EFFECTS OF PETROLEUM DISTILLATE ON VISCOSITY, DENSITY AND SURFACE TENSION OF INTERMEDIATE AND HEAVY CRUDE OILS

A Thesis

by

AZER ABDULLAYEV

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2007

Major Subject: Petroleum Engineering

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Approved by:

Chair of Committee,	Daulat D. Mamora
Committee Members,	Jerome J. Schubert
	Luc T. Ikelle
Head of Department,	Stephen A. Holditch

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ABSTRACT

Effects of Petroleum Distillate on Viscosity, Density
and Surface Tension of Intermediate and Heavy Crude Oils. (August 2007)

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Chair of Advisory Committee: Dr. Daulat Mamora

Experimental and analytical studies have been carried out to better understand the effects of additives on viscosity, density and surface tension of intermediate and heavy crude oils. The studies have been conducted for the following oil samples: San Francisco oil from Columbia with specific gravity of 28^{o}-29^{o} API, Duri oil with gravity of 19^{o}-21^{o} API, Jobo oil with gravity of 8^{o}-9^{o} API and San Ardo oil gravity of 11^{o}-13^{o} API. The additive used in all of the experiments is petroleum distillate. The experiments consist of using petroleum distillate as an additive for different samples of heavy crude oils. The experiments include making a mixture by adding petroleum distillate to oil samples and measuring surface tension, viscosity and density of pure oil samples and mixtures at different temperatures. The petroleum distillate/oil ratios are the following ratios: 1:100, 2:100, 3:100, 4:100 and 5:100.

Experimental results showed that use of petroleum distillate as an additive increases API gravity and leads to reduction in viscosity and surface tension for all the samples. Results showed for all petroleum distillate/oil ratios viscosity and interfacial tension decreases with temperature. As petroleum distillate/oil ratio increases, oil viscosity and surface tension decrease more significantly at lower temperatures than at higher temperatures. After all experiments were completed an analytical correlation was done based on the experiment results to develop “mixing rules”. Using this correlation viscosity, density and surface tension of different petroleum distillate/oil mixtures were obtained (output).These had properties of pure oil and petroleum distillate, mixture ratios and temperatures at which measurement is supposed to be done (output). Using this correlation a good match was achieved. For all of the cases (viscosity, density and surface tension), correlation coefficient (R^2) was more than 0.9 which proved to be optimum for a really good match.

ACKNOWLEDGMENTS

This thesis is dedicated to my parents, Zakir Abdullayev and Fazila Abdullayeva, who loved and supported me throughout my life. I would not wish for better parents.

I want to thank my advisor, Dr. Mamora for always being there to answer my questions and for helping with lab equipment. Without his help this project would be almost impossible to complete. I am also very grateful that Dr. Schubert and Dr. Ikelle were kind enough to agree to be on my committee.

Special thanks to Jose Rivero for his explanations of the equipment operation in the Ramey lab when I first started my experiments. This was time consuming and I really appreciate his effort.

I also want to thank my officemate and friend Mazen Barnawi for his moral support.

This research was made possible through the Ramey Laboratory Research Program and the Crisman Institute for Reservoir Management. Sponsorship of the program provided by US DOE, ChevronTexaco, ConocoPhillips, and also Total SA.

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CHAPTER I

INTRODUCTION

It is a known fact that heavy oil reserves make up a large portion of unconventional resources, which include coal bed methane, tight gas and hydrates. Due to market demand heavy oil production has increased substantially in the last decade.
Crude oils can be split into three groups:

- Heavy Crude: Crude oils with API gravity of 18 degrees or less is characterized as heavy. The oil is viscous and resistant to flow, and tends to have a lower proportion of volatile components. Fifty one percent of California crude oil has an average API of 18 degrees or less.

- Intermediate Crude: Crude oils with an API greater than 18 and less than 36 degrees are referred to as intermediate. Forty eight percent of California crude oil has an average API between 18 and 36 degrees.

- Light Crude: Crude oils with an API gravity of 36 degrees or greater. Light crude oil produces a higher percentage of lighter, higher priced premium products.

Additives like carbon dioxide and light hydrocarbons have been tested and showed to improve the recovery of heavy oils in the laboratory. However, the combined injection of steam and hydrocarbon additives (solvent) is often too costly due to the solvent's costs. Therefore, the need exists to better understand the oil recovery mechanisms associated with steam-hydrocarbon injection, such as steam-propane in order to corroborate the technical and economical feasibility of these processes.

This thesis follows the style of *SPE Reservoir Evaluation & Engineering*.

For the past few years, experimental and simulation studies[1-13] have been carried out in the Ramey Laboratory of the Petroleum Engineering Department in Texas A&M University to investigate the effects of the combined injection of steam and propane in heavy oil recovery. These experiments have shown encouraging results, specifically acceleration in oil recovery when compared to pure steam injection. Results of these experiments were compared and it is also proven that steam/propane gives much better results than hot/water combination[12]. Also for these past years as numerous experiments were carried propane proved itself to be an efficient additive to steam. The use of propane as an additive to steam resulted in lower injection pressures, higher ultimate recovery, and more reduction in viscosity than those of pure steam injection.

In 2005 production mechanisms involved in steam-propane and steam-petroleum distillate injection were studied[15]. The crude oil sample used was from the San Ardo field which has oil gravity of 11^o-12^o API and 3000cp of in-situ oil viscosity. Steam-petroleum distillate resulted in more improvement of injectivity, higher ultimate recovery, more reduction in viscosity than steam propane. Plus petroleum distillate is cheaper as compared to propane. This was a reason for further study of petroleum distillate as an additive.

The proposed research is intended to study petroleum distillate as an additive. The first aspect of the research is to perform a series of experiments to evaluate the effect of petroleum distillate as steam additives on viscosity, density and surface tension of various crude oil samples. The second aspect of the research is to come up with a correlation to estimate oil viscosity, density, and surface tension as a function of petroleum distillate/oil ratio, oil gravity and temperature.

1.1 Research Objectives

The main objective of the research is to evaluate the effect of petroleum distillate as an additive on viscosity, density and surface tension of heavy crude oils. To achieve this objective we will be using petroleum distillate as an additive in four crude oil samples. Heavy oil samples that are used in the experiments are the following:

1. San Ardo with specific gravity of 11^o-13^o API
2. Jobo with specific gravity of 8^o-9^o API
3. Duri with specific gravity of 19^o-21^o API
4. San Francisco with specific gravity of 28^o-29^o API

The idea to make the mixtures by adding petroleum distillate to the listed above oil samples in five different ratios. The petroleum distillate/oil sample: mixture ratios are the followings:

- 1:100
- 2:100
- 3:100
- 4:100
- 5:100

After the mixtures are made, the idea is to measure the viscosity, density and surface tension of pure samples and petroleum distillate/oil sample: mixtures at three different temperatures. This will help us to study the effect of petroleum distillate as an additive on viscosity, density and surface tension in general and conclude if it is reasonable to use petroleum distillate as an additive in industry.

CHAPTER II

LITERATURE REVIEW

As mentioned before, both experimental and simulation studies have been done before to investigate the effects of different additives in heavy oil recovery. In this section, a literature review covering previous studies with the combined use of steam and gaseous additives will be presented.

Redford (1982)[13] conducted experiments to study the effect of adding carbon dioxide, ethane and/or naphtha in combination with steam. His results showed that the addition of carbon dioxide or ethane improved the recovery. Further recovery was reached when naphtha was added.

Metwally (1990)[14] studied cores from the Lindbergh Field to investigate the effects of carbon dioxide and methane on the performance of steam processes. The experiments were conducted to determine the differences in performance of two different scenarios: simultaneous injection of steam and a gaseous additive and an injection of a gas slug prior to steam injection. The results showed that injection of CO_2 slug prior to the steam improved injectivity. On the other hand, the presence of a non-condensable gas with steam did not improve steam drive recovery and resulted in higher residual oil saturation compared to pure steam injection.

Gumrah and Okandan (1992)[15] performed linear and 3D displacement experiments to evaluate the performance of CO_2 addition to steam on the recovery of 24 °API, 12 °API and 10.6 °API oils. The 1D tests indicated that the oil recovery increased with increasing CO_2/steam ratios until an optimum value was reached. The addition of CO_2 did not produce a significant increase in the recovery of the lighter oil. However, the oil production rate was increased considerably for the heavier oils.

Bagci and Gumrah (1998)[16] performed experiments with both 1D and 3D models to investigate the effects of injecting methane and carbon dioxide along with steam in a 12.4 °API heavy oil. The results showed that the use of CO_2 or CH_4 combined with steam yielded a higher incremental oil recovery than of pure steam tests.

Goite (1999)[2,4] conducted several experiments to find out the influence of injecting propane as a gaseous additive to steam injection. Experimental results showed that the optimal concentration of propane lies in the region of 5 to 100.

Ferguson (2000)[3,5] continued Goite's experiments, but this time using a constant steam mass rate. A number of tests were performed to determine the optimum propane: steam mass ratio. Acceleration of production was found in the steam-propane runs compared to pure steam injection. The optimum propane: steam mass ratio was found to be 5:100. The acceleration in oil production was assumed to be due to the dry distillation process in which the lighter oil fractions are vaporized and carried by propane. On contact with the colder part of the reservoir, the light fractions condense and are miscible with the oil, thus lowering the interfacial tension and decreasing the oil viscosity.

Tinns (2001)[6] continued Ferguson's experiments using 5:100 propane/steam mass ratio on 21 °API Kulin oil from Indonesia. Effect of production acceleration was observed in these experiments as well. Viscosity and density measurements indicated an increment in API gravity and a reduction of viscosity in the produced oil. Furthermore, addition of propane to the steam improved injectivity.

Rivero (2002)[7] conducted a series of experiments using propane as a steam additive to evaluate the influence of propane on Hamaca heavy oil. The same effect of production acceleration was observed in these experiments as well. Improvement in steam injectivity was observed with propane/steam mass ration as low as 2.5:100.

Hendroyono (2003)[10] conducted experiments and found acceleration in production with as little as 1.25:100 propane/steam mass ratio. Up to 30% acceleration with optimum ratio (5% propane) was observed. Injectivity was found to be three times higher than with pure steam injection.

Nesse (2004)[12] found that steam-propane injection accelerates the start of production. The propane does not have the same effect with hot water, or water alternating steam. Also found that pure steam injection accelerates oil production more than these two other methods.

Simangunsong (2005)[15] found that the use of propane as an additive to steam resulted in injection pressures lower than those of pure steam injections. Improvement of injectivity is also found for runs using petroleum distillate as an additive to steam. Ultimate oil recovery is found to be higher for experimental runs using petroleum distillate. He also found that the fastest steam front propagation occurs in steam-petroleum distillate runs.

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CHAPTER III

EXPERIMENTAL APPARATUS AND PROCEDURES

There are three equipment pieces used for measurements: The Brookfield DV-III programmable rheometer for measuring viscosity, Anton Paar DMA 4100 Density/Specific Gravity/Concentration Meter for measuring density and KSV Sigma 703 Surface/Interfacial Tension meter for measuring surface tension.

3.1 Brookfield DV-III Programmable Rheometer.

The Brookfield DV-III programmable rheometer (**Fig. 3.1**) measures fluid parameters of shear stress and viscosity at given shear stress. The principle of operation of the DV-III is to drive a spindle (which is immersed in the test fluid) through a calibrated spring. The viscous drag of the fluid against the spindle is measured by the spring deflection. Spring deflection is measured with a rotary transducer. The measuring range of a DV-III (in centipoises) is determined by the rotational speed of spindle, the size and shape of the spindle, the container the spindle is rotating in, and the full scale torque of the calibrated spring. The spindle number used for the measurements is 52 (**Fig.3.2**).

The rheometer is connected to a water bath which lets us to control the temperature at which measurements are made (**Fig. 3.3**).

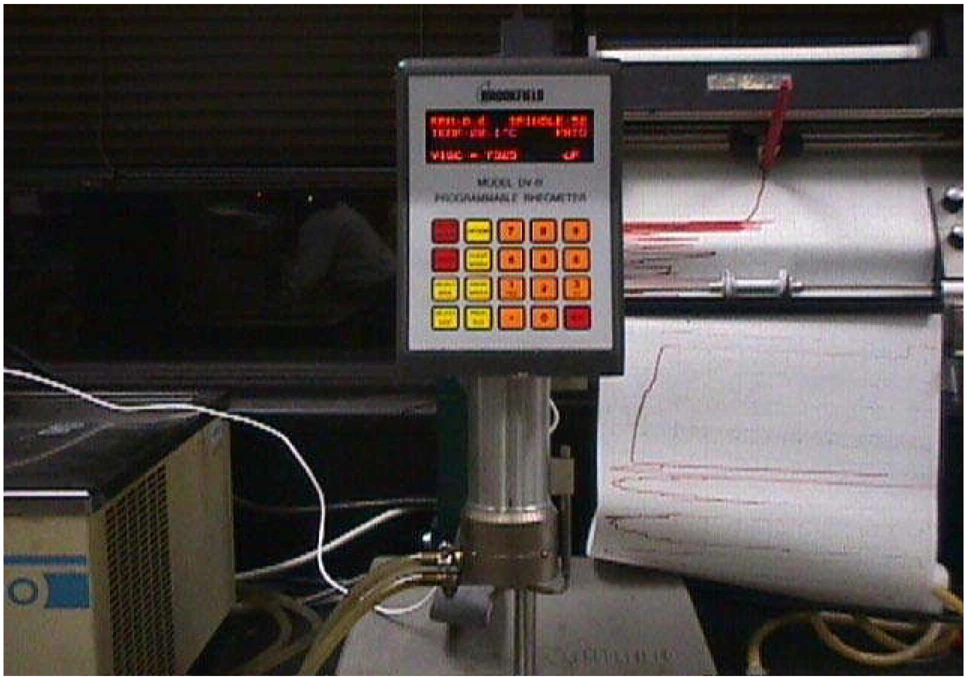

Fig. 3.1. Photograph of the programmable rheometer.

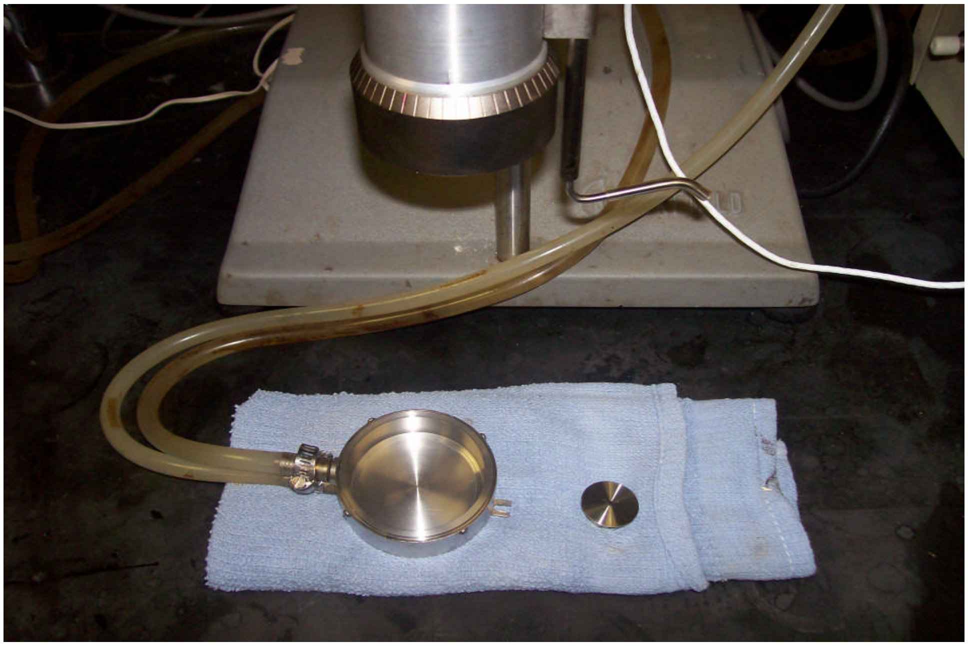

Fig. 3.2. Photograph of the spindle (to the right) and container (to the left) where it rotates.

Fig. 3.3. Photograph of the water bath for rheometer.

3.2 Anton Paar DMA 4100 Density/Specific Gravity/Concentration Meter

The 4-digit meter DMA 4100 (**Fig.3.4**) with fully-automatic compensation is primarily aimed at applications in quality control. It is ideal for checking beverages, liquid foodstuffs and food additives and for liquid chemicals and all types of petrochemical products.

The instrument has great advantages for daily use: rapid measurements – up to 60 per hour – and complete compensation of all influences from the sample viscosity without needing to alter the instrument settings. A built-in electronic thermostat ensures the correct measuring temperature.

At approx. 30 seconds per sample, the DMA 4100 measures up to 60 samples per hour. If you need to measure samples at different temperatures, the patented reference oscillator (AT 399051) eliminates long-term drift. You don't have to wait between measurements, just change the measuring temperature and continue measuring. The DMA 4100 is suitable for determining the density, specific gravity, as well as lots of different concentrations for various applications.

3.3 KSV Sigma 703 Surface/Interfacial Tension Meter

The measurement of surface and interfacial tension as performed by the Sigma 703 tension meter (**Fig. 3.5**) is based on force measurements of the interaction of a probe with surface of interface of two fluids. If one of the fluids is the vapor phase of a liquid being tested the measurement is referred to as surface tension. If the surface investigated is the interface of two liquids the measurement is referred to as interfacial tension. In either case the more dense fluid is referred to herein as the “heavy phase” (oil sample or mixture) and the less dense fluid is referred to as “light phase” (air). Measurements can be performed by insuring that the bulk of the probe is submersed in the light phase prior to beginning the experiment.

In these experiments a probe is hung on a balance and brought into contact with the liquid surface tested. The forces experienced by the balance as the probe interacts with the surface of the liquid can be used to calculate surface tension. The forces present in this situation depend on the following factors: size and shape of the probe, contact angle of the liquid/solid interaction and surface tension of the liquid. The size and shape of the probe are easily controlled. The contact angle is controlled to be zero (complete wetting). This is achieved by using probes with high-energy surfaces. KSV probes are made of a platinum/iridium alloy, which insures complete wetting and easy and reliable cleaning. The mathematical interpretation of the force measurements depends on the shape of the probe used. Two types of probes are commonly used, the DuNouy Ring and the Wilhelmy Plate. In the proposed research the Wilhelmy Plate is used (**Fig. 3.6**).

Fig. 3.4. Photograph of the density meter.

Fig. 3.5. Photograph of the surface/interfacial tension meter.

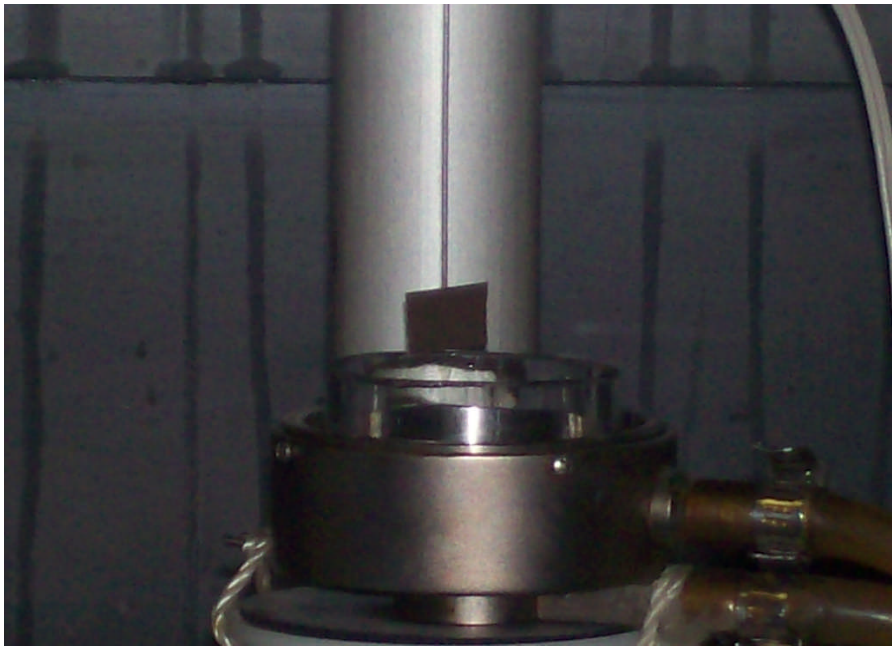

Fig. 3.6. Photograph of the Wilhelmy Plate.

CHAPTER IV

EXPERIMENTAL RESULTS

4.1 Overview

As mentioned before the idea is to make the mixtures by adding petroleum distillate to the listed above oil samples in five different ratios. The oil sample: petroleum distillate mixture ratios are the followings:

- 1:100
- 2:100
- 3:100
- 4:100
- 5:100

After having four crude oil samples and five different petroleum distillate/oil ratios the total number samples reached 24 (Six for each sample of oil). Viscosity, density and surface tension of all 24 samples was measured.

The temperatures at which experiments were conducted for each sample of oil is presented in **Table 4.1.**

Table 4.1. Outline of the experiments

T (°C)	Oil Sample	Specific Gravity (^{0}API)
20	San. Francisco	28 ~ 29
40		
60		
30	Duri	19 ~ 21
45		
60		
40	Jobo	8 ~ 9
50		
60		
40	San Ardo	12 ~ 13
50		
60		

4.2. San Francisco Oil Viscosity Results

Compared to other three oil samples, San Francisco is the lighter. It was easy to conduct the experiments and the results were steady. As predicted, the viscosity for all the samples was decreasing as we increased the temperature. Using petroleum distillate as an additive gave good result. We observed a reduction in viscosity as we were increasing petroleum distillate/oil ratio which proved petroleum distillate to be an efficient additive.

Table 4.2. shows results of the experiments for pure San Francisco samples and all its petroleum distillate/oil ratio. The graphic outline of this table is shown in **Fig. 4.1.** The Figure shows that with an increase of petroleum distillate/oil ratio, viscosity decreases more significantly at lower temperatures than higher temperatures.

Table 4.2. Viscosity results for San Francisco Oil

T (°C)	Viscosity (cp)					
	Pure	1:100	2:100	3:100	4:100	5:100
20	86.2	79.9	68.7	59.2	53.3	50.7
40	29.4	26.1	23.3	22.7	21.9	20.8
60	15.8	13.1	12.5	10.9	9.69	8.14

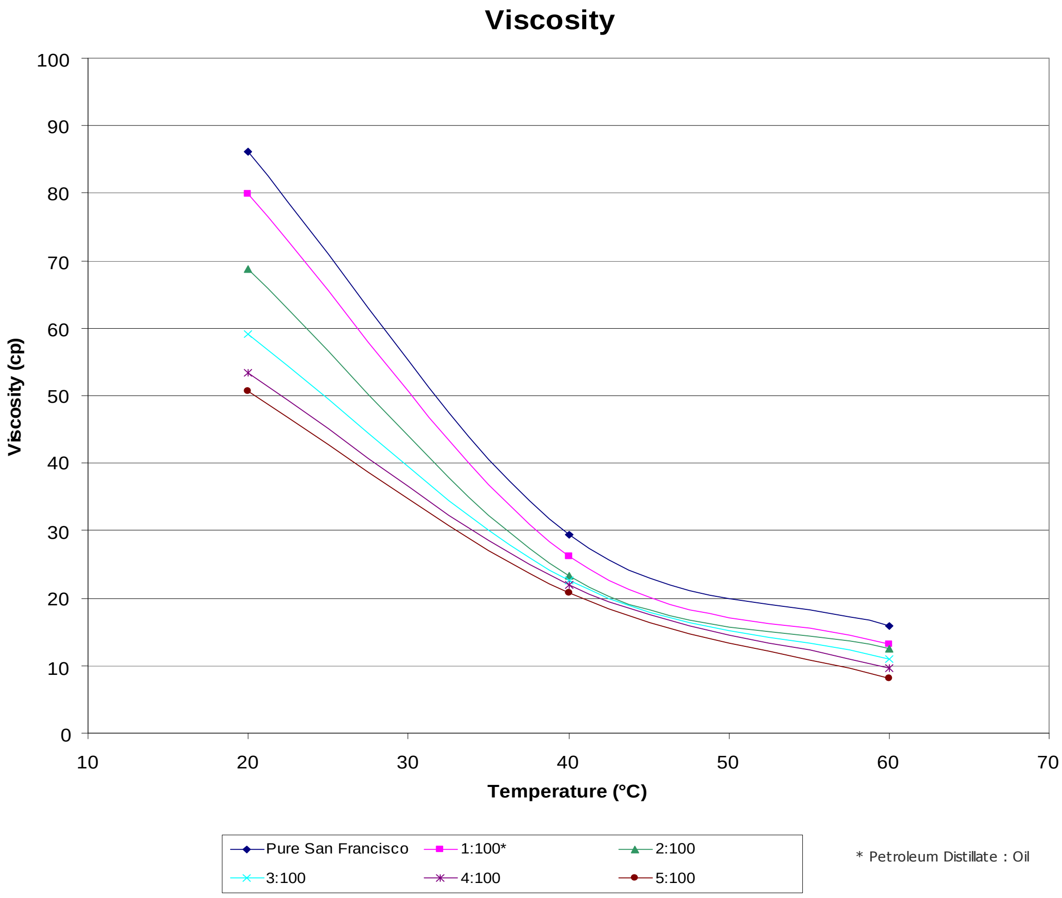

Fig. 4.1. Viscosity results for San Francisco Oil.

4.3. Duri Oil Viscosity Results.

Although Duri oil is heavier than San Francisco it was still easy to conduct viscosity experiments for this oil sample and all its petroleum distillate/oil ratios.

Table 4.3. shows results of the experiments conducted for pure Duri oil sample and all its petroleum distillate/oil ratios. We observed a reduction in viscosity with an increase of temperature and also with an increase in petroleum distillate/oil ratio.

Table 4.3. Viscosity results for Duri Oil

T (°C)	Viscosity (cp)					
	Pure	1:100	2:100	3:100	4:100	5:100
30	869	675	640	516	472	412
45	255	206	193	172	158	142
60	122	106	99.7	84.6	81.1	70.9

The graphic outline of **Table 4.3** is shown in **Fig. 4.2. The** Figure shows that with an increase of petroleum distillate/oil ratio, the viscosity decreases more significantly at lower temperatures than higher temperatures.

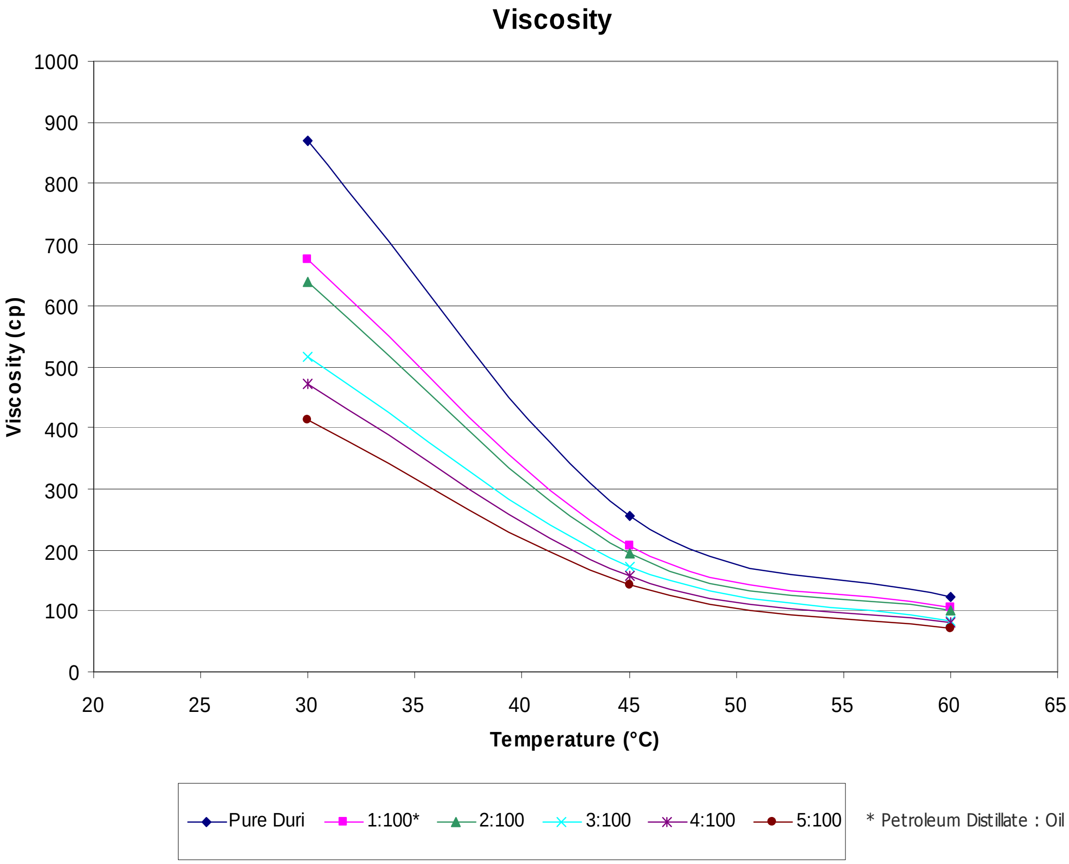

Fig. 4.2. Viscosity results for Duri Oil.

4.4. Jobo Oil Viscosity Results

Compared to San Francisco and Dur,i Jobo oil is pretty heavy. Because of lower API, measurements had to be started at 40 degrees Celsius's. Still the viscosity for all the samples was decreasing as we increase the temperature. Using petroleum distillate as an additive gave good results. We observed a reduction in viscosity as we were increasing the petroleum distillate/oil ratio which proved petroleum distillated to be an efficient additive.

Table 4.4. shows the results of the experiments conducted for pure Jobo samples and all its petroleum distillate/oil ratios. We observed a reduction in viscosity with an increase of temperature and also with an increase petroleum distillate/oil ratio.

Table 4.4. Viscosity results for Jobo Oil

T (°C)	Viscosity (cp)					
	Pure	**1:100**	**2:100**	**3:100**	**4:100**	**5:100**
40	2885	2373	1909	1731	1408	1239
50	1251	1074	889	788	727	548
60	610	506	455	403	342	287

The graphic outline of **Table 4.4** is shown in **Fig. 4.3. The** figure shows that with an increase of petroleum distillate/oil ratio the viscosity decreases more significantly at lower temperatures than higher temperatures.

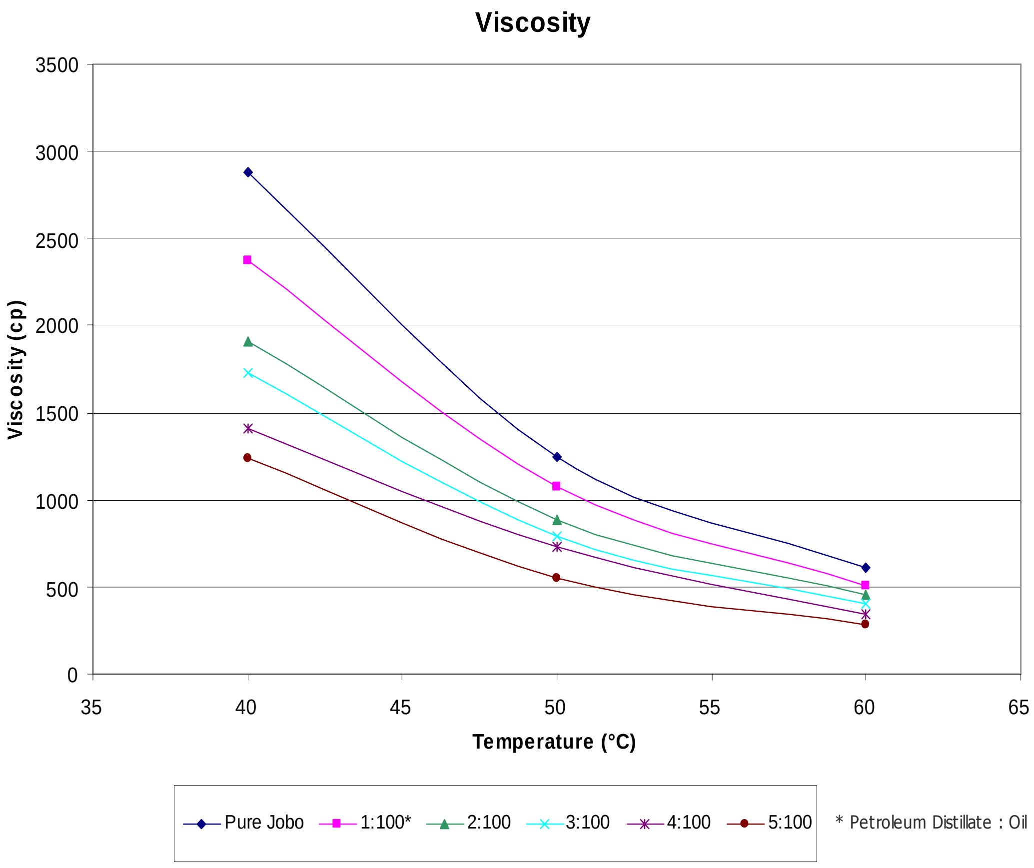

Fig. 4.3. Viscosity results for Jobo Oil.

4.5. San Ardo Oil Viscosity Results

San Ardo oil out of all turned out to be the heaviest when it comes to viscosity. Just like in the case with Jobo oil because of lower API measurements had to be started at 40 degrees Celsius's. The viscosity for all the samples was decreasing as we increase the temperature. Using petroleum distillate as an additive gave good results. We observed reduction in viscosity as we were increasing petroleum distillate/oil ratio which proved petroleum distillated to be an efficient additive.

Table 4.5. shows results of the experiments conducted for pure San Ardo samples and all its petroleum distillate/oil ratios. We observed a reduction in viscosity with an increase of temperature and also with an increase petroleum distillate/oil ratio.

Table 4.5. Viscosity results for San Ardo Oil

T (°C)	Viscosity (cp)					
	Pure	**1:100**	**2:100**	**3:100**	**4:100**	**5:100**
40	7292	5805	5139	3356	2775	2345
50	2862	2354	1916	1428	1265	995
60	1270	1097	898	692	586	532

The graphic outline of **Table 4.5** is shown in **Fig. 4.4.** The figure shows that with an increase of petroleum distillate/oil ratio the viscosity decreases more significantly at lower temperatures than higher temperatures. There's a bigger reduction in viscosity observed when we go lower in petroleum distillate/oil ratio- from 3:100 to 4:100.

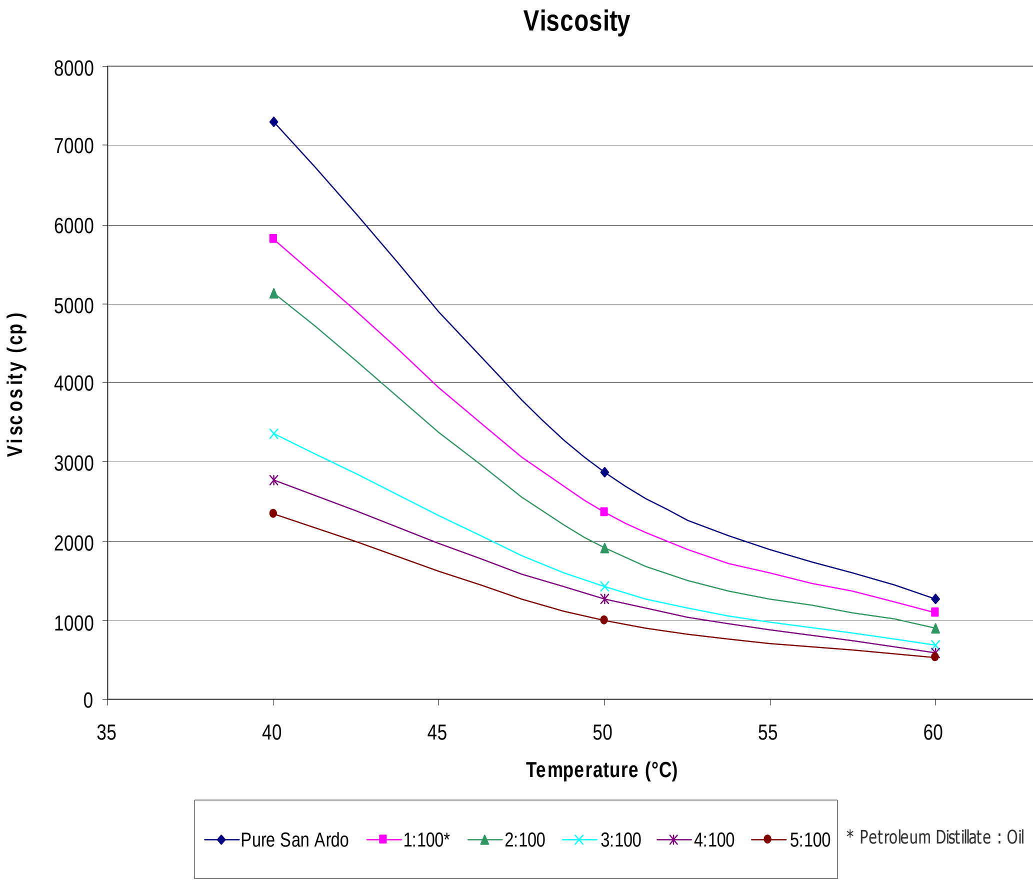

Fig. 4.4. Viscosity results for San Ardo Oil.

4.6 San Francisco Oil Density Results

Table 4.6 shows the experimental results for density of San Francisco oil.

Table 4.6. San Francisco Oil density.

T (°C)	**Density (g/cm^3)**					
	Pure	**1/100**	**2/100**	**3/100**	**4/100**	**5/100**
20	0.9046	0.9033	0.9017	0.9013	0.8996	0.8982
40	0.8908	0.8893	0.8879	0.8872	0.8856	0.8842
60	0.8773	0.8758	0.8743	0.8737	0.8721	0.8707

The graphic outline of **Table 4.6** is shown in the **Fig. 4.5**. The figure shows that with an increase of temperature, the density decreases for all the mixtures, including pure sample. The figure shows steady decrease in density with increase of petroleum distillate/oil ratio. There’s less reduction observed in density with increase of petroleum distillate/oil ratio-from 2:100 to 3:100

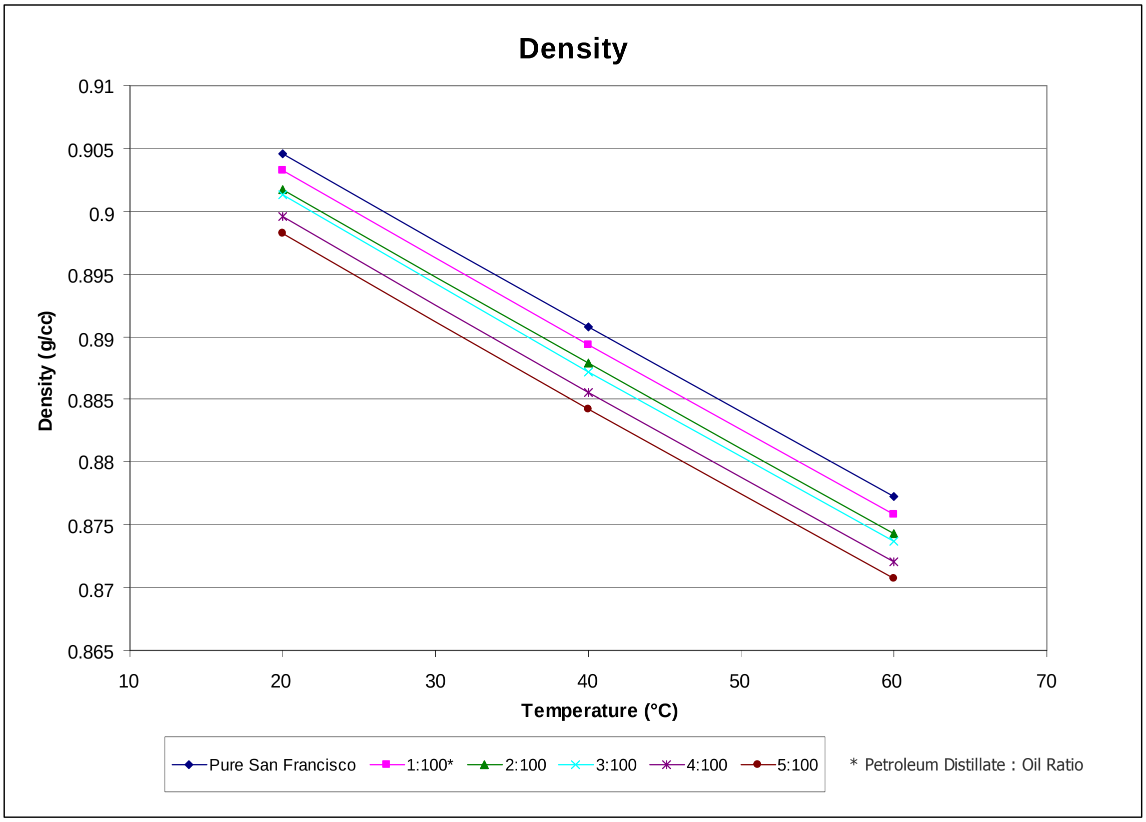

Fig. 4.5. Density results for San Francisco Oil.

4.7 Duri Oil Density Results

Table 4.7 shows the experimental results for density of Duri oil.

Table 4.7. Duri Oil density.

T (°C)	Density (g/cm^3)					
	Pure	1/100	2/100	3/100	4/100	5/100
30	0.9237	0.9228	0.919	0.9179	0.9162	0.9151
45	0.9114	0.9091	0.9079	0.906	0.9047	0.9032
60	0.9018	0.8998	0.8985	0.8966	0.8952	0.8937

The graphic outline of **Table 4.7** is shown in the **Fig. 4.6**. Experiments went well and the figure shows that with an increase of temperature, the density decreases for all the mixtures and pure sample. The figure shows steady decrease in density with increase of petroleum distillate/oil ratio. There is more reduction in density observed at temperature 40 ^{0}C with an increase of petroleum distillate/oil ratio- from 1:100 to 2:100.

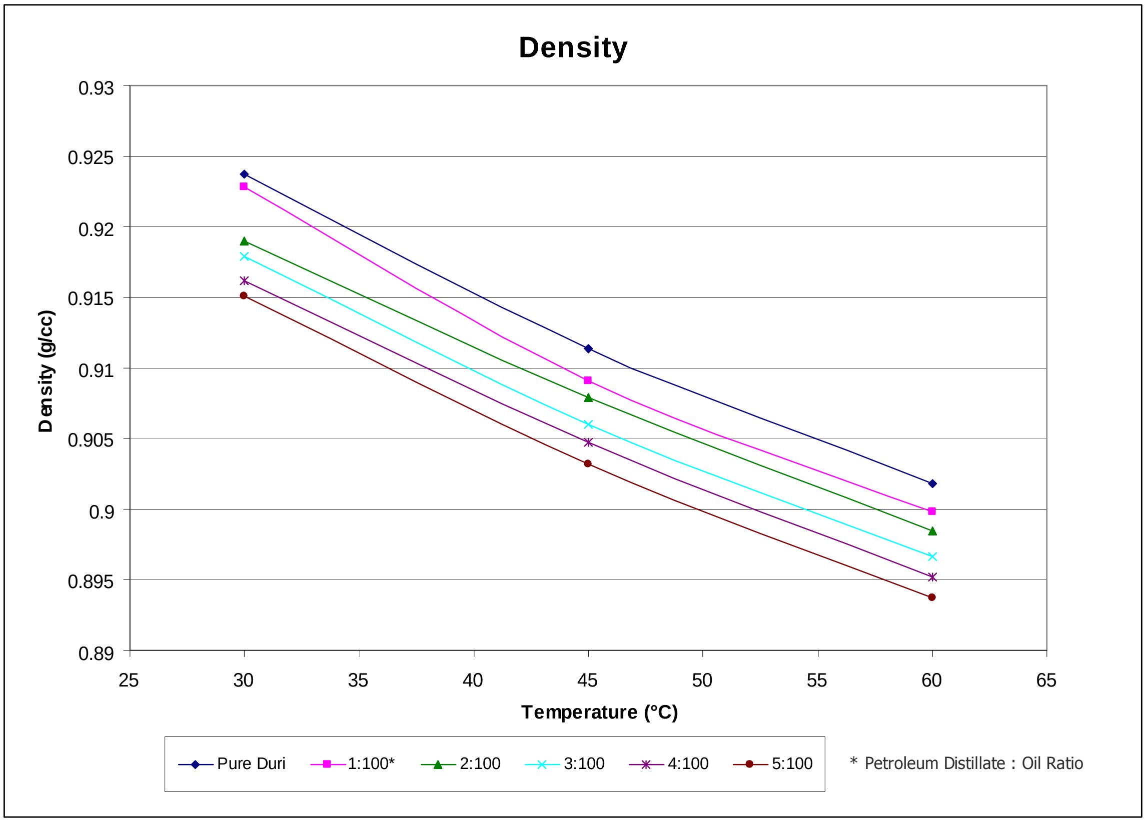

Fig. 4.6. Density results for Duri Oil.

4.8 Jobo Oil Density Results

Table 4.8 shows the experimental results for density of Jobo oil.

Table 4.8. Jobo Oil density.

T (°C)	Density (g/cm^3)					
	Pure	1/100	2/100	3/100	4/100	5/100
40	0.967	0.9647	0.9622	0.9616	0.9559	0.9545
50	0.9606	0.9584	0.9565	0.9554	0.9495	0.9486
60	0.9543	0.952	0.9501	0.949	0.9433	0.9429

The graphic outline of **Table 4.8** is shown in the **Fig. 4.7**. Experiments went well and the figure shows that with an increase of temperature, the density decreases for all the mixtures and pure sample. The figure shows decrease in density with an increase of petroleum distillate/oil ratio for all samples. There is more reduction in density observed at all three temperatures with an increase of petroleum distillate/oil ratio- from 3:100 to 4:100.

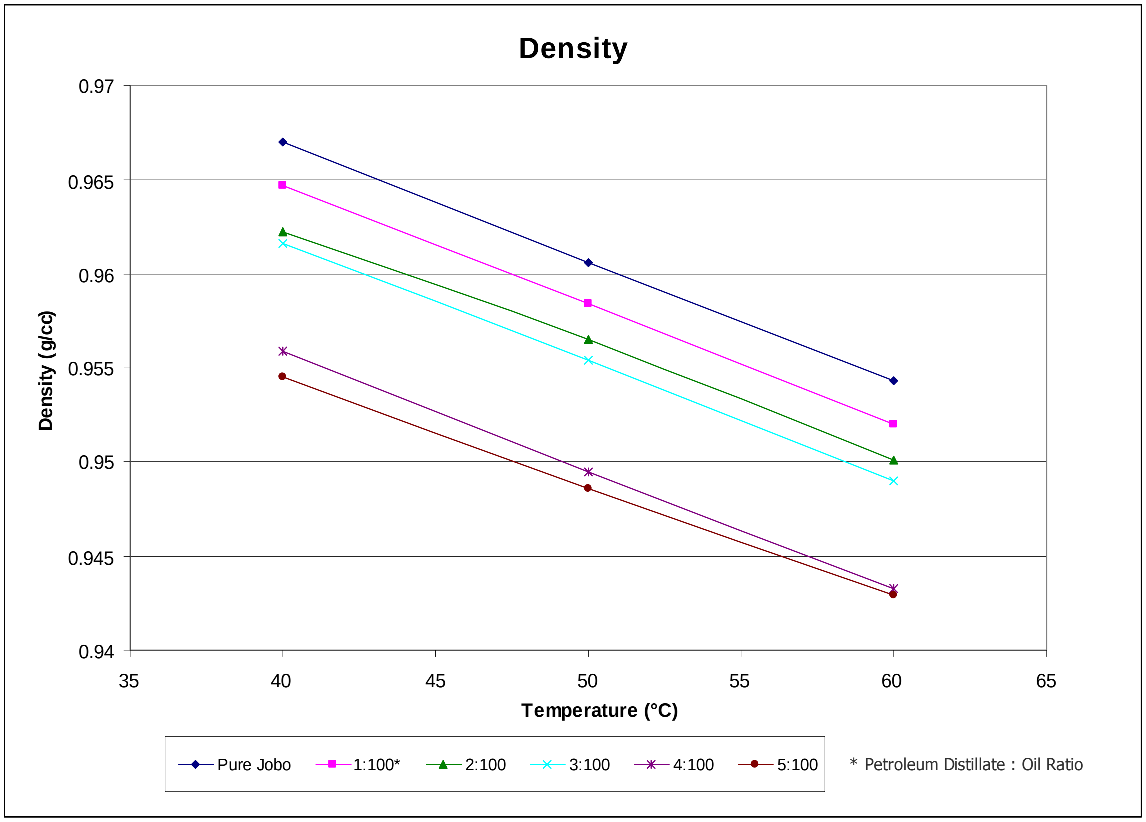

Fig. 4.7. Density results for Jobo Oil.

4.9 San Ardo Oil Density Results

Table 4.9 shows the experimental results for density of San Ardo oil.

Table 4.9. San Ardo Oil density.

T (°C)	Density (g/cm^3)					
	Pure	1/100	2/100	3/100	4/100	5/100
40	0.9713	0.9691	0.9658	0.9645	0.9619	0.9592
50	0.9651	0.9629	0.9603	0.9582	0.9557	0.953
60	0.9588	0.9566	0.9541	0.9518	0.9495	0.9467

The graphic outline of **Table 4.9** is shown in the **Fig. 4.8**. Experiments went well and the figure shows that with an increase of temperature, the density decreases for all the mixtures and pure sample. The figure shows steady decrease in density with increase of petroleum distillate/oil ratio for all samples.

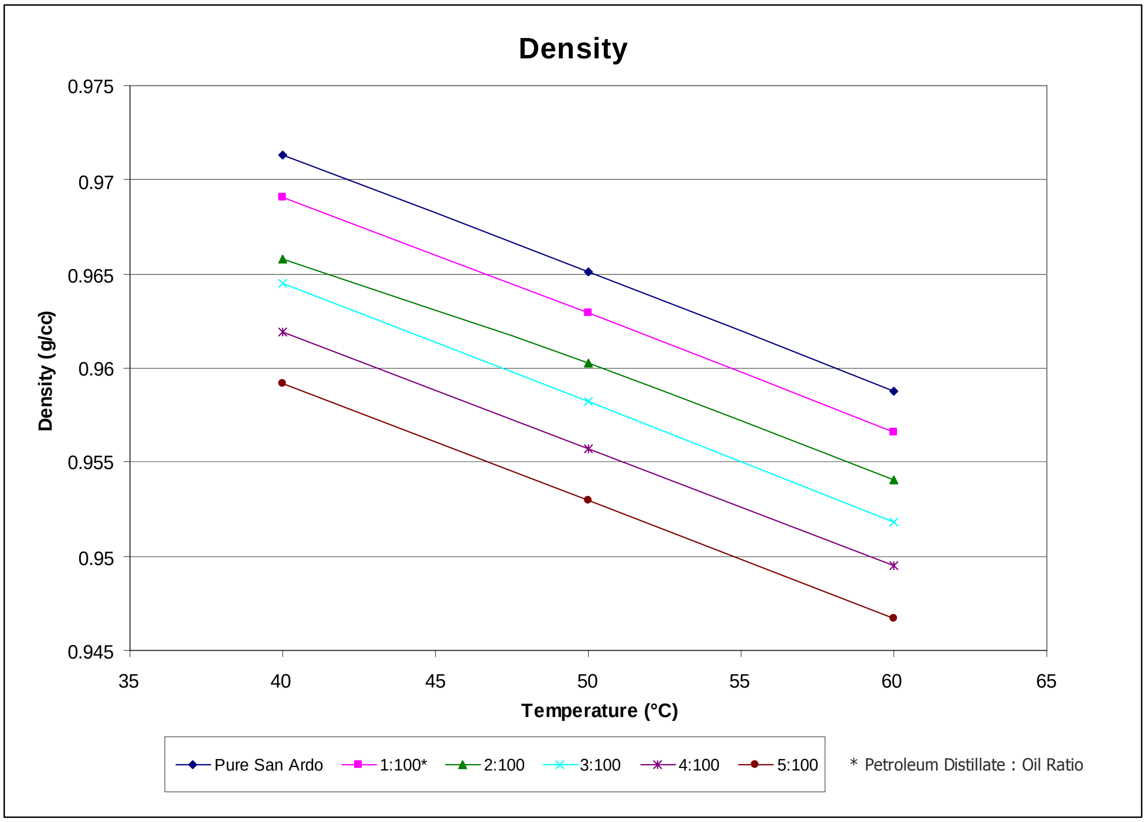

Fig. 4.8. Density results for San Ardo Oil.

4.10 San Francisco Oil Surface Tension Results

Table 4.10 shows the experimental results for surface tension of San Francisco oil.

Table 4.10. San Francisco Oil surface tension.

T (°C)	Surface Tension (dynes/cm)					
	Pure	1/100	2/100	3/100	4/100	5/100
20	38.43	36.68	35.55	34.5	34	33.5
40	33.4	32.575	32.05	31.7	31.51	31.3
60	31.125	30.6	30.32	30.233	30	29.75

The graphic outline of **Table 4.10** is shown in **Fig. 4.9**. Experiments went well and the figure shows that with an increase of temperature, the surface tension decreases for all the mixtures and pure samples. For this particular oil sample surface tension decreases more significantly at lower temperatures than at higher temperatures

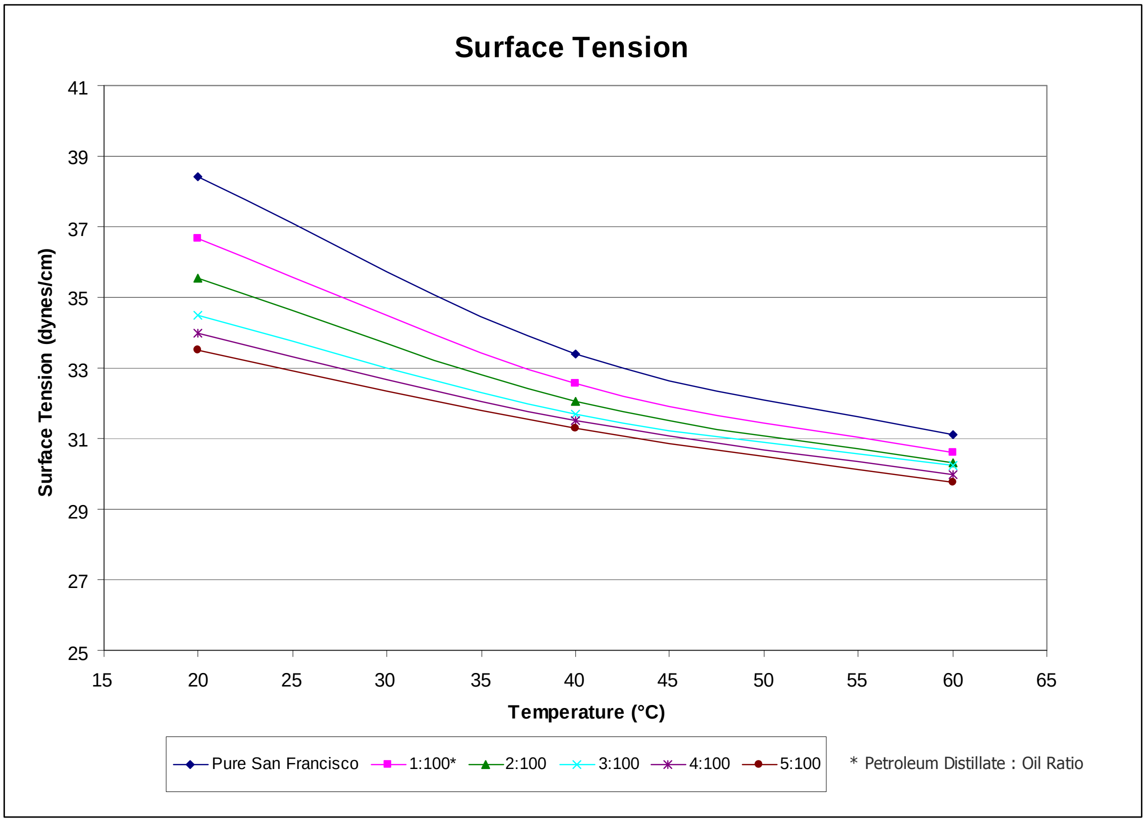

Fig. 4.9. Surface tension results for San Francisco Oil.

4.11 Duri Oil Surface Tension Results

Table 4.11 shows the experimental results for surface tension of Duri oil.

Table 4.11. Duri Oil surface tension.

T (°C)	Surface Tension (dynes/cm)					
	Pure	**1/100**	**2/100**	**3/100**	**4/100**	**5/100**
30	26.1	24.2	22.7	21.9	20.8	19.5
45	22.9	20.9	19.1	18.4	17.4	16.5
60	21.1	19.4	17.5	16.4	15.2	14.7

The graphic outline of **Table 4.11** is shown in the **Fig. 4.10**. Experiments went well and the figure shows that with an increase of temperature, the surface tension decreases for all the mixtures and pure samples.

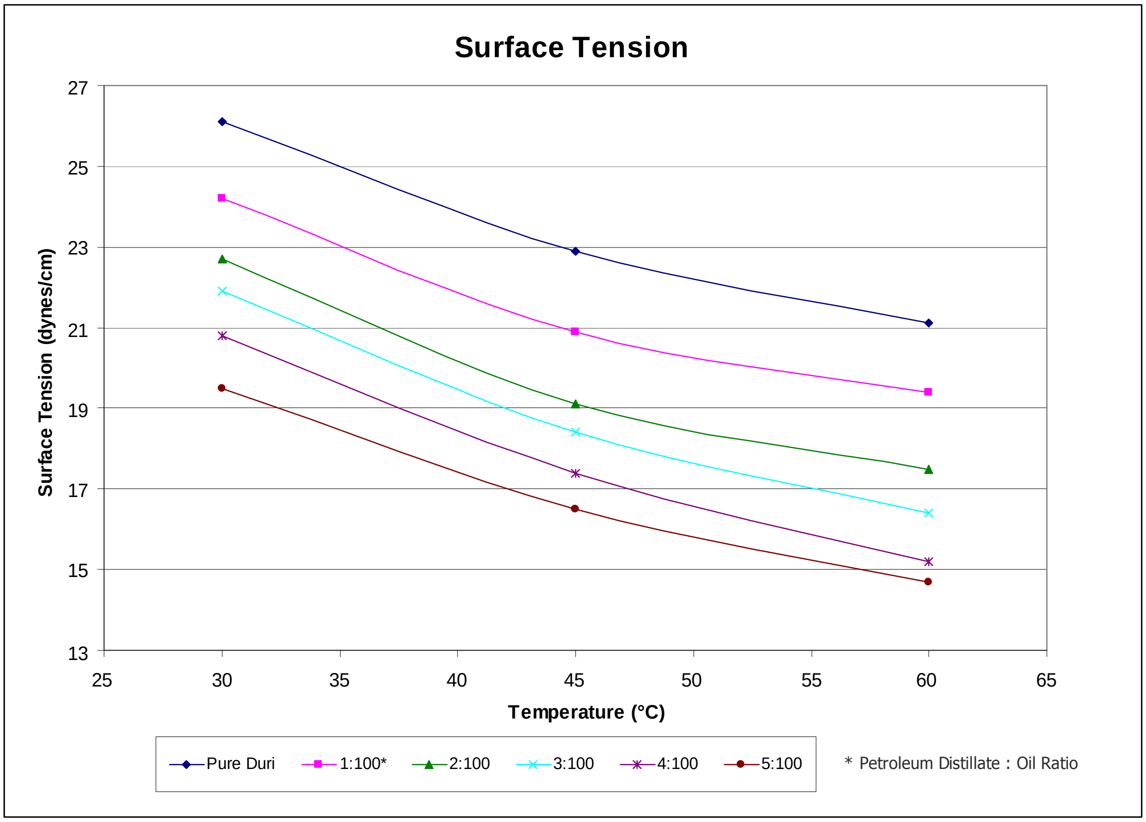

Fig. 4.10. Surface tension results for Duri Oil.

4.12 Jobo Oil Surface Tension Results

Table 4.12 shows the experimental results for surface tension of Jobo oil.

Table 4.12. Jobo Oil surface tension.

T (°C)	Surface Tension (dynes/cm)					
	Pure	1/100	2/100	3/100	4/100	5/100
40	21.6	20.6	20.1	19.5	18.9	18.2
50	19.5	18.7	18.1	17.6	17	16.4
60	18.1	17.5	16.9	16.3	15.8	15.3

The graphic outline of **Table 4.12** is shown in the **Fig. 4.11**. Experiments went well and the figure shows that with an increase of temperature, the surface tension decreases for all the mixtures and pure samples. For this particular sample the decrease in surface tension is steady for all the mixtures.

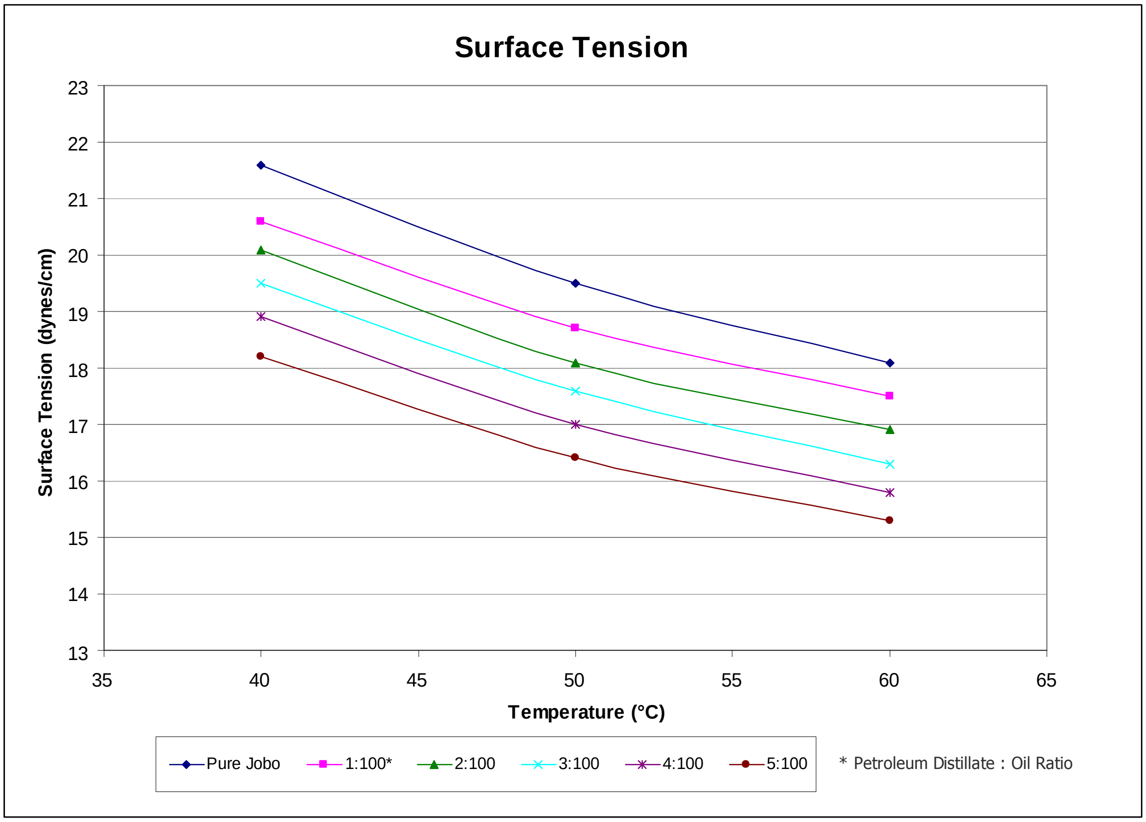

Fig. 4.11. Surface tension results for Jobo Oil.

4.13 San Ardo Oil Surface Tension Results

Table 4.13 shows the experimental results for surface tension of San Ardo oil.

Table 4.13. San Ardo Oil surface tension.

T (°C)	Surface Tension (dynes/cm)					
	Pure	1/100	2/100	3/100	4/100	5/100
40	26.4	24.1	22.9	22	21.1	19.7
50	22.8	21.1	20.3	19.5	18.9	18.1
60	20.2	19.5	18.9	18.4	18	17.5

The graphic outline of **Table 4.13** is shown in the **Fig. 4.12**. Experiments went well and the figure shows that with an increase of temperature, the surface tension decreases for all the mixtures and pure samples. For this particular oil sample surface tension decreases more significantly at lower temperatures than at higher temperatures.

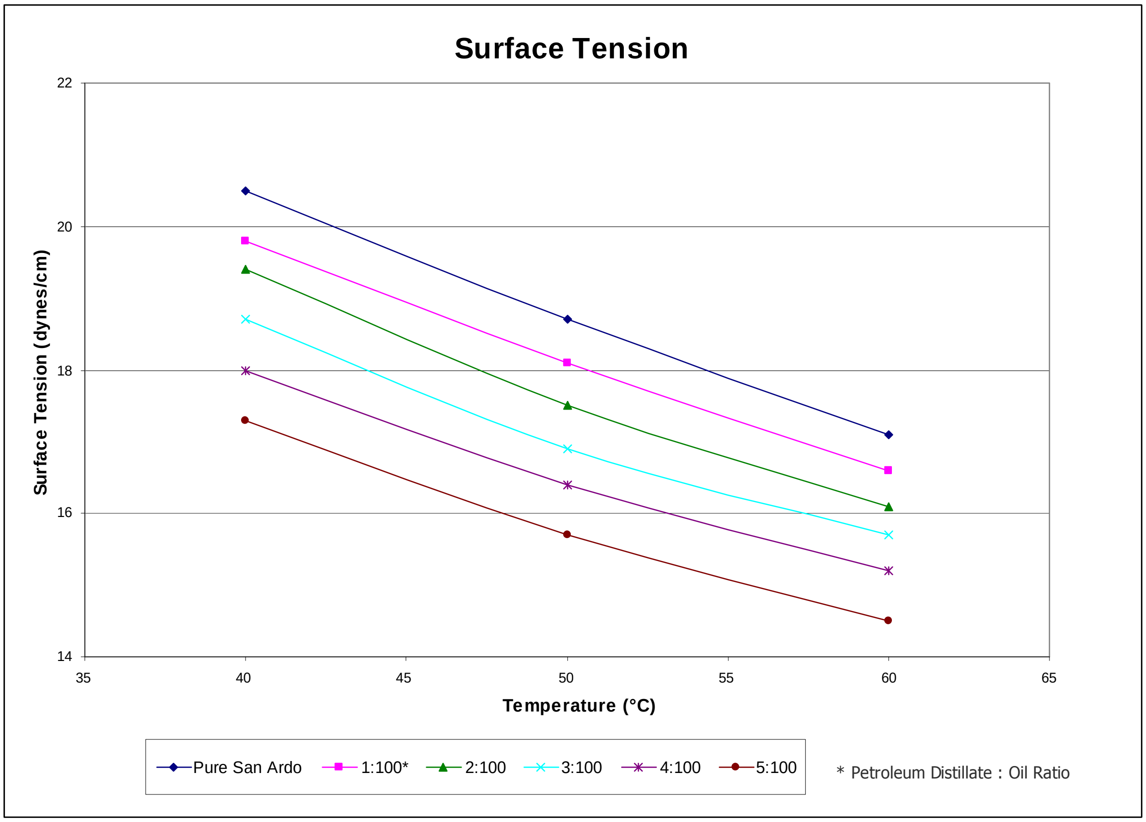

Fig. 4.12. Surface tension results for San Ardo Oil.

CHAPTER V

ANALYTICAL CORRELATION

After all experiments were conducted and encouraging results were achieved, the next step was to come up with a correlation for the viscosity, density and surface tension.

Correlations achieved were based on trial and error methods. Calculated correlations are good only for the oil samples used and petroleum distillate additive. They are also good only for the range of temperatures that were used for the experiments. In the correlation we have given experimental data such as properties of the additive (petroleum distillate) and oil. The idea was to have these specific gravity of the oil sample, temperature at which sample property supposed to be measured and ratio of the mixture as input. So that any other student continuing the research could easily calculate the viscosity, density and surface tension for any mixture at any temperature.

5.1 Viscosity Correlation.

The idea was to be able to calculate the viscosity of any petroleum distillate: oil ratio mixtures at any given temperature that was used during measurements. This correlation was achieved by using trial and error method. The equation for this correlation is the following type:

$$y = ax^b \quad , \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \text{(eq. 5.1)}$$

For all oil samples the general correlation was achieved where:

y = viscosity of the mixture
x = variable, for all oil samples is $\dfrac{T}{(1-R_m)^4}$

a = correlation coefficient, varies with specific gravity of the oil sample

b = correlation coefficient, varies with specific gravity of the oil sample

So now one can easily calculate viscosity of the desired mixture at a desired temperature, for the desired mixture ratio. Calculate $\frac{T}{(1-R_m)^4}$ term first and then calculate the viscosity of the mixture using correlation coefficients.

5.1.1. San Francisco Viscosity Correlation

The general equation for this correlation is eq. 5.1. For San Francisco Oil correlation equation is the following:

$y = 8924.9x^{-1.5853}$, ……………………………………………………………(eq. 5.2)

As mentioned before in eq. 5.1

y = viscosity of the mixture

$x = \frac{T}{(1-R_m)^4}$

Viscosity correlation for San Francisco oil gave a good fit ($R^2 = 0.9858$).

The graphic outline of this correlation can be seen in the **Fig. 5.1**.

5.1.2. Duri oil Viscosity Correlation

The general equation for this correlation is eq. 5.1. For Duri Oil correlation equation is the following:

$y = 5E{+}06x^{-2.62}$, …………………………………..……………………… (eq. 5.3)

Viscosity correlation for Duri oil gave a good fit ($R^2 = 0.9964$).

The graphic outline of this correlation can be seen in the **Fig. 5.1**

5.1.3. Jobo oil Viscosity Correlation

The general equation for this correlation is eq. 5.1. For Jobo Oil correlation equation is the following:

$y = 2E{+}09x^{-3.6116}$, ……………………………………………………..………(eq. 5.4)

Viscosity correlation for Jobo oil gave a good fit ($R^2 = 0.9963$).

The graphic outline of this correlation can be seen in the **Fig. 5.1**

5.1.4. San Ardo oil Viscosity Correlation

The general equation for this correlation is eq. 5.1. For Jobo Oil correlation equation is the following:

$y = 2E{+}10x^{-4.0959}$, ………………………………………………………………(eq. 5.5)

Viscosity correlation for San Ardo oil gave a good fit ($R^2 = 0.9846$).

The graphic outline of this correlation can be seen in the **Fig. 5.1**.

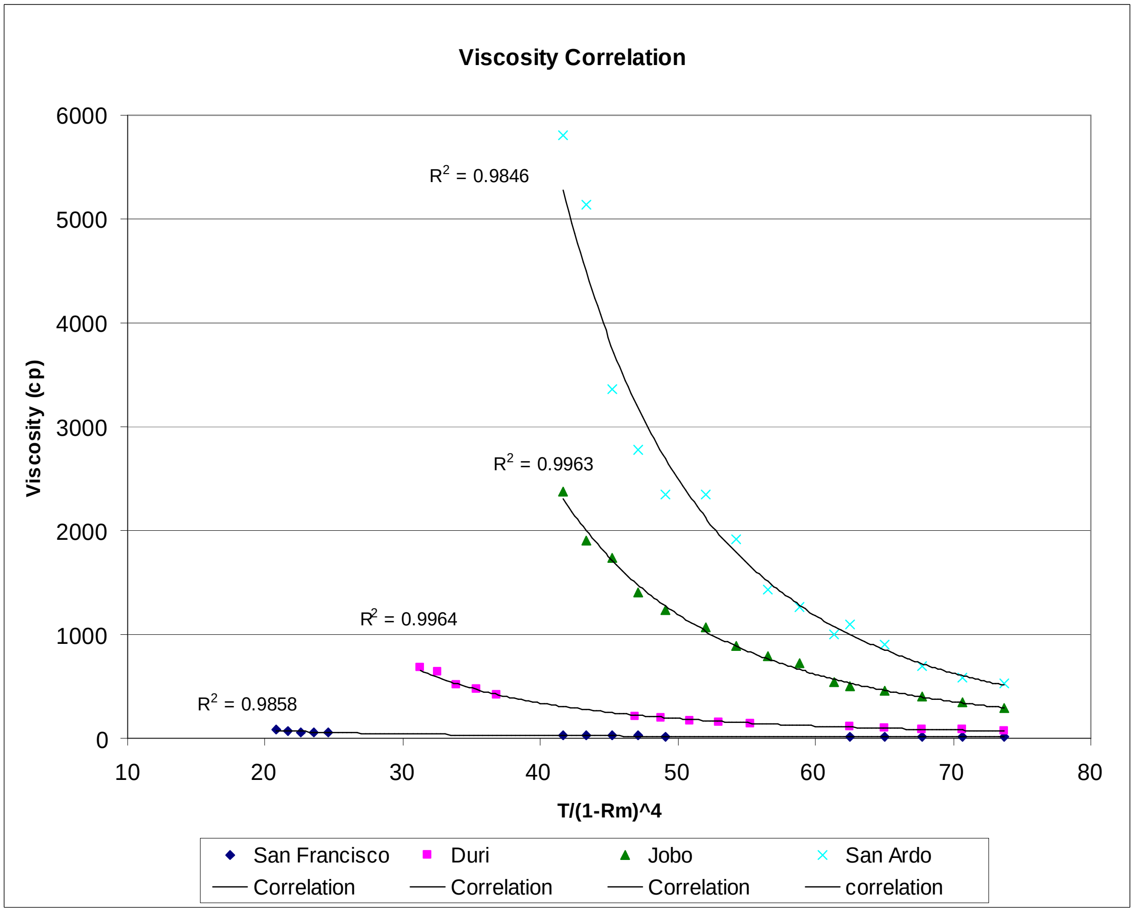

Fig. 5.1. Viscosity correlation.

5.2 Density Correlation

The idea was to be able to calculate the density of any petroleum distillate: oil ratio mixtures at any given temperature that was used during measurements using this correlation. This correlation was achieved by using trial and error method. The equation for this correlation is the following type:

$$y = ax + b \quad , \ldots\ldots \quad \text{(eq. 5.6)}$$

For all oil samples general correlation was achieved where:

y = viscosity of the mixture
x = variable, for all oil samples is $\frac{T}{(1-R_m)^4}$

a = correlation coefficient, varies with specific gravity of the oil sample

b = correlation coefficient, varies with specific gravity of the oil sample

So now one can easily calculate density of the desired mixture at a desired temperature, for the desired mixture ratio. Calculate $\frac{T}{(1-R_m)^4}$ term first and then calculate the viscosity of the mixture using correlation coefficients.

5.2.1. San Francisco oil Density Correlation

The general equation for this correlation is eq. 5.6. For San Francisco Oil density correlation equation is the following:

$y = -0.0006x + 0.9145$, …………………………………………..……………(eq. 5.7)

As mentioned in eq.5.6:

y = viscosity of the mixture

$x = \frac{T}{(1-R_m)^4}$

The density correlation for San Francisco oil gave a good fit ($R^2 = 0.9961$).

The graphic outline of this correlation can be seen in the **Fig. 5.2**

5.2.2. Duri oil Density Correlation

The general equation for this correlation is eq. 5.6. For Duri Oil density correlation equation is the following:

$y = -0.0006x + 0.9394$, ……………………………..…………………………(eq. 5.8)

The density correlation for Duri oil gave a good fit ($R^2 = 0.9855$).

The graphic outline of this correlation can be seen in the **Fig. 5.2**.

5.2.3. Jobo oil Density Correlation

The general equation for this correlation is eq. 5.6. For Jobo oil density correlation equation is the following:

y = -0.0006x + 0.9896, ………………………………………………….……(eq. 5.9)

The density correlation for Jobo oil gave a good fit ($R^2 = 0.945$).

The graphic outline of this correlation can be seen in the **Fig. 5.2**

5.2.4. San Ardo oil Density Correlation

The general equation for this correlation is eq. 5.6. For San Ardo oil density correlation equation is the following:

y = -0.0006x + 0.9929, ………………………………………….……………(eq. 5.10)

The density correlation for San Ardo oil gave a good fit ($R^2 = 0.9612$).

The graphic outline of this correlation can be seen in the **Fig. 5.2**.

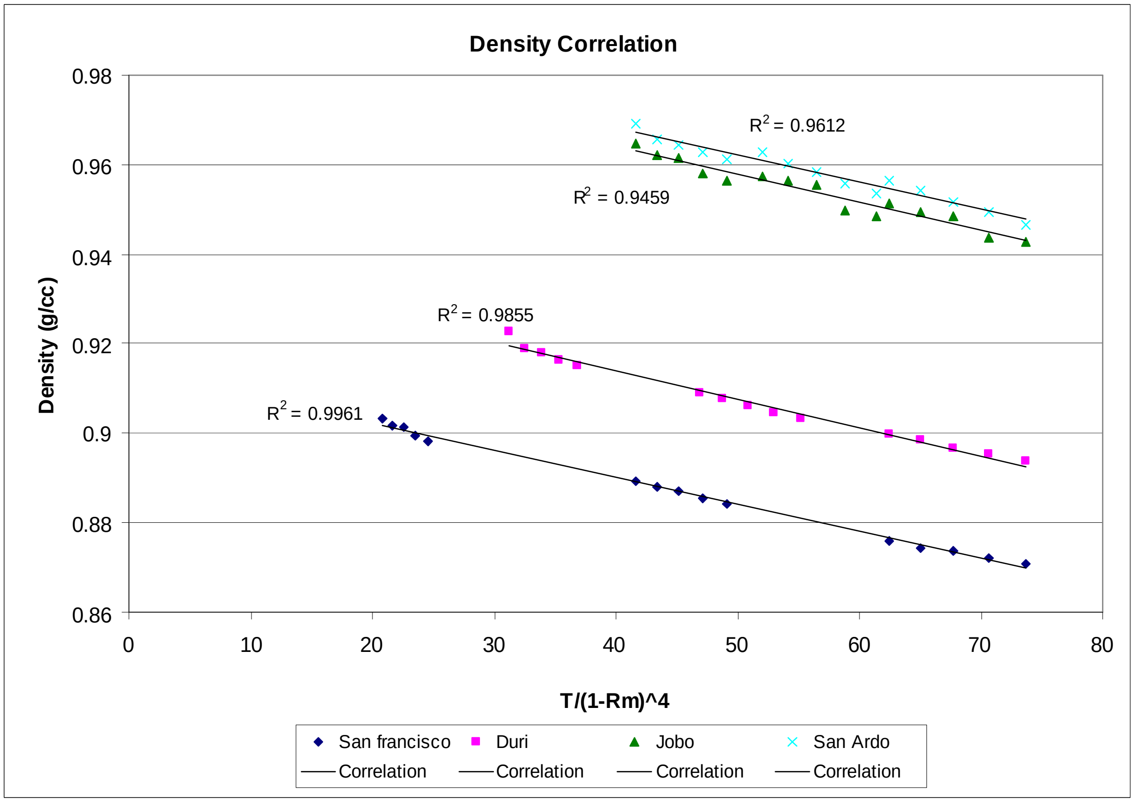

Fig. 5.2. Density correlation.

5.3 Surface Tension Correlation.

The idea was to be able to calculate the surface tension of any petroleum distillate: oil ratio mixtures at any given temperature that was used during measurements. This correlation was achieved by using trial and error method. The equation for this correlation is the following type:

$$y = ax^b \quad , \ldots\ldots \quad \text{(eq. 5.11)}$$

For all oil samples general correlation was achieved where:

y = viscosity of the mixture
x = variable, for all oil samples is $\frac{T}{(1-R_m)^8}$

a = correlation coefficient, varies with specific gravity of the oil sample

b = correlation coefficient, varies with specific gravity of the oil sample

So now one can easily calculate surface tension of the desired mixture at a desired temperature, for the desired mixture ratio. Calculate $\frac{T}{(1-R_m)^8}$ term first and then calculate the viscosity of the mixture using correlation coefficients.

5.3.1. San Francisco oil Surface Tension Correlation

The general equation for this correlation is eq. 5.11. For San Francisco Oil correlation equation is the following:

$y = 50.179x^{-0.1205}$, ……………………………………………………………(eq. 5.12)

As mentioned before in eq. 5.11

y = viscosity of the mixture

x = $\frac{T}{(1-R_m)^8}$

The surface Tension correlation for San Francisco oil gave a good fit ($R^2 = 0.9899$).

The graphic outline of this correlation can be seen in the **Fig. 5.3**

5.3.2. Duri oil Surface Tension Correlation

The general equation for this correlation is eq. 5.11. Duri oil correlation equation is the following:

$y = 95.446x^{-0.3911}$, ……………………………………..…………………………(eq. 5.13)

The surface Tension correlation for Duri oil gave a good fit ($R^2 = 0.9826$).

The graphic outline of this correlation can be seen in the **Fig. 5.3**.

5.3.3. Jobo oil Surface Tension Correlation

The general equation for this correlation is eq. 5.11. For Jobo oil correlation equation is the following:

$y = 95103.65x^{-0.426}$, ……………………………….…………………………(eq. 5.14)

The surface tension correlation for Jobo oil gave a good fit ($R^2 =$ 0.9959).

The graphic outline of this correlation can be seen in the **Fig. 5.3**.

5.3.4. San Ardo oil Surface Tension Correlation

The general equation for this correlation is eq. 5.11. For San Ardo oil correlation equation is the following:

$y = 100.19x^{-0.4282}$, ……………………………………………………………..(eq. 5.15)

The surface tension correlation for Jobo oil gave a good fit ($R^2 =$ 0.9965).

The graphic outline of this correlation can be seen in the **Fig. 5.3.**

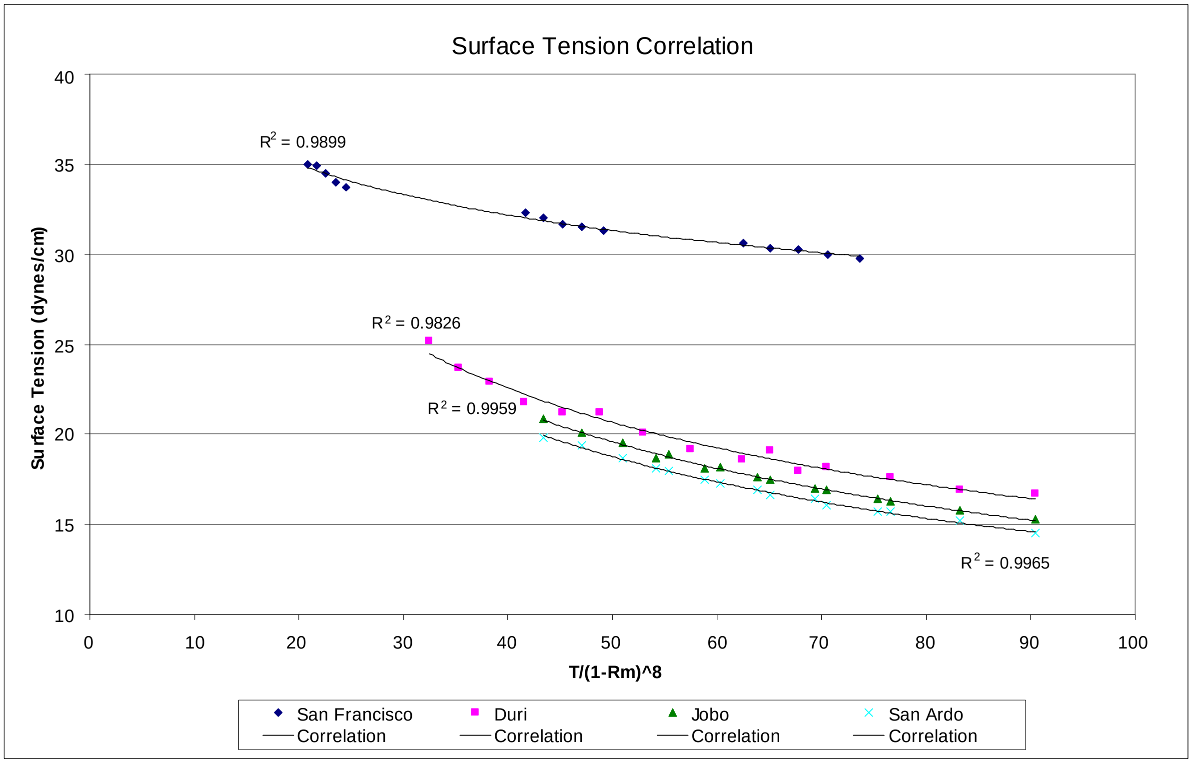

Fig. 5.3. Surface tension correlation.

CHAPTER VI

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1. Summary

All of the runs performed were successful. The runs were performed for four pure oil samples (San Francisco, Duri, Jobo and San Ardo) and their mixtures at different temperatures. The aim was to use petroleum distillate as an additive and see its effects on these oil samples' viscosity, density and surface tension. After all experimental data was measured; trial and error correlation was developed for viscosity, density and surface tension.

6.2. Conclusions

Below are the conclusions that were made after analyzing experiment results:

1. Using petroleum distillate as an additive helped reduce viscosity and surface tension for all the oil samples and their mixtures.

2. Using petroleum distillate increased API gravity increased for all oil samples and their mixtures.

3. As we increase the petroleum distillate: oil ratio we get more reduction in viscosity and surface tension as well as increase in API gravity.

4. With increase in petroleum distillate: oil ratios, oil viscosity decrease more significantly at lower temperatures than at higher temperatures. This brings up a question

if petroleum distillate will be as effective when applied on the field as it is in the lab conditions.

5. For intermediate San Francisco oil, with increase in petroleum distillate: oil ratios, oil viscosity decrease more significantly at lower temperatures than at higher temperatures.

6. Developed analytical correlation for viscosity, density and surface tension gave good results in all cases.

6.3. Recommendations

In order to achieve even better understanding of effect of petroleum distillate on different oil properties following recommendations are proposed:

1. Use petroleum distillate as an additive for different oil samples.
2. Repeat experiments this time using higher petroleum distillate: oil ratios.
3. Repeat experiments at higher temperatures

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