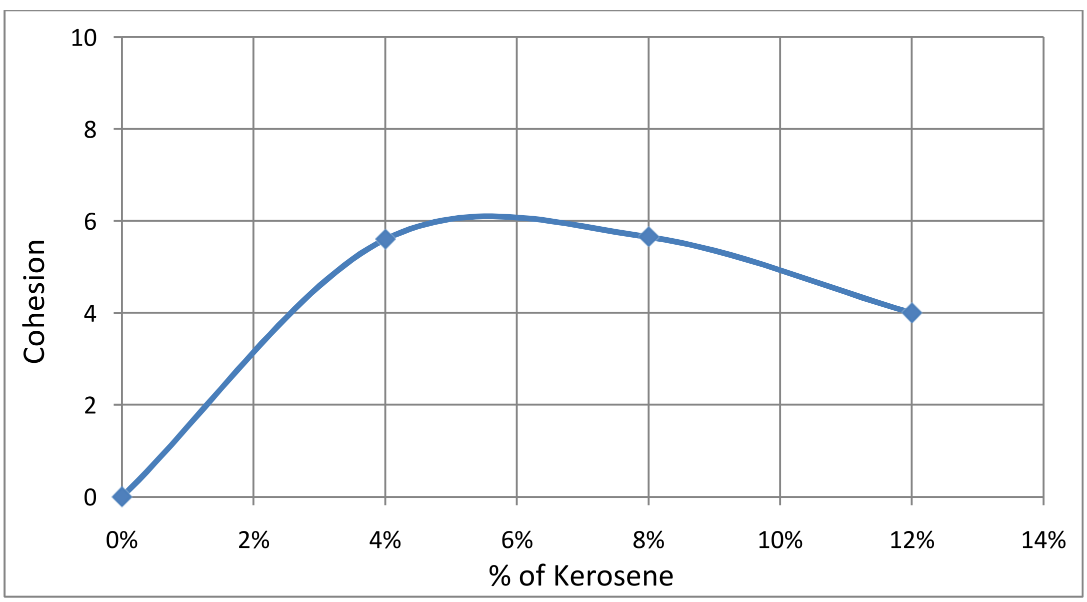


FIGURE 4.20 Effect of Kerosene on Cohesion for Sand-3

TABLE 4.12 Shear Strength results of Sand-3 with different % of Kerosene added at different normal stresses

	Shear Strength (kPa)			
Normal Stress (kPa)	0%	4%	8%	12%
27.5	23.485	26.6558	25.4108	23.6881
55	46.97	47.7116	45.1715	43.3761
110	93.94	89.8231	84.693	82.7523

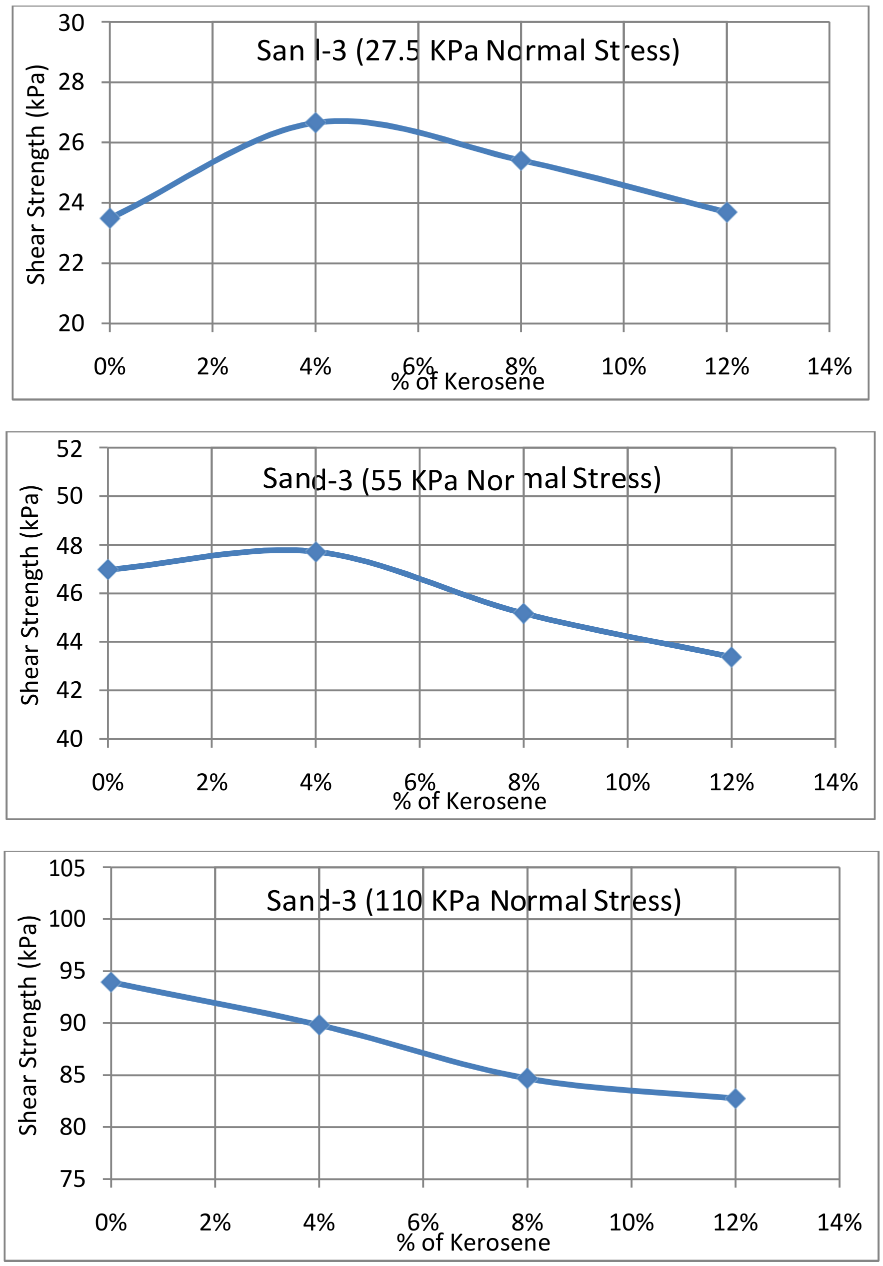


FIGURE 4.21 Effect of Kerosene on Shear Strength for Sand-3 at different normal stresses

4.1.4 Effect of adding different percentages of diesel and kerosene on the angle of internal friction

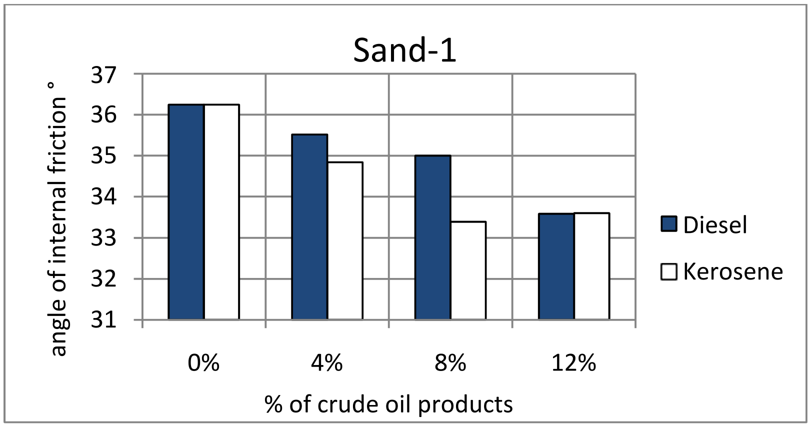


FIGURE 4.22 Effect of different % of diesel and kerosene on friction angle of sand-1

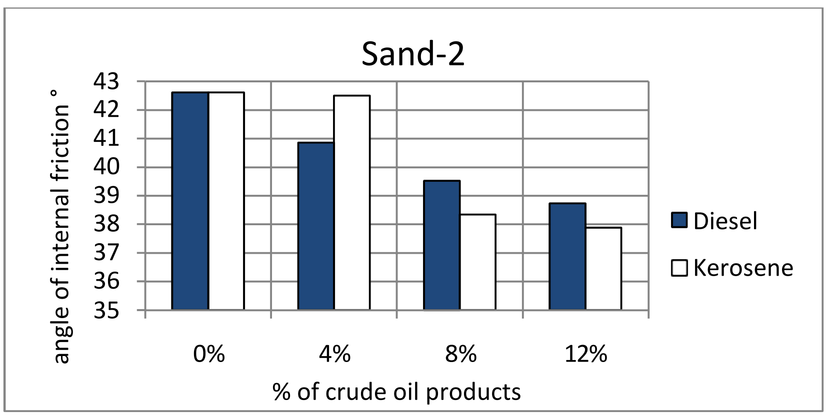


FIGURE 4.23 Effect of different % of diesel and kerosene on friction angle of sand-2

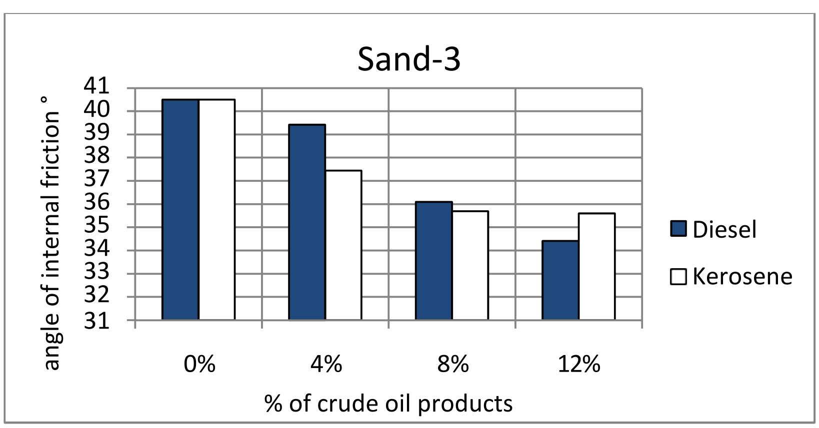


FIGURE 4.24 Effect of different % of diesel and kerosene on friction angle of sand-3

4.1.5 Effect of adding different percentages of diesel and kerosene on the shear strength

4.1.5.1 Sand-1

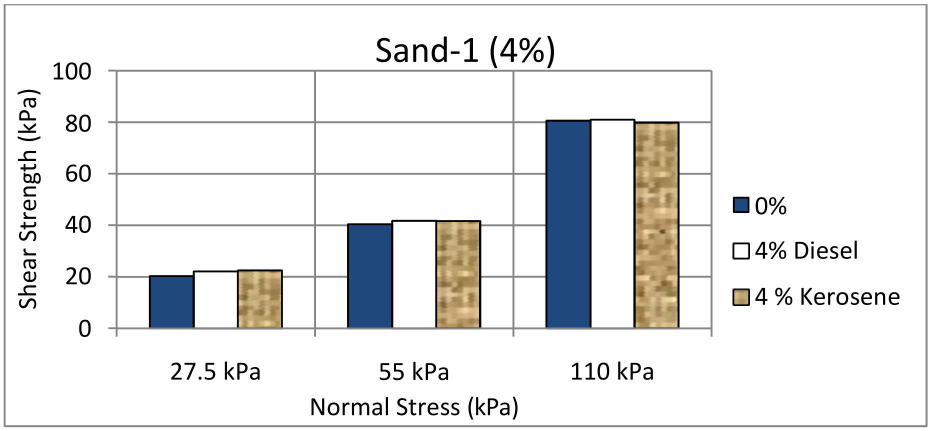


FIGURE 4.25 Effect of 4% of diesel and kerosene on shear strength of sand-1

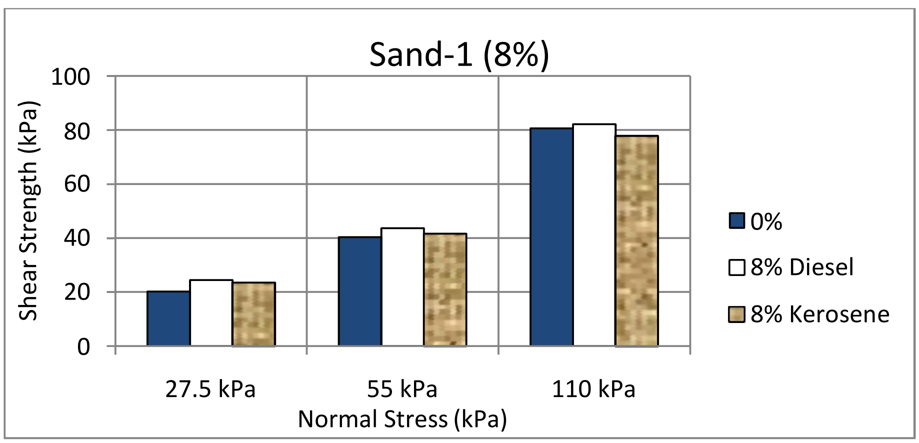


FIGURE 4.26 Effect of 8% of diesel and kerosene on shear strength of sand-1

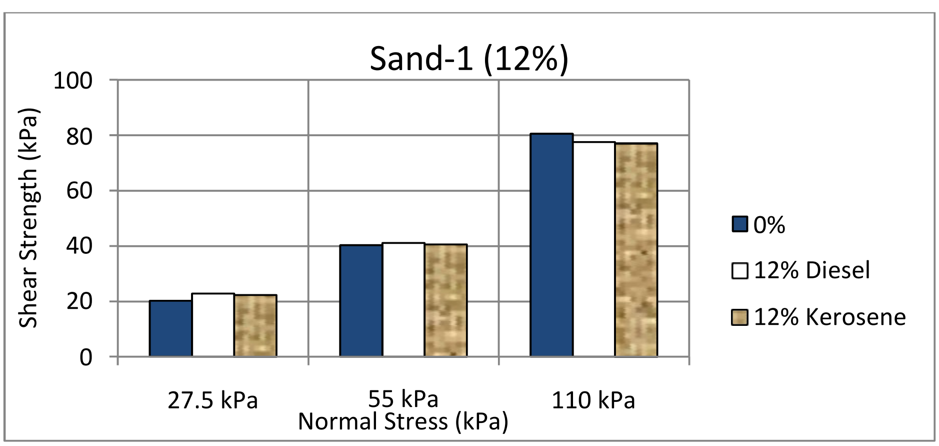


FIGURE 4.27 Effect of 12% of diesel and kerosene on shear strength of sand-1

4.1.5.2 Sand-2

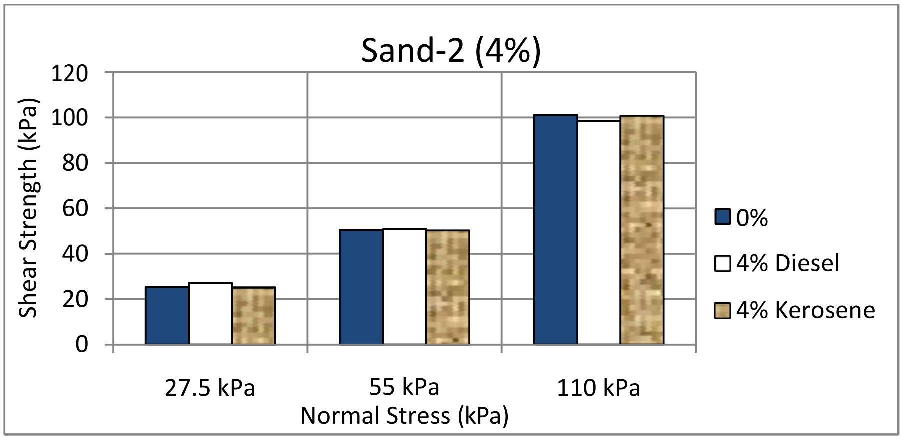


FIGURE 4.28 Effect of 4% of diesel and kerosene on shear strength of sand-2

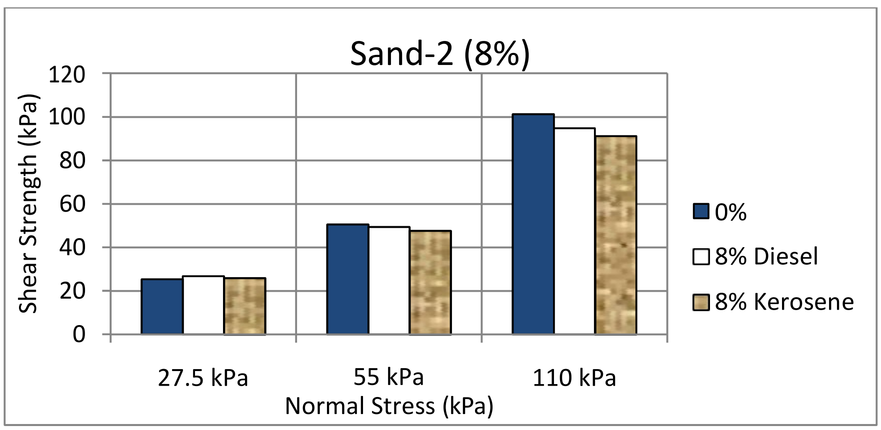


FIGURE 4.29 Effect of 8% of diesel and kerosene on shear strength of sand-2

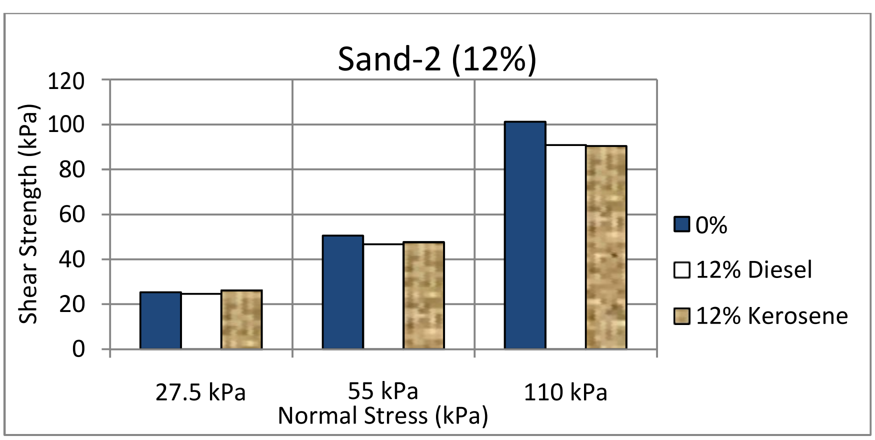


FIGURE 4.30 Effect of 12% of diesel and kerosene on shear strength of sand-2

4.1.5.3 Sand-3

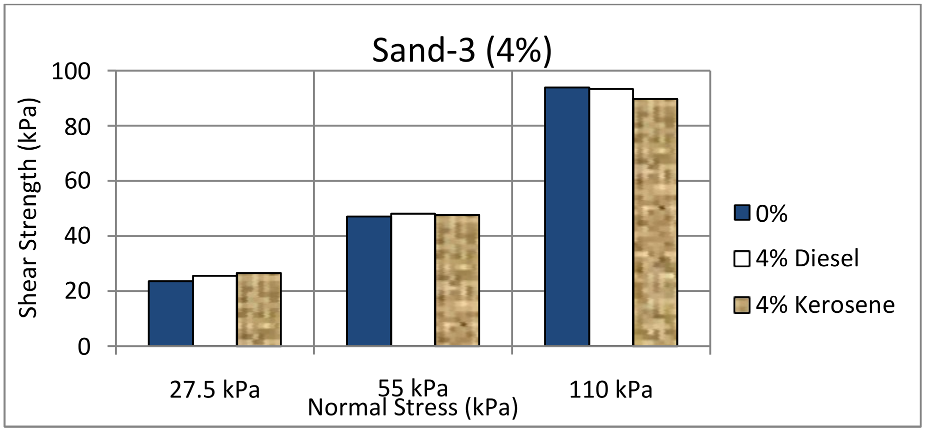


FIGURE 4.31 Effect of 4% of diesel and kerosene on shear strength of sand-3

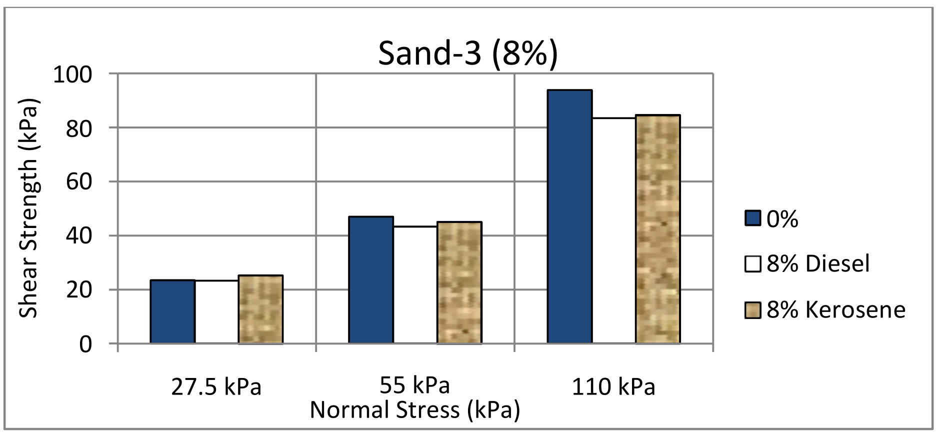


FIGURE 4.32 Effect of 8% of diesel and kerosene on shear strength of sand-3

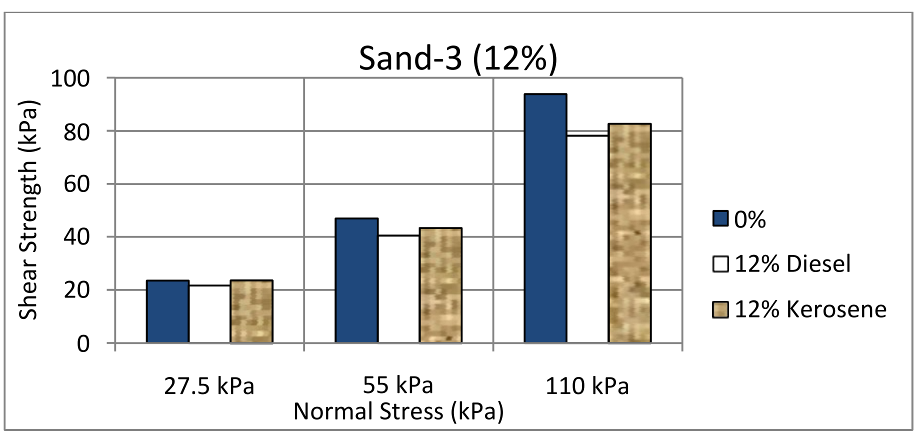


FIGURE 4.33 Effect of 12% of diesel and kerosene on shear strength of sand-3

4.2 PERMEABILLITY

4.2.1 Sand-1

TABLE 4.13 Permeability results of Sand-1 with different % of Diesel and Kerosene added

	Diesel						Units
	0%	2%	4%	6%	8%	10%	
permeability	0.019514	0.0165	0.007	0.0028	0.002	0.001643	cm/s
	Kerosene						Units
	0%	2%	4%	6%	8%	10%	
permeability	0.019514	0.022	0.0225	0.0175	0.01	0.002269	cm/s

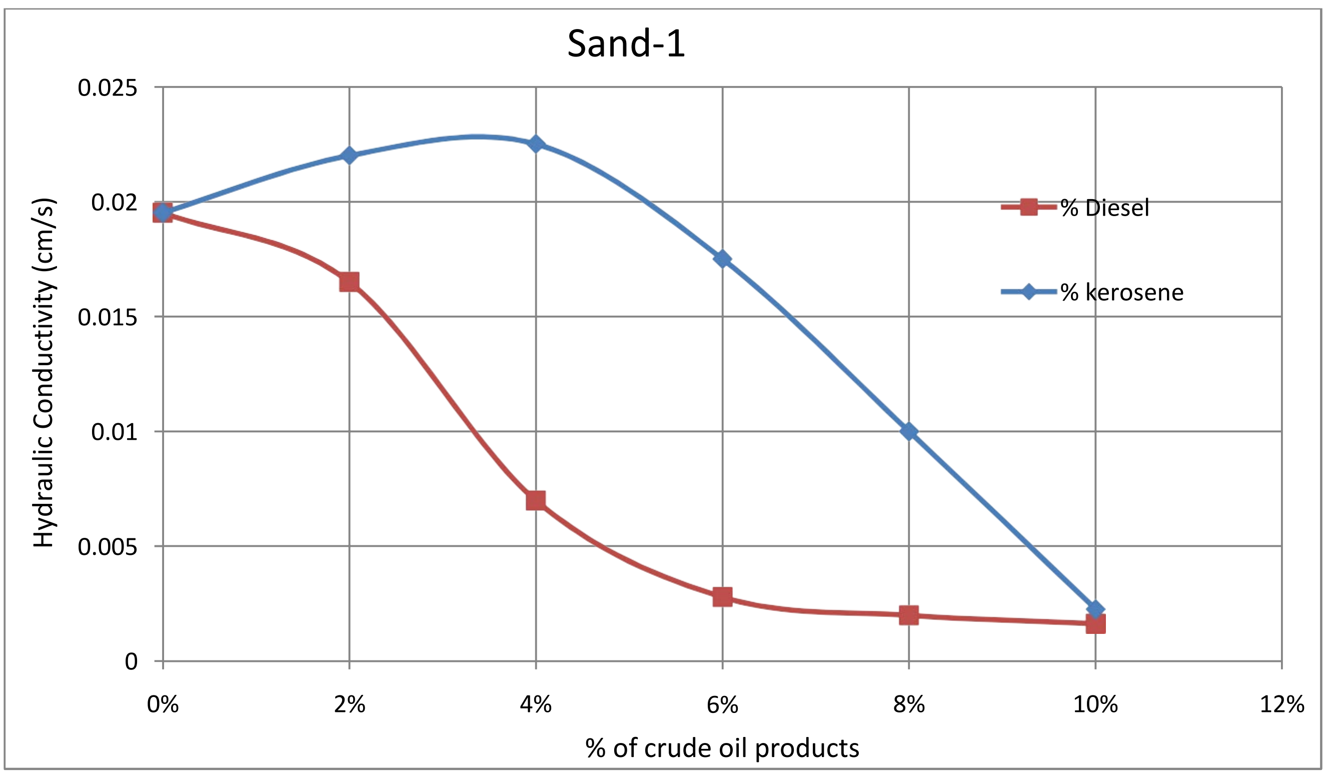


FIGURE 4.34 Effect of diesel and kerosene on the Hydraulic Conductivity of Sand-1

Constant head permeability test were carried out on sand-1. The results have shown an inverse correlation between permeability and crude oil products content. The rate of reduction of permeability was faster for the sand by the addition of diesel than by the addition of kerosene. The maximum change in permeability was noticed between 0% and 5% diesel; after the addition of 5% diesel onward, it was noticed that the effect of diesel on permeability was very small. On the other hand, the change in permeability was very small when kerosene was added up to 5%; with an increase in amount of kerosene of more than 5%, a large drop in the permeability was observed.

The decrease in hydraulic conductivity was a result of the trapped diesel and kerosene that occupied the pore spaces of the soil; the pore volume of the soil would decrease and this would result in a decrease in permeability.

Added to that, diesel and kerosene has a hydrophobia property, it would prevent the contact of water with soil particles. As a result, as the diesel and kerosene increased, the capillary tension would decrease. Moreover, diesel and kerosene are more effective in reducing the friction between the soil particles resulting in a reduction in the spacing between the soil grains.

4.2.2 Sand-2

TABLE 4.14 Permeability results of Sand-2 with different % of Diesel and Kerosene added

	Diesel						Units
	0%	2%	4%	6%	8%	10%	
permeability	0.013405	0.0073	0.0042	0.0031	0.0023	0.001538	cm/s
	Kerosene						Units
	0%	2%	4%	6%	8%	10%	
permeability	0.013405	0.0087	0.0048	0.0034	0.0033	0.00326	cm/s

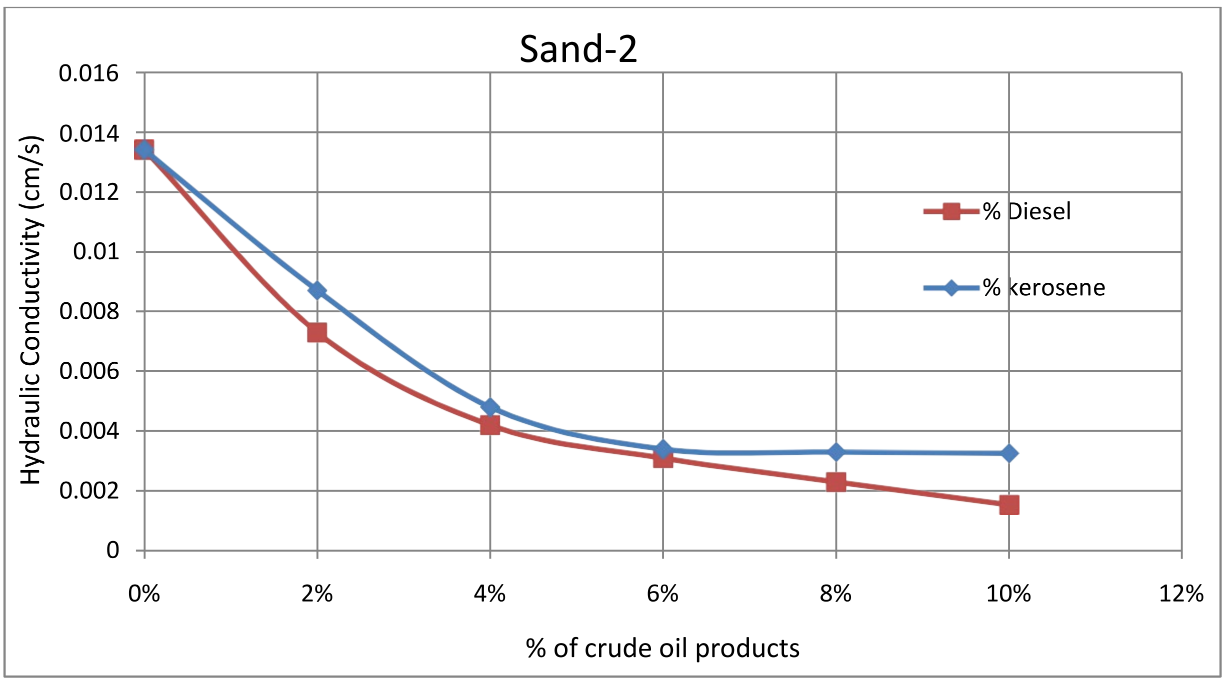


FIGURE 4.35 Effect of diesel and kerosene on the Hydraulic Conductivity of Sand-2

Constant head permeability test were carried out on sand-2. The results have shown an inverse correlation between permeability and crude oil products content which means that the addition of diesel and kerosene has caused a reduction in the permeability of the sand. The maximum change in permeability was noticed between 0% and 5% diesel and kerosene. The rate of reduction of permeability was faster for the sand by the addition of diesel than by the addition of kerosene. This was seen at 3% and 10% oil contents. After the addition 5% diesel and kerosene onward, it was noticed that the effect of crude oil products on permeability was very small.

4.2.3 Sand-3

TABLE 4.15 Permeability results of Sand-3 with different % of Diesel and Kerosene added

	Diesel						Units
	0%	2%	4%	6%	8%	10%	
permeability	0.009292	0.004	0.0016	0.00115	0.0009	0.000931	cm/s
	Kerosene						Units
	0%	2%	4%	6%	8%	10%	
permeability	0.009292	0.0035	0.00222	0.002106	0.002013	0.002026	cm/s

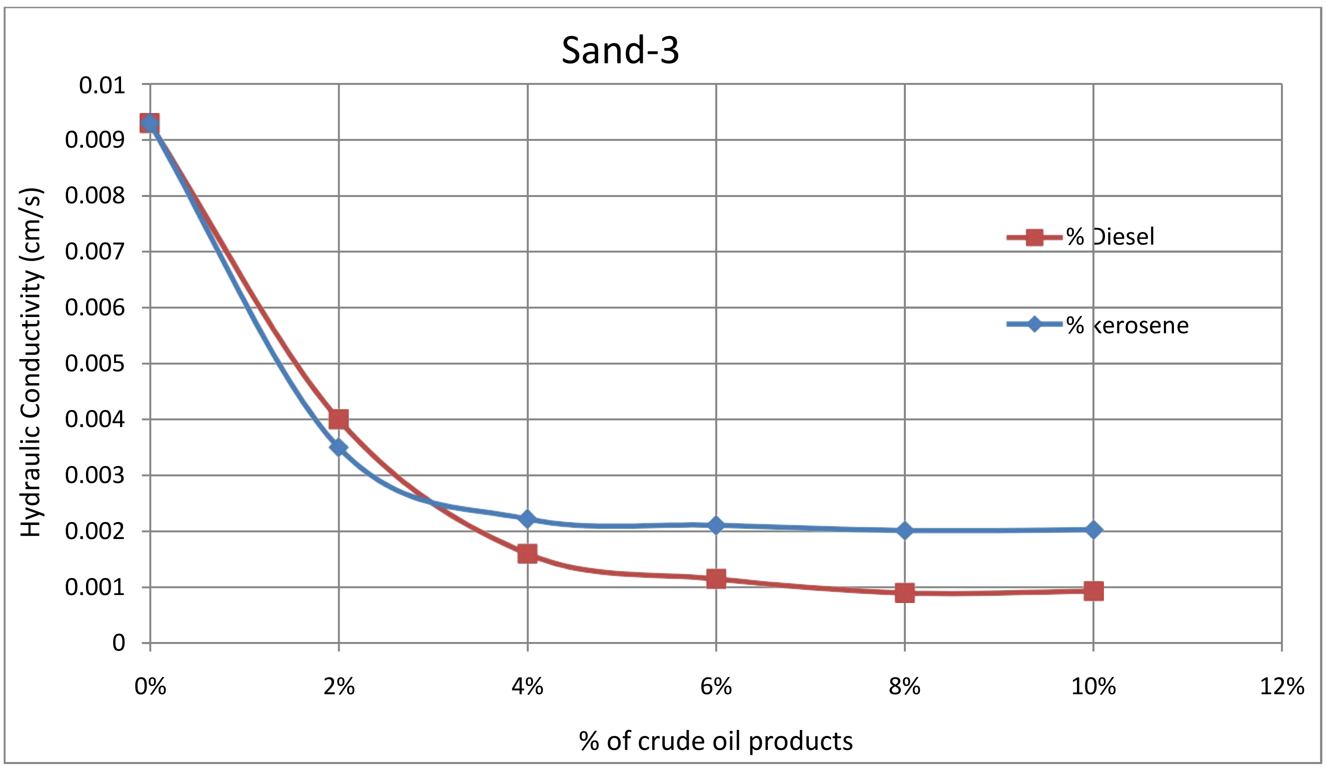


FIGURE 4.36 Effect of diesel and kerosene on the Hydraulic Conductivity of Sand-3

Constant head permeability test were carried out on sand-3. The results have shown an inverse correlation between permeability and crude oil products content which means that the addition of diesel and kerosene has caused a reduction in the permeability of the sand. The maximum change in permeability was noticed between 0% and 5% diesel and kerosene. The rate of reduction of permeability was faster for the sand by the addition of diesel than by the addition of kerosene after the addition of 3% diesel and kerosene. After the addition 5% diesel and kerosene onward, it was noticed that the effect of crude oil products on permeability was very small.

4.2.4 Effect of adding different percentages of diesel and kerosene on permeability

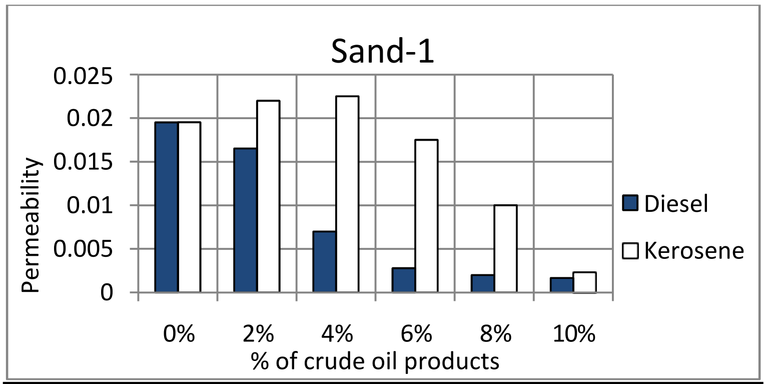


FIGURE 4.37 Effect of different % of diesel and kerosene on permeability ofsand-1

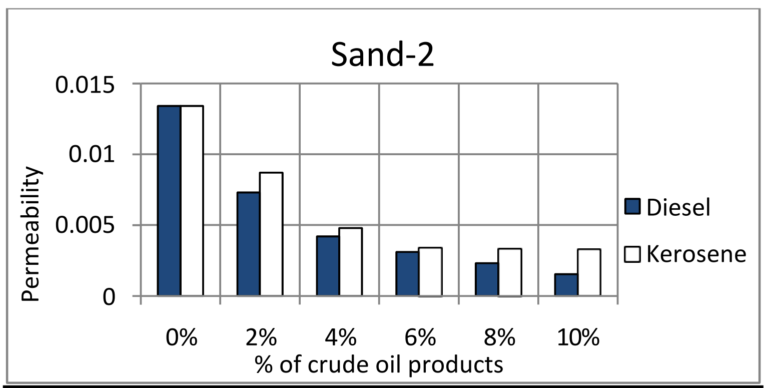


FIGURE 4.38 Effect of different % of diesel and kerosene on permeability ofsand-2

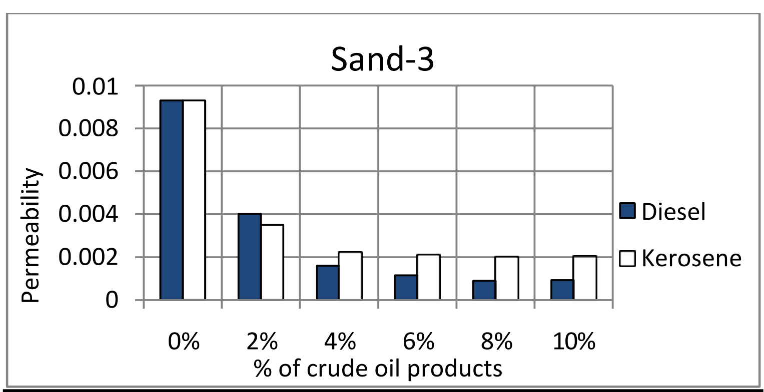


FIGURE 4.39 Effect of different % of diesel and kerosene on permeability ofsand-3

CHAPTER 5 REGRESSION ANALYSES

5.1 Models Statistics

It was recognized from testing that the shear strength, angle of internal friction, cohesion and permeability of sandy soil are complicated and affected by several parameters. Models that predict different properties of sandy soils with reasonable accuracy were sought. Utilizing the experimental data obtained by the tests methods, a multiple regression analyses was performed. In order to evaluate the important effect of crude oil products on the geotechnical properties on the soil, multiple regression analyses was performed on the test data to include variables such as coefficient of curvature, coefficient of uniformity, specific gravity, normal stress and percentage of diesel/ kerosene. Several trials among variables were done using EXCEL computer program to select the best fit formulas. The best fit models that could represent the shear strength, friction angle, cohesion and permeability are those that have a correlation coefficient (R^2) close to 1, a low value of standard error of estimation (SEE). The trial outputs that were done are listed below with the addition of diesel and with the addition of kerosene.

5.1.1 Addition of Diesel

TABLE 5.1 Multiple regression analysis output when diesel was added

Model details	Model Statistics	Model output	Independent Variable Output					
Shear Strength	*Multiple R*	0.99845	*variable, xi units*	NS	C_c	C_u	SG	D
	R Square	0.99691	*coefficient of xi*	0.776103	-18.1109	4.94204	3.651151	-0.36769
	Adjusted R Square	0.96425	*Standard Error*	0.017168	14.24793	1.323539	5.536816	0.131669
	Standard Error	3.53305	*t Stat*	45.20595	-1.27113	3.733957	0.659431	-2.79252
	Observations	36	*P-value*	7.24E-30	0.213139	0.000761	0.514488	0.00888

Model details	Model Statistics	Model output	Independent Variable Output				
Friction angle	*Multiple R*	0.999835	*variable, xi units*	C_c	C_u	SG	D
	R Square	0.999669	*coefficient of xi*	-12.39776	1.18289	17.733	-0.3588
	Adjusted R Square	0.874545	*Standard Error*	5.884398	0.546355	2.280278	0.05438
	Standard Error	0.842451	*t Stat*	-2.10689	2.165059	7.776681	-6.59867
	Observations	12	*P-value*	0.068203	0.062296	5.35E-05	0.00017

Model details	Model Statistics	Model output	Independent Variable Output				
Cohesion	*Multiple R*	0.970823	*variable, xi units*	C_c	C_u	SG	D
	R Square	0.942497	*coefficient of xi*	6.423044	0.577086	-6.251155	10.88616
	Adjusted R Square	0.795933	*Standard Error*	6.362732	0.600373	2.688865	2.688865
	Standard Error	0.910581	*t Stat*	1.009479	0.961213	-2.32483	4.420573
	Observations	12	*P-value*	0.342299	0.364593	0.048552	0.002225

Model details	Model Statistics	Model output	Independent Variable Output				
Permeability (D =< 4%)	*Multiple R*	0.992411	*variable, xi units*	C_c	C_u	SG	D
	R Square	0.984879	*coefficient of xi*	0.092071	-0.0032	-0.0006	-0.00245
	Adjusted R Square	0.575806	*Standard Error*	0.015203	0.000894	0.000128	0.000365
	Standard Error	0.001788	*t Stat*	6.056061	-3.58193	-4.67267	-6.71384
	Observations	9	*P-value*	0.001771	0.015842	0.005469	0.00111

Model details	Model Statistics	Model output	Independent Variable Output				
Permeability (D > 4%)	*Multiple R*	0.99249	*variable, xi units*	C_c	C_u	SG	D
	R Square	0.985036	*coefficient of xi*	0.013664872	0.000239	-8.9E-05	-0.00024
	Adjusted R Square	0.576058	*Standard Error*	0.002743611	0.000163	2.36E-05	6.59E-05
	Standard Error	0.000323	*t Stat*	4.980616572	1.468398	-3.75041	-3.71656
	Observations	9	*P-value*	0.004173512	0.20193	0.013288	0.013761

5.1.2 Addition of Kerosene

TABLE 5.2 Multiple regression analysis output when kerosene was added

Model details	Model Statistics	Model output	Independent Variable Output					
Shear Strength	*Multiple R*	0.9986015	*variable, xi units*	NS	C_c	C_u	SG	Kr
	R Square	0.997205	*coefficient of xi*	0.767656	-36.4176	3.78618	10.72383	-0.29438
	Adjusted R Square	0.9645862	*Standard Error*	0.016289	13.51799	1.255733	5.253157	0.124924
	Standard Error	3.3520499	*t Stat*	47.1284	-2.69401	3.015117	2.041406	-2.35652
	Observations	36	*P-value*	2.03E-30	0.011293	0.00509	0.049801	0.024946

Model details	Model Statistics	Model output	Independent Variable Output				
Friction angle	*Multiple R*	0.9997556	*variable, xi units*	C_c	C_u	SG	Kr
	R Square	0.9995113	*coefficient of xi*	-14.2612	1.387319	18.08404	-0.36808
	Adjusted R Square	0.8743281	*Standard Error*	7.092862	0.658559	2.748574	0.065548
	Standard Error	1.0154635	*t Stat*	-2.01063	2.106599	6.579428	-5.6154
	Observations	12	*P-value*	0.0792	0.068233	0.000173	0.000501

Model details	Model Statistics	Model output	Independent Variable Output				
Cohesion	*Multiple R*	0.97134	*variable, xi units*	C_c	C_u	SG	Kr
	R Square	0.943502	*coefficient of xi*	-10.5087	-0.83669	-0.43951	13.80499
	Adjusted R Square	0.797315	*Standard Error*	7.967865	0.751829	3.367187	3.08386
	Standard Error	1.140295	*t Stat*	-1.31889	-1.11288	-0.13053	4.476529
	Observations	12	*P-value*	0.223706	0.29808	0.899371	0.002065

Model details	Model Statistics	Model output	Independent Variable Output				
Permeability (Kr =< 4%)	*Multiple R*	0.987426	*variable, xi units*	C_c	C_u	SG	Kr
	R Square	0.975009	*coefficient of xi*	0.155627	-0.00714	-0.00107	-0.00106
	Adjusted R Square	0.560015	*Standard Error*	0.025163	0.001479	0.000213	0.000604
	Standard Error	0.00296	*t Stat*	6.184742	-4.82749	-5.04556	-1.75036
	Observations	9	*P-value*	0.155627	-0.00714	-0.00107	-0.00106

Model details	Model Statistics	Model output	Independent Variable Output				
Permeability (Kr > 4%)	*Multiple R*	0.912806	variable, xi units	Cc	Cu	SG	Kr
	R Square	0.833215	coefficient of xi	0.073476	-0.00347	-0.00042	-0.00129
	Adjusted R Square	0.333145	Standard Error	0.033194	0.001968	0.000286	0.000797
	Standard Error	0.003905	t Stat	2.213535	-1.76106	-1.46713	-1.61544
	Observations	9	P-value	0.077758	0.138535	0.202258	0.167138

5.2 Determined Equations

Different models of shear strength, friction angle, cohesion and permeability of sandy soil were analyzed using multiple regression analysis and a list of equations was determined.

TABLE 5.3 List of equations determined by multiple regression analysis

	Shear Strength
DIESEL	$SS = 0.7761\ NS - 18.1109\ C_c + 4.942\ C_u + 3.65115\ G_S - 0.3677\ D$
KEROSENE	$SS = 0.76765\ NS - 36.4176\ C_c + 3.78618\ C_u + 10.7238\ G_S - 0.29438\ Kr$

	Friction Angle
DIESEL	$\phi = - 12.3977\ C_c + 1.1829\ C_u + 17.733\ G_S - 0.35884\ D$
KEROSENE	$\phi = - 14.2612\ C_c + 1.38932\ C_u + 18.084\ G_S - 0.36808\ Kr$

	Cohesion
DIESEL	$C = 6.423044\ C_c + 0.577086\ C_u - 6.251155\ G_S + 10.88616\ D^{0.1}$
KEROSENE	$C = - 10.5087\ C_c - 0.83669\ C_u - 0.43951\ G_S + 13.805\ Kr^{0.1}$

	Permeability
Diesel (D =< 4%)	$k = 0.092071\ C_c - 0.0032\ C_u - 0.0006\ G_S - 0.00245\ D$
Diesel (D> 4%)	$k = 0.013664872\ C_c + 0.000239\ C_u - 8.9E\text{-}05\ G_S - 0.00024\ D$
Kerosene (Kr =< 4%)	$k = 0.155627\ C_c - 0.00714\ C_u - 0.00107\ G_S - 0.00106\ Kr$
Kerosene (Kr> 4%)	$k = 0.073476\ C_c - 0.00347\ C_u - 0.00042\ G_S - 0.00129\ Kr$

<u>From the equation:</u>

SS – Shear strength in kPa
ϕ – Angle of internal friction in degrees
C – Cohesion
k – Permeability in cm/s
NS – Normal stress in kPa
C_c – Coefficient of curvature
C_u – Coefficient of uniformity
G_S – Specific gravity
D – Percentage of diesel
Kr - Percentage of kerosene

5.3 Mathematical modeling to predict Shear Strength

A total of 72 shear strength data sets were analyzed for shear strength with the addition of crude oil products on the soil samples. From these data sets, 36 sets were found by the addition of diesel and 36 sets by the addition of kerosene. The accuracy of the regression models was checked. Comparison of experimental values and predicted values of shear strength are presented in tables below. The accuracy of the results and the percentages of relative error for the different specimens tested are shown in the figures.

The significantly high coefficients of correlation values indicate that the approximation concept used for the analyses performed well for the soil samples. Coefficient of curvature, coefficient of uniformity, specific gravity, normal stress and percentage of diesel/ kerosene were used as independent variable during the analyses of the models.

5.3.1 Shear Strength (Diesel)

TABLE 5.4 Measured, predicted and relative error values for the shear strength with different % of diesel added

Sample No.	Measured (kPa)	Predicted (kPa)	Relative Error (%)
1	20.16	21.91	8.67
2	40.32	43.25	7.28
3	80.63	85.93	6.58
4	25.30	30.95	22.32
5	50.60	52.29	3.34
6	101.20	94.97	-6.15
7	23.49	25.55	8.78
8	46.97	46.89	-0.17
9	93.94	89.57	-4.65
10	22.13	20.43	-7.66
11	41.76	41.78	0.04
12	81.02	84.46	4.25
13	26.99	29.47	9.22
14	50.78	50.82	0.08
15	98.35	93.50	-4.93
16	25.50	24.08	-5.60
17	48.11	45.42	-5.59
18	93.32	88.10	-5.59
19	24.41	18.96	-22.30
20	43.66	40.31	-7.68
21	82.17	82.99	1.00
22	26.74	28.00	4.74
23	49.42	49.35	-0.16
24	94.80	92.03	-2.92
25	23.25	22.60	-2.79
26	43.31	43.95	1.48
27	83.41	86.63	3.86
28	22.86	17.49	-23.48
29	41.12	38.84	-5.56
30	77.64	81.52	5.00
31	24.66	26.53	7.62
32	46.71	47.88	2.50
33	90.82	90.56	-0.29
34	21.64	21.13	-2.33
35	40.48	42.48	4.95
36	78.15	85.16	8.97

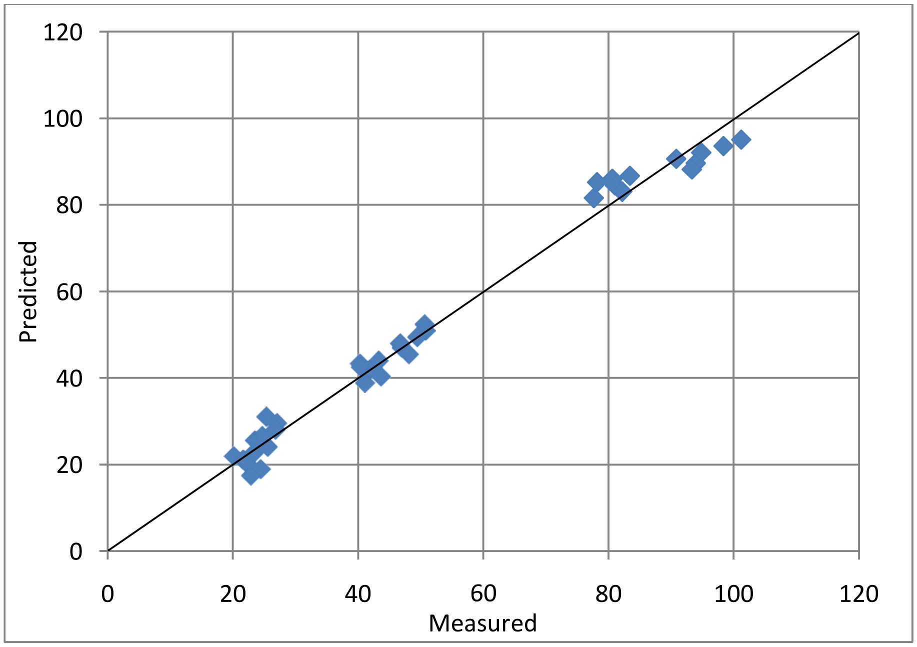


FIGURE 5.1 Accuracy of shear strength model with different % of diesel added

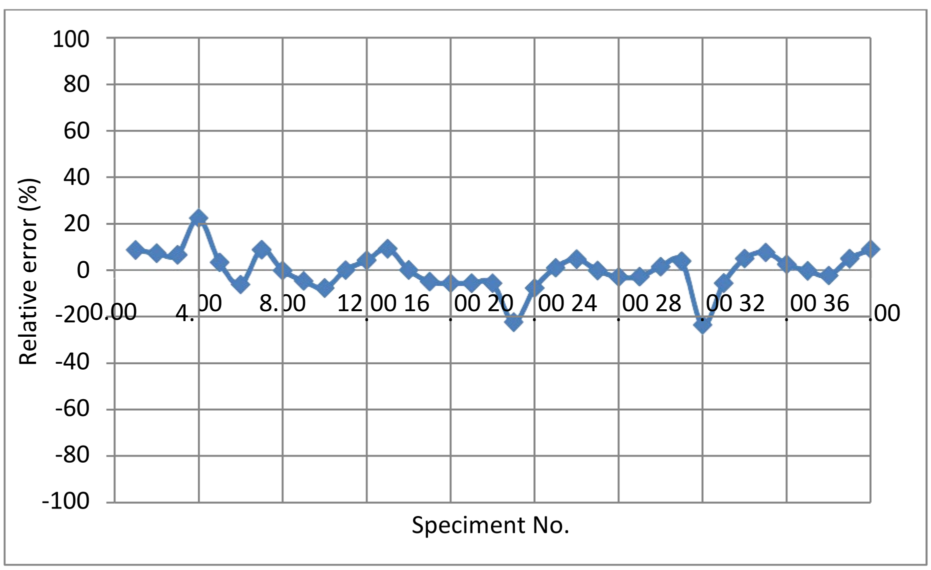


FIGURE 5.2 Error in Test data for shear strength with different % of diesel added

5.3.2 Shear Strength (Kerosene)

TABLE 5.5 Measured, predicted and relative error values for the shear strength with different % of kerosene added

Sample No.	Measured (kPa)	Predicted (kPa)	Relative Error (%)
1	20.16	20.99	4.11
2	40.32	42.10	4.42
3	80.63	84.32	4.57
4	25.30	30.53	20.68
5	50.60	51.64	2.06
6	101.20	93.86	-7.25
7	23.49	26.43	12.52
8	46.97	47.54	1.20
9	93.94	89.76	-4.45
10	22.49	19.81	-11.93
11	41.63	40.92	-1.72
12	79.92	83.14	4.03
13	25.20	29.35	16.49
14	50.40	50.47	0.13
15	100.80	92.69	-8.05
16	26.66	25.25	-5.28
17	47.71	46.36	-2.84
18	89.82	88.58	-1.38
19	23.57	18.63	-20.97
20	41.70	39.74	-4.69
21	77.94	81.96	5.16
22	26.00	28.18	8.36
23	47.76	49.29	3.21
24	91.26	91.51	0.27
25	25.41	24.07	-5.28
26	45.17	45.18	0.02
27	84.69	87.40	3.20
28	22.32	17.45	-21.81
29	40.59	38.56	-5.00
30	77.13	80.78	4.73
31	26.29	27.00	2.69
32	47.69	48.11	0.89
33	90.47	90.33	-0.15
34	23.69	22.89	-3.36
35	43.38	44.00	1.45
36	82.75	86.22	4.20

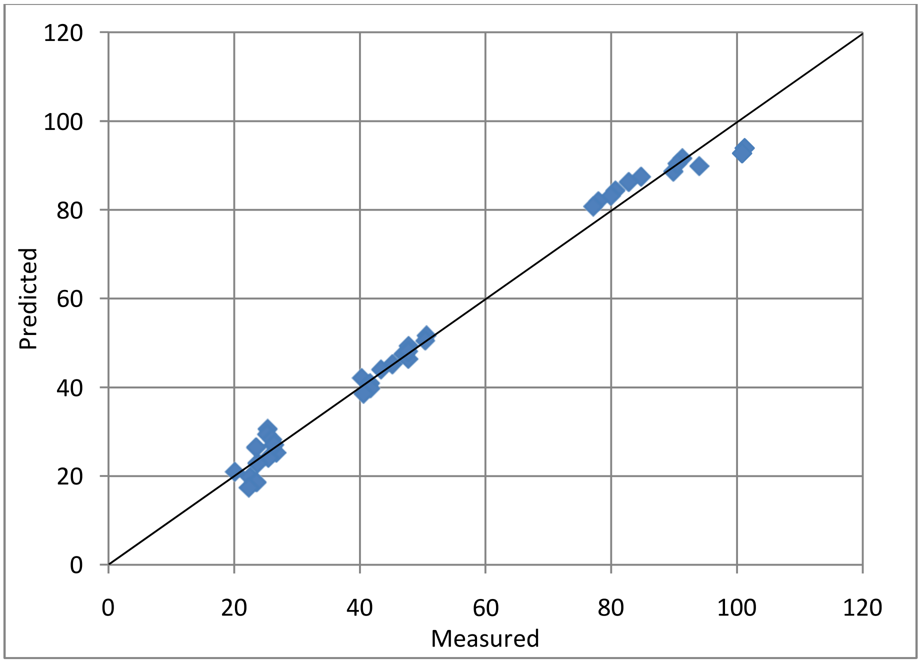


FIGURE 5.3 Accuracy of shear strength model with different % of kerosene added

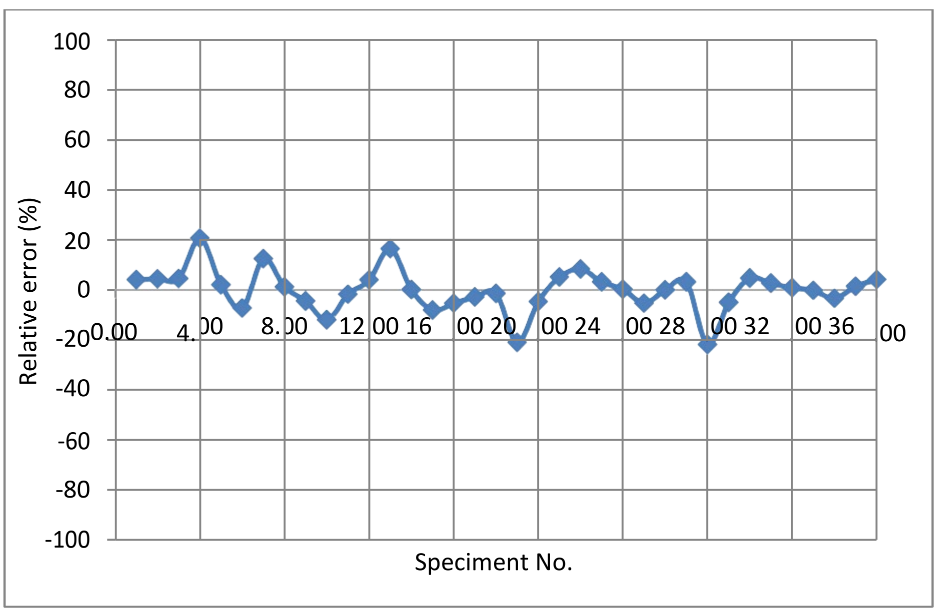


FIGURE 5.4 Error in Test data for shear strength with different % of kerosene added

5.4 Mathematical modeling to predict angle of internal friction

A total of 24 shear strength data sets were analyzed for friction angle with the addition of crude oil products on the soil samples. From these data sets, 12 sets were found by the addition of diesel and 12 sets by the addition of kerosene. The accuracy of the regression models was checked. Comparison of experimental values and predicted values of friction angle are presented in tables below. The accuracy of the results and the percentages of relative error for the different specimens tested are shown in the figures.

The significantly high coefficients of correlation values indicate that the approximation concept used for the analyses performed well for the soil samples. Coefficient of curvature, coefficient of uniformity, specific gravity, normal stress and percentage of diesel/ kerosene were used as independent variable during the analyses of the models.

5.4.1 Friction Angle (Diesel)

TABLE 5.6 Measured, predicted and relative error values for the friction angle with different % of diesel added

Sample No.	Measured (°)	Predicted (°)	Relative Error (%)
1	36.24	37.24	2.75
2	42.61	42.58	-0.07
3	40.50	39.76	-1.82
4	35.52	35.80	0.80
5	40.86	41.15	0.71
6	39.42	38.32	-2.78
7	35.00	34.37	-1.80
8	39.52	39.71	0.49
9	36.10	36.89	2.19
10	33.58	32.93	-1.94
11	38.73	38.28	-1.17
12	34.41	35.45	3.03

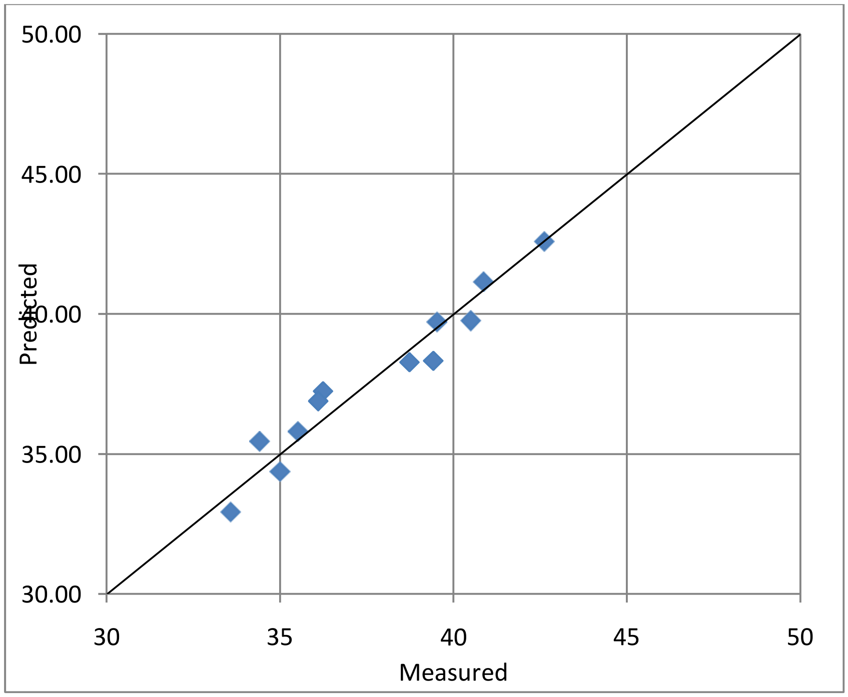


FIGURE 5.5 Accuracy of friction angle model with different % of diesel added

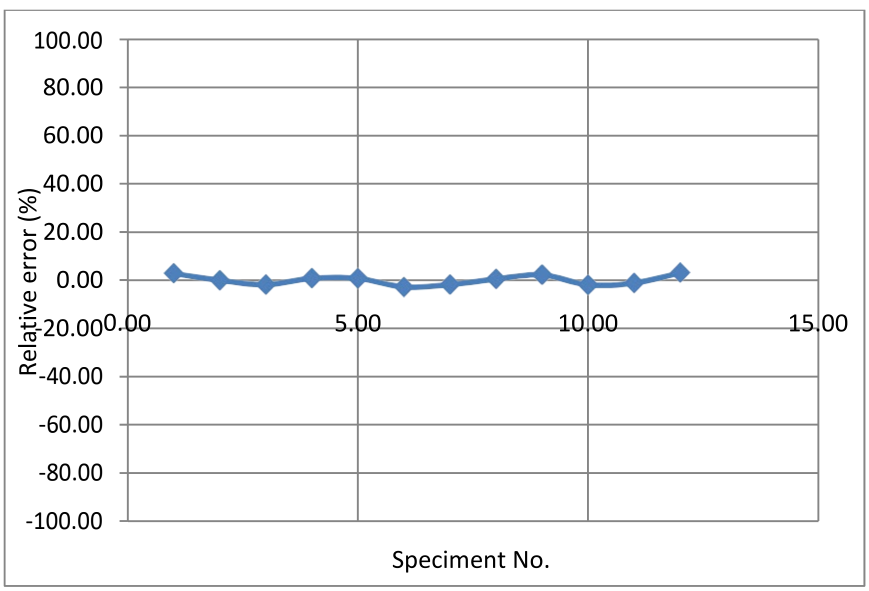


FIGURE 5.6 Error in Test data for friction angle with different % of diesel added

5.4.2 Friction Angle (Kerosene)

TABLE 5.7 Measured, predicted and relative error values for the friction angle with different % of kerosene added

Sample No.	Measured (°)	Predicted (°)	Relative Error (%)
1	36.24142	36.72504	1.334456
2	42.614	42.54297	-0.16669
3	40.49733	39.5178	-2.41875
4	34.84	35.25273	1.184645
5	42.5	41.07066	-3.36316
6	37.44	38.04549	1.617221
7	33.38488	33.78042	1.184778
8	38.344	39.59834	3.271298
9	35.7	36.57318	2.445871
10	33.6	32.30811	-3.84492
11	37.88	38.12603	0.649503
12	35.6	35.10086	-1.40207

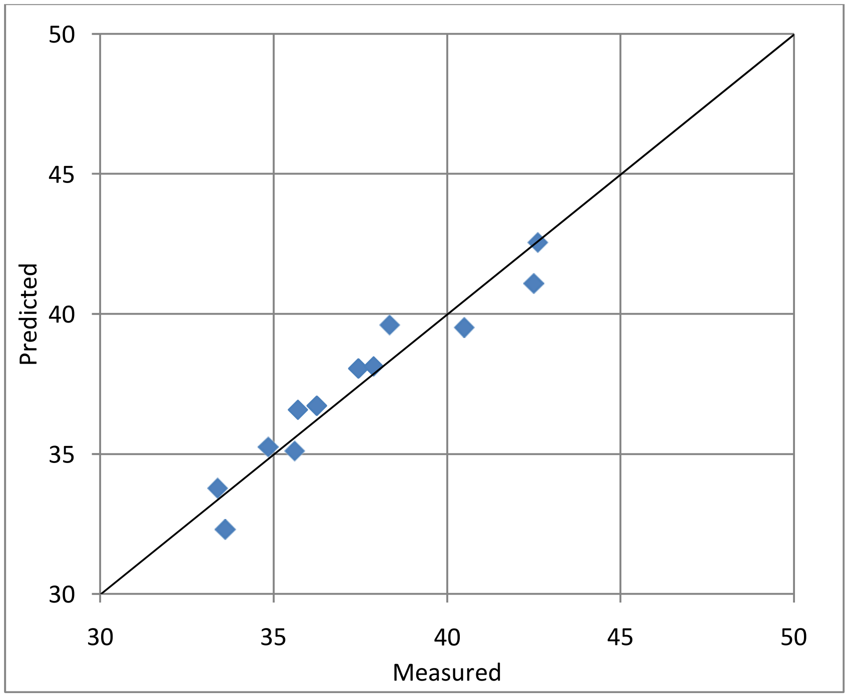


FIGURE 5.7 Accuracy of friction angle model with different % of kerosene added

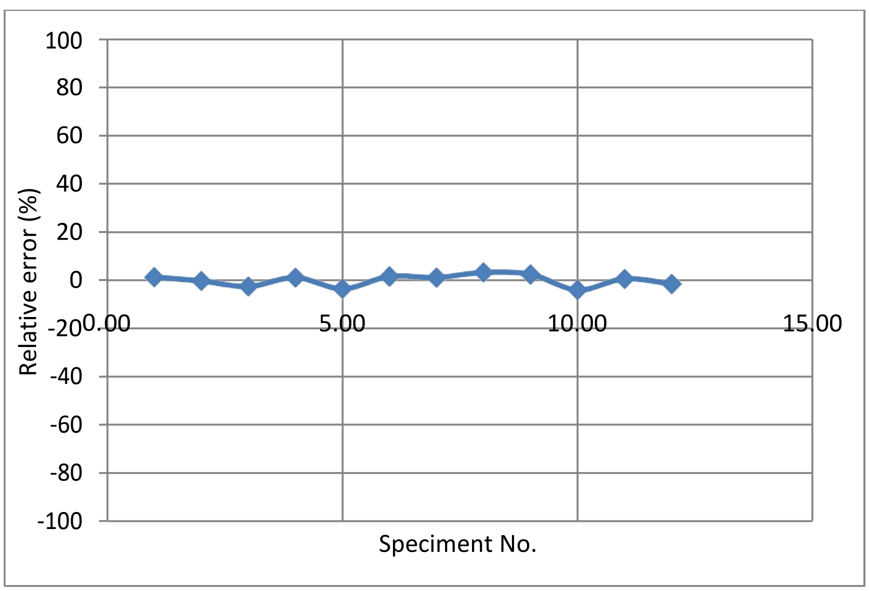


FIGURE 5.8 Error in Test data for friction angle with different % of kerosene added

5.5 Mathematical modeling to predict Cohesion

A total of 24 shear strength data sets were analyzed for cohesion with the addition of crude oil products on the soil samples. From these data sets, 12 sets were found by the addition of diesel and 12 sets by the addition of kerosene. The accuracy of the regression models was checked. Comparison of experimental values and predicted values of cohesion are presented in tables below. The accuracy of the results for the different specimens tested are shown in the figures.

The coefficients of correlation values indicate the approximation accuracy used for the analyses performed for the soil samples. Coefficient of curvature, coefficient of uniformity, specific gravity, normal stress and percentage of diesel/ kerosene were used as independent variable during the analyses of the models.

5.5.1 Cohesion (Diesel)

TABLE 5.8 Measured and predicted values and relative error values for the cohesion with different % of diesel added

Sample No.	Measured (kPa)	Predicted (kPa)
1	0.5	1.386026
2	0.8	0.861026
3	0.8	0.623526
4	2.5	3.004781
5	3.2	2.479781
6	2.9	2.242281
7	5.15	3.902302
8	4.05	3.377302
9	3.2	3.139802
10	4.6	4.456892
11	2.6	3.931892
12	2.8	3.694392

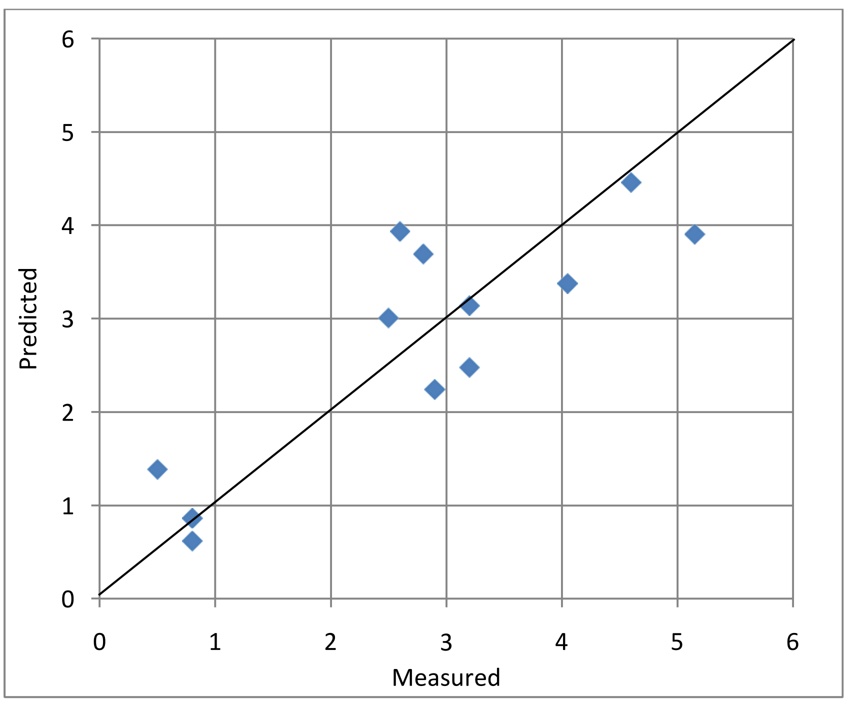


FIGURE 5.9 Accuracy of cohesion model with different % of diesel added

5.5.2 Cohesion (Kerosene)

TABLE 5.9 Measured and predicted values for the cohesion with different % of kerosene added

Sample No.	Measured (kPa)	Predicted (kPa)
1	0.9	1.15301
2	0.35	0.46551
3	1.5	1.90301
4	3.35	3.205789
5	1.5	2.518289
6	5.6	3.955789
7	5.45	4.343956
8	4.25	3.656456
9	5.65	5.093956
10	4.05	5.047244
11	4.9	4.359744
12	4	5.797244

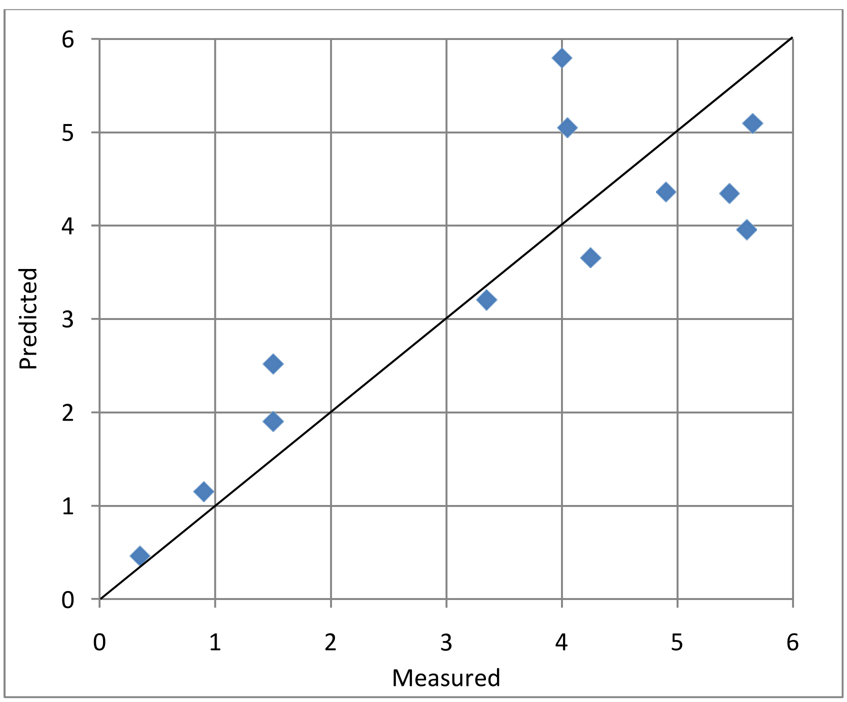


FIGURE 5.10 Accuracy of cohesion model with different % of kerosene added

5.6 Mathematical modeling to predict Permeability

A total of 24 shear strength data sets were analyzed for permeability with the addition of crude oil products on the soil samples. From these data sets, 12 sets were found by the addition of diesel and 12 sets by the addition of kerosene. The accuracy of the regression models was checked. Comparison of experimental values and predicted values of permeability are presented in tables below. The accuracy of the results and the percentages of relative error for the different specimens tested are shown in the figures.

The coefficients of correlation values indicate the approximation accuracy used for the analyses performed for the soil samples. Coefficient of curvature, coefficient of uniformity, specific gravity, normal stress and percentage of diesel/ kerosene were used as independent variable during the analyses of the models.

5.6.1 Permeability (Diesel)

TABLE 5.10 Measured and predicted values for the permeability when % of diesel added is less than or equal to 4%

Sample No.	Measured (cm/s)	Predicted (cm/s)
1	0.019514	0.01924
2	0.013405	0.013204
3	0.009292	0.009866
4	0.0165	0.014338
5	0.0073	0.008302
6	0.004	0.004964
7	0.007	0.009436
8	0.0042	0.0034
9	0.0016	6.22E-05

TABLE 5.11 Measured and predicted values for the permeability when % of diesel added is more than 4%

Sample No.	Measured (cm/s)	Predicted (cm/s)
1	0.0028	0.002637
2	0.0031	0.002802
3	0.00115	0.001483
4	0.002	0.002148
5	0.0023	0.002313
6	0.0009	0.000994
7	0.001643	0.001658
8	0.001538	0.001823
9	0.000931	0.000504

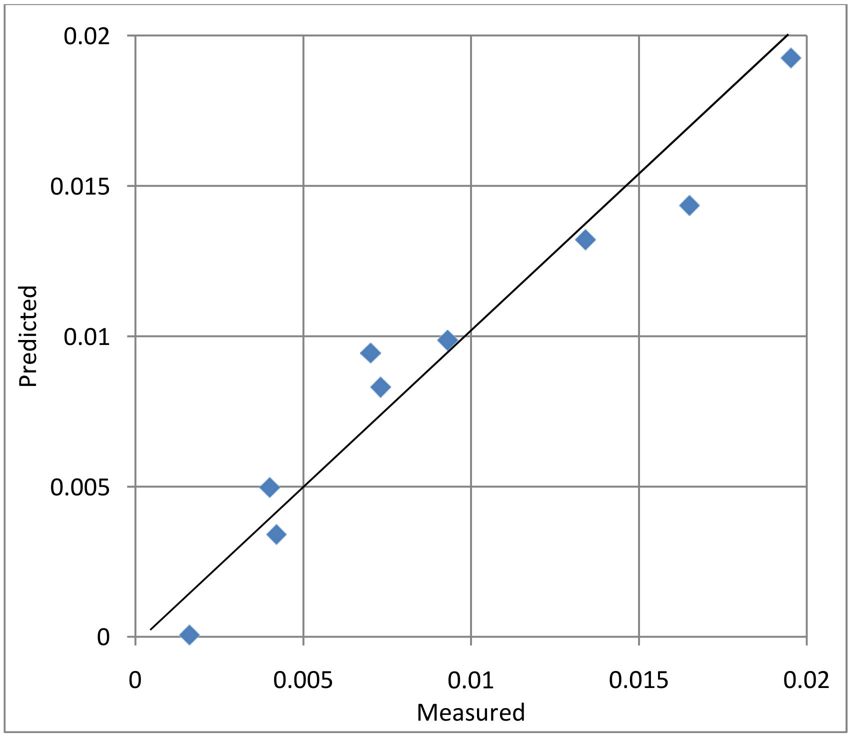


FIGURE 5.11 Accuracy of permeability model when % of diesel added is less than or equal to 4%

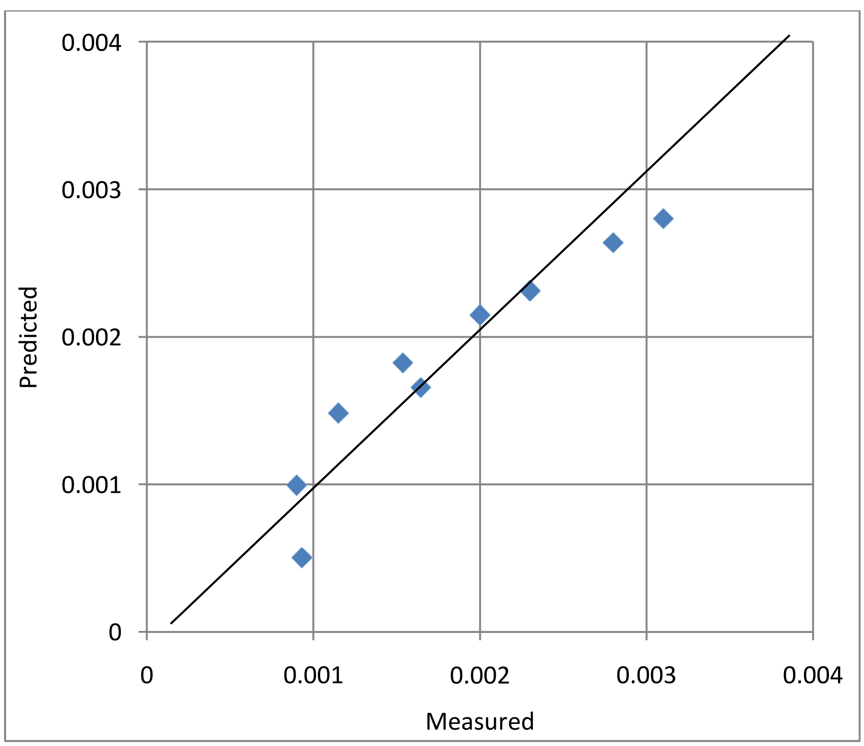


FIGURE 5.12 Accuracy of permeability model when % of diesel added is more than 4%

5.6.2 Permeability (Kerosene)

TABLE 5.12 Measured and predicted values for the permeability when % of kerosene added is less than or equal to 4%

Sample No.	Measured (cm/s)	Predicted (cm/s)
1	0.019514	0.023453
2	0.013405	0.011084
3	0.009292	0.007119
4	0.022	0.021338
5	0.0087	0.008968
6	0.0035	0.005004
7	0.0225	0.019223
8	0.0048	0.006853
9	0.00222	0.002889

TABLE 5.13 Measured and predicted values for the permeability when % of kerosene added is more than 4%

Sample No.	Measured (cm/s)	Predicted (cm/s)
1	0.0175	0.012498
2	0.0034	0.005895
3	0.002106	0.004624
4	0.01	0.009923
5	0.0033	0.00332
6	0.002013	0.002048
7	0.002269	0.007348
8	0.00326	0.000745
9	0.002026	0.00053

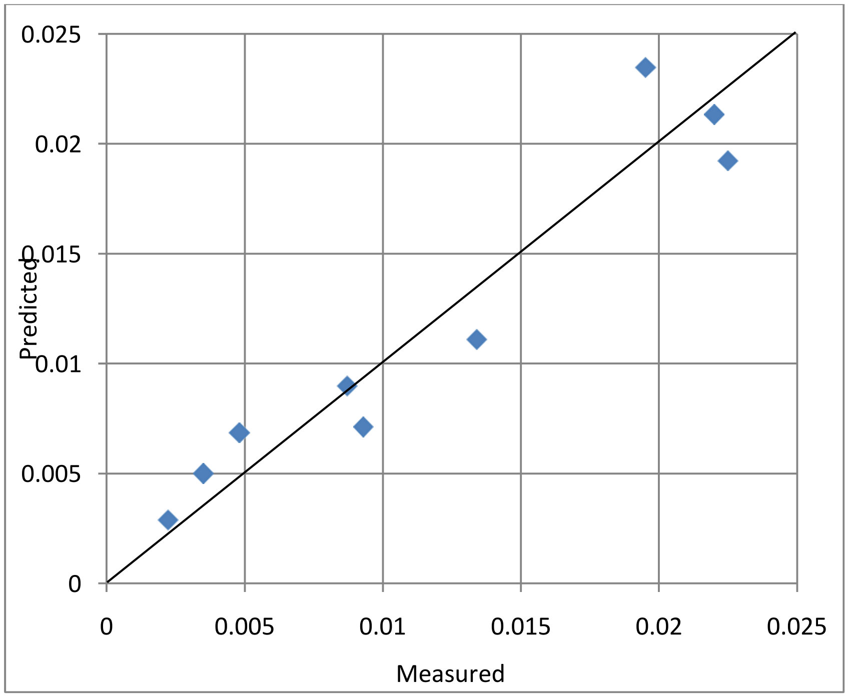


FIGURE 5.13 Accuracy of permeability model when % of kerosene added is less than or equal to 4%

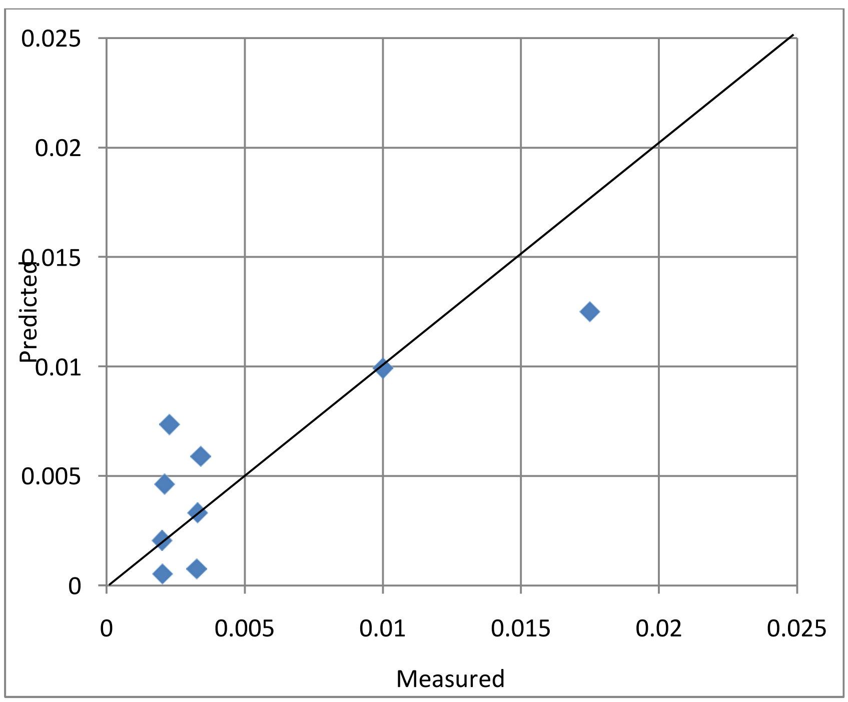


FIGURE 5.14 Accuracy of permeability model when % of kerosene added is more than 4%

CHAPTER 6 CONCLUSION

6.1 Summary and Conclusions

A testing research was carried out to study and analyze the effects of crude oil products – kerosene and diesel – on some of the geotechnical properties of three types of soil. The results of these experiments have shown important results by changing the shear strength, friction angle, cohesion and the coefficient of permeability of the soil. By analyzing the data, this would provide a comprehensive idea of the behavior of contaminated soil due to the addition of crude oil products. Added to that, this may provide guidance and information to engineers and researchers in the future.

In the first part of the research, classifying the soil was an important issue. In order to study the effect of crude oil products on sandy soil, it would be important to find soils with different gradations. Sieve size distribution was used to measure the gradation of the sand. This was done for the three different soils and they were classified using the Unified Soil Classification System. The crude oil products used were diesel and kerosene. From the values obtained it was noticed that all of the values of Cu were less than 6 and all the values of Cc were less than 1. Therefore, it was concluded that the three soil samples were poorly graded sands with different gradations.

In all the research experiments the maximum dry unit weight and the optimum moisture content were chosen to be the base conditions. Therefore, in order to determine these values, the standard proctor compaction test was used. This test determines the optimum amount of water to be mixed with soil in order to obtain maximum compaction for a given soil sample. The standard sizes of the apparatus used for the test were based on ASTM D-698. This was done for the three different soils. It was found that the maximum dry unit weight for sand-1, sand-2 and sand-3 were 106.3 lb/ft^3, 99.2 lb/ft^3 and 104.8 lb/ft^3 and their optimum moisture content were 4%, 16% and 14%.

The shear strength of the soil sample was determined using a displacement controlled direct shear apparatus found in the Geotechnical Engineering Lab in the American University of Sharjah. The horizontal displacement, vertical displacement and the shear force were determined using direct shear machine. This test was repeated for the three soil samples separately with different percentages of crude oil product (kerosene and diesel).

From the results, it was seen that as the percentage of crude oil products increased, the angle of internal friction of the sand would decrease. An apparent cohesion was found and increased gradually as diesel and kerosene were added to the soil. The maximum increase was noticed at 8 percent of crude oil product being added. When more than 8 percent was added, less increase in cohesion was noticed. At low normal stress, as the percentage of crude oil products added to the soil is increased, the shear strength increases up to a certain percent and then it decreases. At high normal stress, as the percentage of crude oil products added to the soil is increased, the shear strength decrease. It was noticed that as we increase the normal stress, the shear strength of the soil would show more noticeable reduction.

A slightly greater decrease in the friction angle was noticed for the addition of kerosene than that with the addition of diesel. A slightly greater value of apparent cohesion was noticed for the addition of kerosene than that with the addition of diesel. A slightly greater decrease in shear strength was noticed for the addition of kerosene than that with the addition of diesel.

In this study, the constant head method was used since the soil is a granular. The experiment was carried according to ASTM D-2434 standard specifications. From this the coefficient of permeability was determined. This test was carried out for the three soil sample separately with different percentages of crude oil products (kerosene and diesel).

The results have shown an inverse correlation between permeability and crude oil products content which means that the addition of diesel and kerosene has caused a reduction in the permeability of the sand. The maximum change in permeability was noticed between 0% and 5% diesel and kerosene. The rate of reduction of permeability was faster for the sand by the addition of diesel than by the addition of kerosene.

A total of 120 data sets were analyzed for shear strength, friction angle, cohesion and permeability with the addition of crude oil products on the soil samples. The accuracy of the regression models was checked. Comparison of experimental values and predicted values of were presented and the accuracy of the results and the percentages of relative error for the different specimens tested were found. The significantly high coefficients of correlation values indicated that the approximation concept used for the analyses performed well for the soil samples. Different models of shear strength, friction angle, cohesion and permeability of sandy soil were analyzed using multiple regression analysis and a list of equations was determined.

6.2 Recommendations for Future Research

Based on the findings of this research study, the following recommendations are made for future research:

- The study was made for sandy soil. It is important to include different types of soil such as silt and clay and develop additional characterization models to evaluate their geotechnical properties.
- There is a need to investigate the effect of viscosity of different crude oil products such as heavy oil on the shear strength parameters. Results from such a study can provide additional verification of the effect viscosity on the geotechnical properties of soil.
- The effectiveness of the laboratory test procedures should be validated through expanded test program to include additional soils and oil sand samples.
- Further validation and verification of the models can be accomplished using the results of addition laboratory tests and field test, which can be performed on soil sample obtained location where crude oil products have leaked.
- There is a need to investigate the effects of chemicals such as glycerol, propanol and acetone on soil.
- There is a need to investigate the effect of crude oil products on the dry unit weight of soil.
- A naturally oil contaminated soil can be studied and compared to the results obtained in this research.

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VITA

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