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Assessment of Common Oil Viscosity Correlations for Libyan Crude Oils

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A B S T R A C T

Reservoir oil viscosity plays a key role in the design and optimization of injection/production strategies and surface facilities for efficient reservoir management. The direct measurement method to determine the viscosity of the reservoir fluid involves reservoir fluid sampling, which is costly and frequently unavailable. In the absence of experimentally measured properties of crude oils, the petroleum engineer must determine the properties from empirically derived correlations. The main aim of this paper is to test several well-known viscosity correlations against a new dataset collected from different Libyan crudes. Statistical analyses and graphical methods have been used simultaneously to evaluate the performance and accuracy of each correlation. For dead oil viscosities, none of the available correlations yielded satisfactory results and exhibited high errors; however, the Ng and Egbogah (1983) and Beggs-Robinson (1975) correlations have the lower errors with AAPE% of 31.18 and 33.66, respectively. For live oil viscosities, the Beggs-Robinson correlation (1975) proved to be more accurate than the others, with AAPE% of 20.17 and 24.96, respectively. Labedi (1982) and Khan *et al.* (1987) for undersaturated oil viscosity are the most reliable correlation equations among published correlations, with AAPE% of 3.01 and 3.60, respectively.

1 Introduction

In general, viscosity is defined as the internal resistance of the fluid to flow. Temperature, pressure, oil gravity, gas gravity, and gas solubility all have a significant impact on oil viscosity. [1]. It is critical in several other processes, including pipeline design, equipment manufacturing and processing, well testing, and reservoir simulation. Traditionally, bottom-hole sample analysis in the lab or the recombination of liquids and gases extracted from the separators are used to measure this property. It is possible to measure the viscosities of reservoir oils isothermally, at various reservoir pressures, and at reservoir temperatures. However, experimental measurement of reservoir oil viscosity at various temperatures can be highly expensive due to the high cost of sample equipment and associated testing. In the absence of laboratory PVT data, fluid properties are mostly predicted from empirical correlations as well as the Equation of States (EoS) [2].

Oil viscosity correlations can be broadly classified into two types. The first type is those that use oil field data that is normally available, for example, oil API gravity, reservoir temperature, saturation pressure, and gas solubility. The second kind refers to those empirical and/or semiempirical models that use some parameters that were not included in the first one, such as reservoir fluid composition, pour point temperature, acentric factor, normal boiling point, molar mass, and critical temperature. For this reason, viscosity correlations that need compositional data are redundant and unprofitable [3–5].

Numerous reservoir oil viscosity correlations have been widely used in the petroleum industry during the past decades. Most of them can be seen in many commercial types of software and can be used in reservoir simulation

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procedures. The empirical viscosity correlations developed are divided into three major types: dead oil viscosity, saturated oil viscosity, and undersaturated oil viscosity [6]. Figure 1 shows a typical viscosity curve at reservoir temperature as a function of pressure, illustrating regions related to dead, saturated, and under-saturated oils' viscosities. The purpose of this paper is to test several well-known viscosity correlations against measured data collected from different Libyan oil fields. Statistical and graphical methods are used to evaluate the relative performance of each correlation.

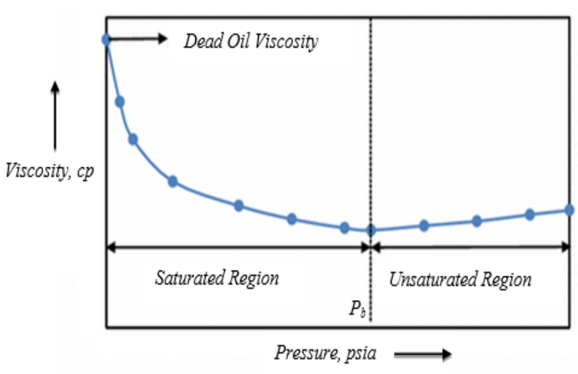

Figure 1. Oil viscosity as a function of pressure.

The purpose of this paper is to test several well-known viscosity correlations against measured data collected from different Libyan oil fields. Statistical and graphical methods are used to evaluate the relative performance of each correlation.

2 Related Work

Over the last decades, several empirical correlations have been introduced to predict crude oil viscosity [7-20]. Most of these correlations are based on a specific region and often fail to predict the oil viscosity in other regions due to the variety in crude oil nature and composition, as mentioned earlier. Generally, these correlations are developed for three conditions: above the bubble point, below and at the bubble point, and dead oil.

3 Methodology

Table 1 summarizes the selected correlation for this study's oil viscosity estimation and demonstrates the data's origin.

TABLE 1. STUDIED OIL VISCOSITY CORRELATIONS

Authors	Published Year	Origin of Data	Reference
Beal	1946	US	7
The Chew-Connally	1959	USA, Canada, and South America	17
The Beggs-Robinson	1975	US	8
Labedi	1982	Libya	13
Vazquez and Beggs	1980	Worldwide	19
Glaso	1980	North Sea	9
Ng and Egbogah	1983	-	10
Khan *et al.*	1987	Saudi Arabia	18
AL-khafaji *et al.*	1987	Iraq	11
Kartoatmodjo and Schmidt	1994	Worldwide	14
Petrosky & Farshad	1995	Gulf of Mexico	12
Dindoruk & Christm	2004	Gulf of Mexico	15
Naseri *et al.*	2005	Iran	3
Khazam *et al.*	2016	Libya	16

3.1 Data Description

Experimental PVT data were collected from various Libyan oil reservoirs of different chemical compositions. Sixty-two laboratory PVT reports and a total of 487 data points were obtained. Table 2 represents a description of the data utilized in this study within wide ranges of pressure, temperature, solution gas-oil ratio, oil gravity, and oil viscosity.

TABLE 2. DATA RANGE OF LABORATORY PVT DATA

Property	**Unit**	**Min**	**Max**
Bubbel point pressure (P_b)	psia	123	6100
Temperature (T)	$^{\circ}$F	132	300
Solution GOR at P_b (R_{sb})	scf/STB	28	2156
Stock-Tank Oil Gravity (γ_{API})	$^{\circ}$API	24.7	46.8
Specific Gas Gravity (γ_g)	Air =1	0.701	1.462
Dead oil viscosity (μ_{od})	cp	0.774	5.036
Saturated oil viscosity (μ_{ob})	cp	0.200	3.811
UnderSaturated oil viscosity (μ_o)	cp	0.123	6.584
Oil formation volume factor (B_o)	bbl/STB	1.035	2.220

3.2 Performance Evaluation Tools

To evaluate the performance of the studied correlations in terms of their accuracy, both statistical and graphical tools have been utilized simultaneously.

3.2.1 Statistical Error Analysis

Choosing the best correlation was assessed with many statistical indicators and looked upon as an optimization process where each statistical indicator complements the others. The accuracy of the estimated viscosity was compared to the measured value using the following statistical parameters:

$$\text{Percent Error (PE)} = \frac{\mu_{cal} - \mu_{mes}}{\mu_{mes}} \quad (1)$$

$$\text{Average Percent Error (APE)} = \frac{1}{n}\sum_{i=1}^{n} PE_i \quad (2)$$

Average Absolute Relative Error (AARE)

$$\frac{1}{n}\sum_{i=1}^{n}\left|\frac{\mu_{cal} - \mu_{mes}}{\mu_{mes}}\right| x\ 100 \quad (3)$$

$$\text{Minimum Error} = \min_{i=1}^{n}\left[\left|\frac{\mu_{cal} - \mu_{mes}}{\mu_{mes}}\right|\right] \quad (4)$$

$$\text{Maximum Error} = \max_{i=1}^{n}\left[\left|\frac{\mu_{cal} - \mu_{mes}}{\mu_{mes}}\right|\right] \quad (5)$$

$$\text{Standard Deviation (SD)} = \sqrt{\frac{\sum_{i=1}^{n}(\text{PE}_i - \text{APE}_i)^2}{n-1}} \quad (6)$$

where:
μ_{Mes} = mmeasured Viscosity, cp
μ_{Cal} = calculated Viscosity, cp
n = number of points

In this study, average absolute relative error (AARE) has been considered the main screening criterion to select the best correlations. Therefore, the correlation providing the smallest "AARE" value is the best. If more correlations have equal AARE, the ones with the lowest standard deviation (SD) value are defined as the best.

3.2.2 Cross Plots

To visualize the accuracy and performance of a correlation, all the estimated values are plotted versus the measured values, and thus a crossplot is formed. On the crossplot, a 45° straight line is drawn with estimated values equaling experimental values. The closer the plotted data points are to this line, the better the correlation.

4 Results and Discussion

The accuracy and validity of the most well-known correlations have been investigated. This section is divided into three parts, including dead oil viscosity, saturated oil viscosity, and under-saturated oil viscosity. The accuracy of those correlations is confirmed according to statistical analysis and the graphical method, which was previously discussed.

4.1 Dead-Oil Viscosity

The accuracy of a particular correlation by comparison with data in a PVT lab report is shown in Table 3. As can be seen, Ng and Egbogah (1983), Beggs-Robinson (1975), and Khazam et al. (2016) correlations have given the best results for these reservoirs among the other used correlations. Even though the results of the aforementioned correlations are more accurate than those of the previous correlations, they are still not precise enough.

TABLE 3. STATISTICAL ERROR ANALYSIS OF DEAD OIL VISCOSITY CORRELATIONS.

Correlations	APE	AAPE	Min	Max	SD
Ng and Egbogah (1983)	15.32	31.18	1.78	98.32	34.89
The Beggs-Robinson (1975)	32.66	33.66	2.62	73.15	22.06
Khazam *et al.* (2016)	-5.844	35.16	0.02	190.59	54.54
Petrosky & Farshad (1995)	32.97	40.00	8.03	73.81	28.79
Glaso (1980)	42.34	44.46	4.18	77.79	23.39
Dindoruk & Christm (2001)	44.14	44.67	7.14	73.91	19.35
Beal (1946)	49.44	49.44	9.05	84.02	18.04
Kartoatmodjo and Schmidt (1994)	50.87	50.87	3.41	81.94	24.01
AL-Khafaji *et al.* (1987)	59.23	59.23	7.82	87.63	19.25
Naseri *et al.* (2005)	70.45	70.45	16.68	90.64	16.29

Regarding the high AARE by more than 25%, the controversy about the accuracy of the proposed saturated oil viscosity correlation in this study and several publications is completely unavoidable. The causes of such erroneous results among these published correlation equations are most likely due to a mistake in laboratory PVT measurement and a flaw in all correlation equations. Appendix A shows crossplots between the estimated and experimental viscosity values for all studied correlations. The crossplots show that there is a lot of dispersion on the plot and that the studied correlations deviate from the measured Libyan data with noticeable scattered abnormal trends.

4.2 Saturated Oil Viscosity

The statistical error analysis for oil viscosity at bubble point (μ_{ob}) correlations is demonstrated in Table 4. The top three published correlation equations are provided by The Beggs-Robinson Correlation (1975), Khazam *et al.* (2016), and Labedi (1982). On the other hand, Khan *et al.* (1987) and Petrosky & Farshad (1995) have given the worst results for predicting oil viscosity among the mentioned correlations. Appendix B shows crossplots between the estimated and experimental viscosity values for *each* of the studied *correlations*.

TABLE 4. STATISTICAL ERROR ANALYSIS OF BUBBLE POINT OIL VISCOSITY (M_{OB}) CORRELATIONS.

Correlations	APE	AAPE	Min	Max	SD
The Beggs-Robinson Correlation (1975)	0.33	20.17	0.21	88.69	27.89
Khazam *et al.* (2016)	-16.46	24.96	0.56	129.56	30.29
Labedi (1982)	-3.14	28.90	2.12	112.78	40.24
The Chew-Connally Correlation (1959)	-23.11	30.79	0.12	120.79	34.36
Khan *et al.* (1987)	17.92	42.19	2.51	98.38	44.05
Petrosky & Farshad (1995)	-77.79	78.90	0.29	216.97	51.12

4.3 Undersaturated Oil Viscosity

Based on statistical analysis, as seen in Table 5, the best results were obtained by Labedi (1982) and Khan *et al.* (1987), while some correlations exhibit significant deviations, such as the Vasquez-Beggs correlation (1980) and Kartoatmodjo and Schmidt (1994), as seen in Figures C.6 and C.7. Labedi's correlation has the fewest scatter points around the trendline compared to other correlations. Hence, Labedi's correlation is the most accurate correlation in this study to predict undersaturated oil viscosity. Appendix C shows crossplots between the calculated and experimental viscosity values for each of the studied correlations.

TABLE 5. STATISTICAL ERROR ANALYSIS OF UNDERSATURATED OIL VISCOSITY CORRELATIONS

Correlations	APE	AAPE	Min	Max	SD
Labedi (1982)	1.14	3.01	0	21.90	4.78
Khan *et al* (1987)	-0.04	3.60	0	28.56	6.21
Petrosky & Farshad (1995)	-0.78	3.85	0	29.52	6.30
Beal (1946)	3.66	4.54	0	31.00	6.23
Khazam *et al.* (2016)	-0.97	5.65	0	55.2	9.39
The Vasquez-Beggs (1980)	-6.82	8.38	0	125.19	16.02
Kartoatmodjo and Schmidt (1994)	8.06	9.46	0	43.87	10.20

It should be noted that correlations for undersaturated oil viscosity are more accurate than correlations for dead oil and bubble point regions. This could be because pressure differentials govern oil viscosity variation in an undersaturated region, and gas solubility is constant in this region.

5 Conclusions

The following conclusions are drawn based on of the dataset analyzed in this study:

1. A new dataset from different Libyan fields was collected, screened, and utilized for our study. These covered a wide range of crude oil gravity ranges (25 to 47 ˚API) and reservoir temperatures (132 to 300 ˚F) normally found in Libyan reservoirs.

2. For dead oil viscosity, it was found that all of the correlations exhibit high errors; however, the Ng and Egbogah (1983) and Beggs-Robinson (1975) correlations have the lower errors with AAPE% of 31.18 and 33.66, respectively.

3. For oil viscosity at the bubble point, the Beggs-Robinson correlation (1975) and Khazam et al. (2016) are the most reliable correlation equations among published correlation equations, with AAPE% of 20.17 and 24.96, respectively. Khan et al. (1987) and Petrosky & Farshad (1995) have given the worst results for predicting oil viscosity among the mentioned correlations, with AAPE% of 42.19 and 78.90, respectively.

4. For undersaturated oil viscosity, the best results are obtained by Labedi (1982) and Khan et al. (1987), with AAPE% of 3.01 and 3.60, respectively, while some correlations exhibit significant deviations, such as the Vasquez-Beggs correlation (1980) and Kartoatmodjo and Schmidt (1994), with AAPE% of 8.38 and 9.46, respectively.

5. The use of the published oil viscosity correlations should be within the range of application, and any outside the range will give bad performance and may affect all reservoir engineering calculations..

Acknowledgements

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Appendix A: Cross plots of dead oil viscosity correlations.

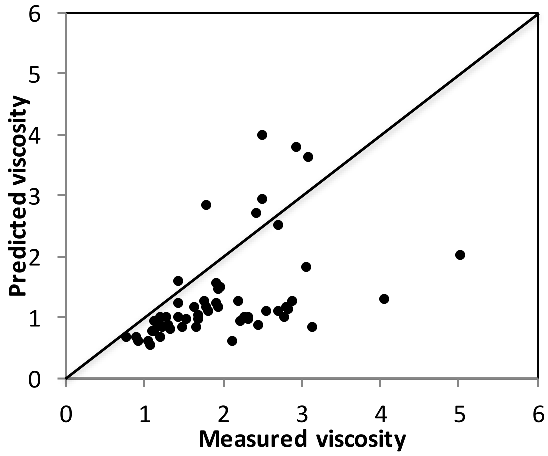


Figure A.1. Ng and Egbogah (1983)

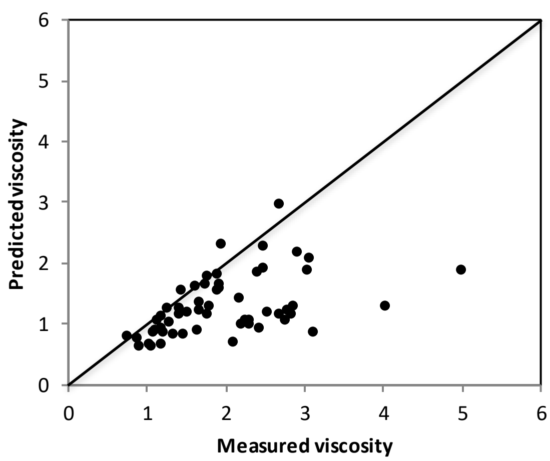


Figure A.2. The Beggs-Robinson (1975)

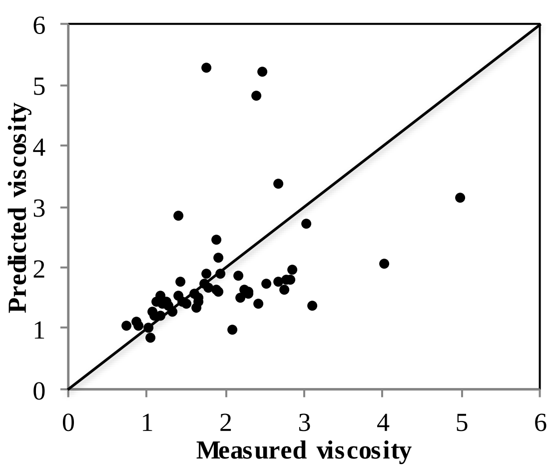


Figure A.3. Khazam *et al.* (2016)

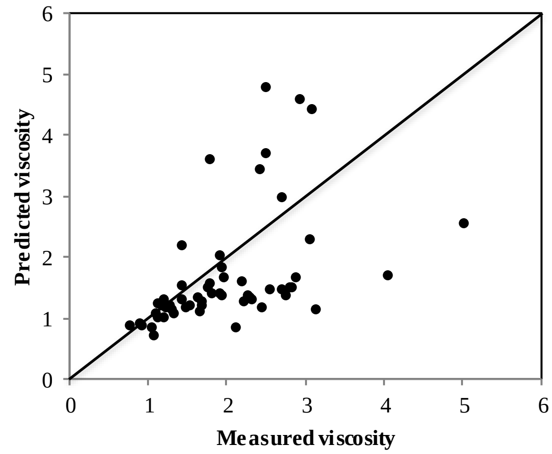


Figure A.4. Petrosky & Farshad (1995)

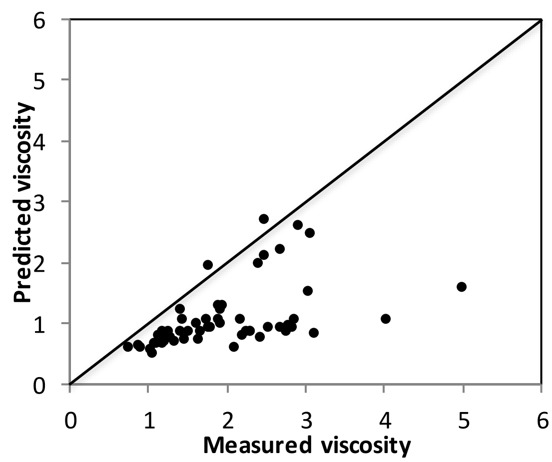


Figure A.5. Dindoruk & Christm (2001)

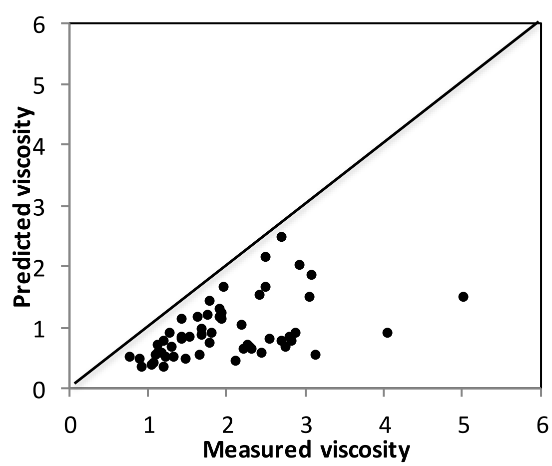


Figure A.6. Beal (1946)

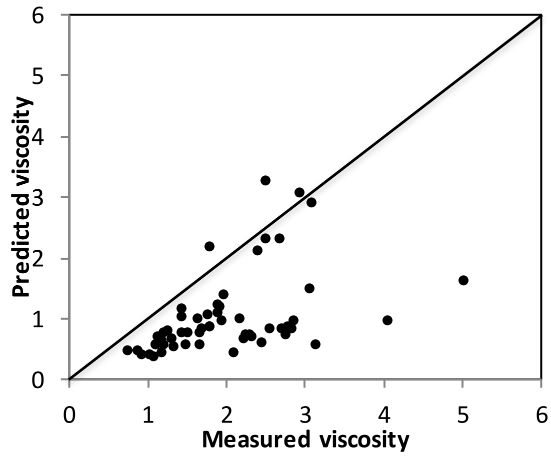


Figure A.7. Kartoatmodjo and Schmidt (1994)

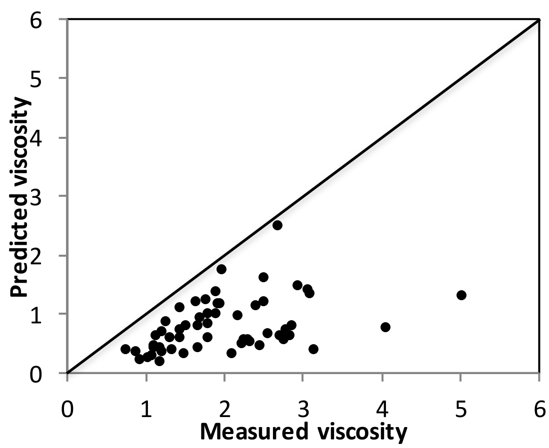


Figure A.8. AL-Khafaji et al. (1987)

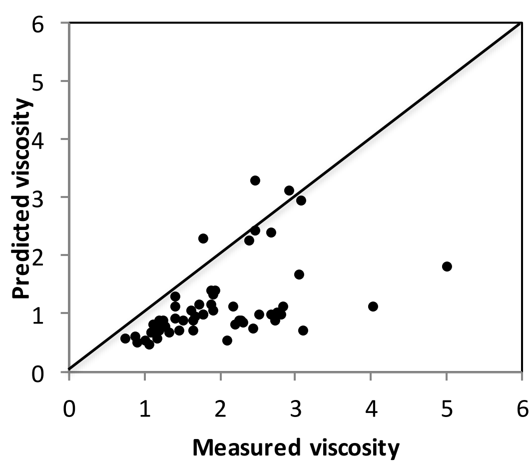


Figure A.9. Glaso Correlation (1980)

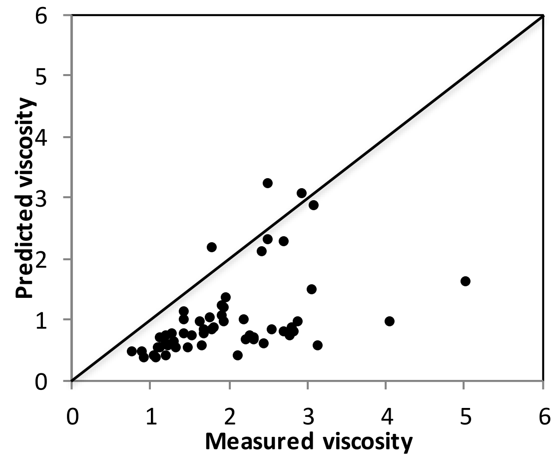


Figure A.10. Naseri et al. (2005)

Appendix B: Cross plots of saturated oil viscosity correlations.

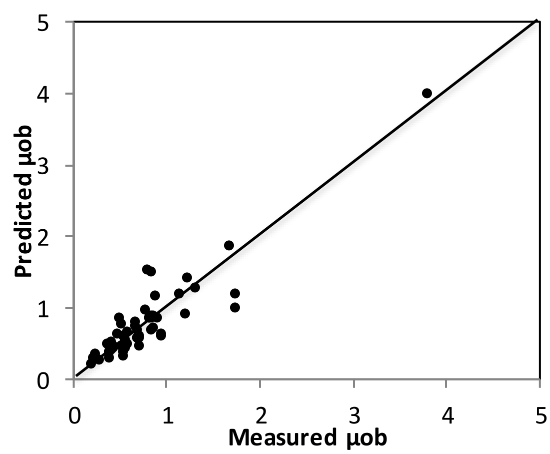


Figure B.1. The Beggs-Robinson (1975)

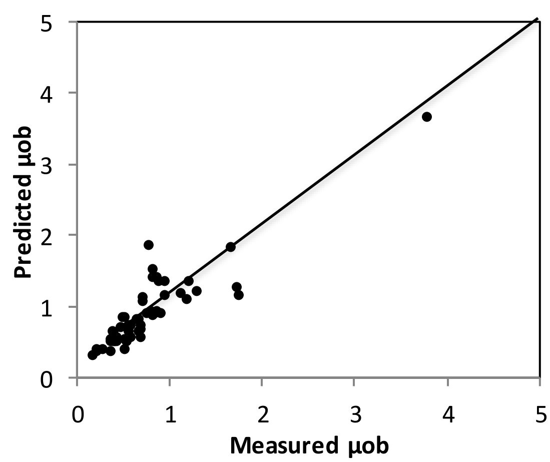
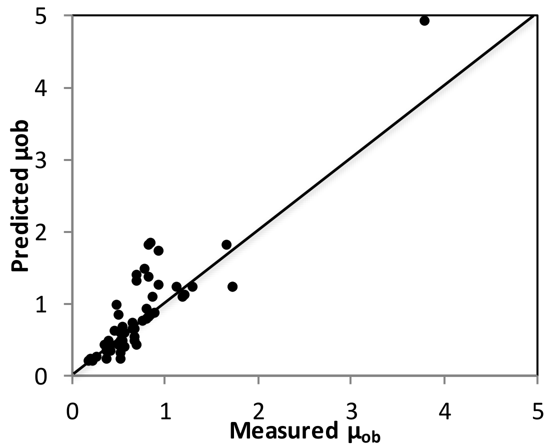


Figure B.2. Khazam et al. (2016)



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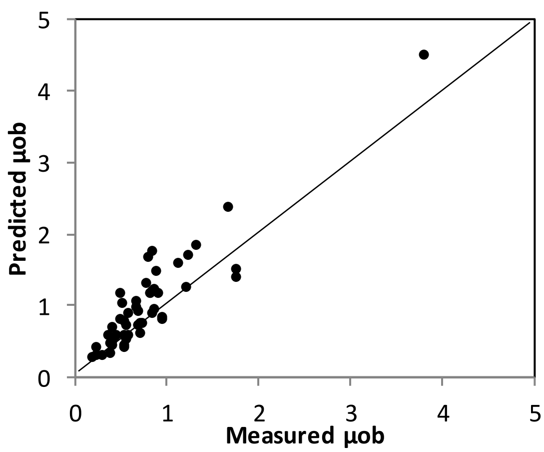

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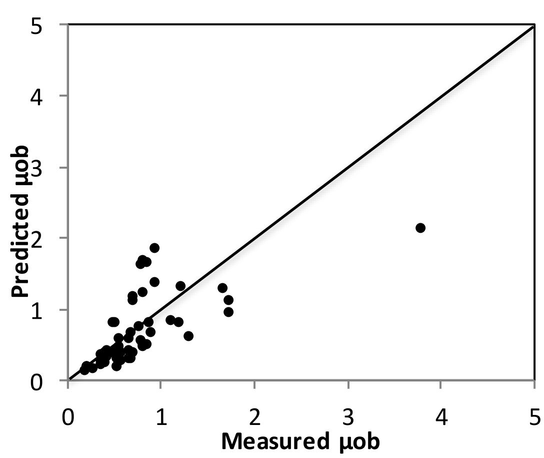


Figure B.5. Khan *et al*. (1987)

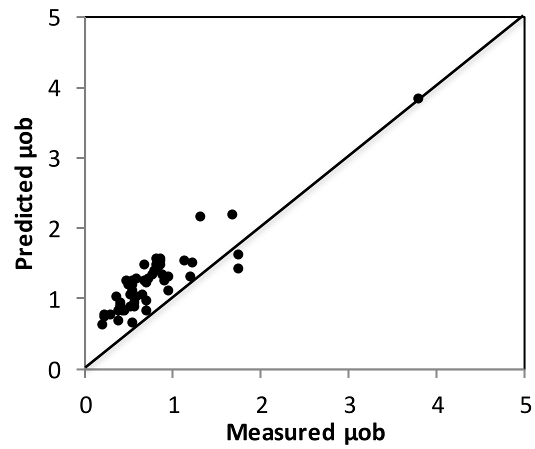


Figure B.6. Petrosky &Farshad (1995)

Appendix C: Cross plots of undersaturated oil viscosity correlations.

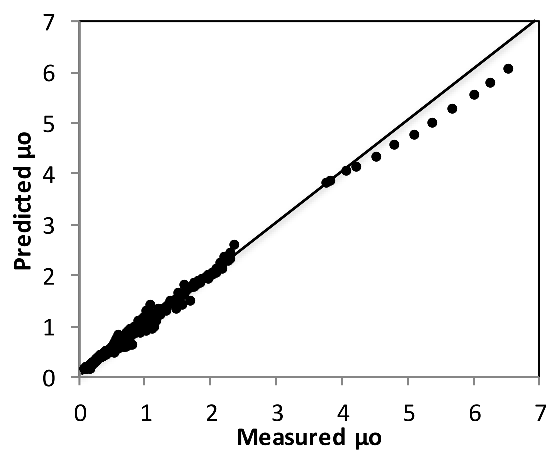


Figure C.1. Khan *et al*. (1987)

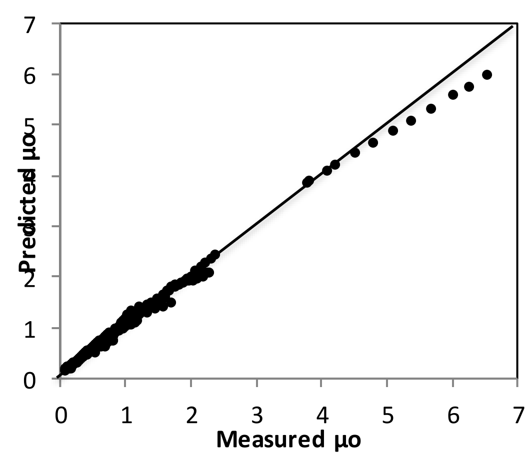


Figure C.2. Labedi (1982)

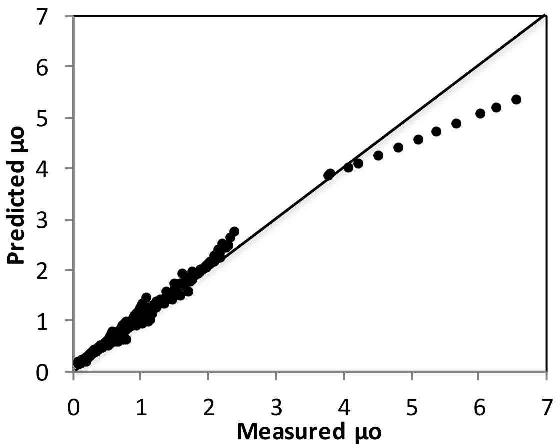


Figure C.3. Petrosky & Farshad (1995)

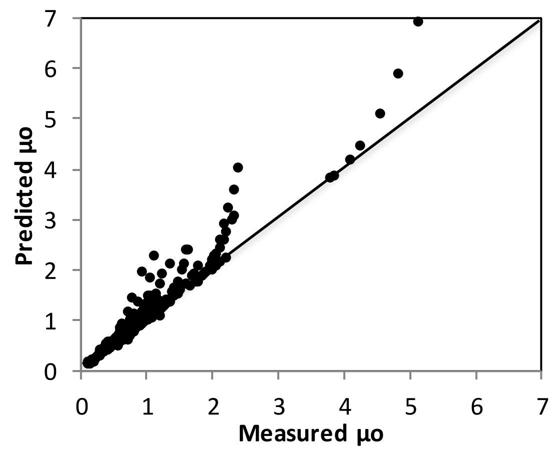
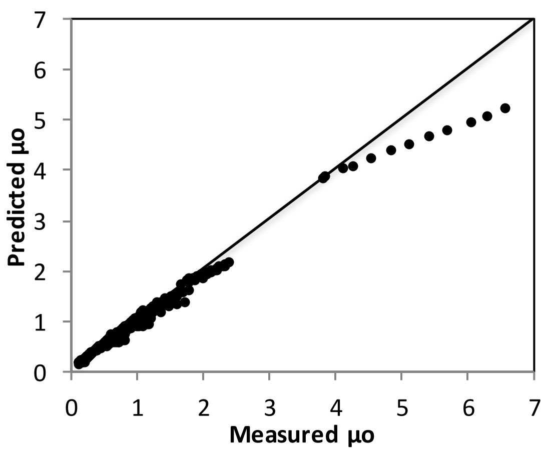


Figure C.6. The Vasquez-Beggs (1980)



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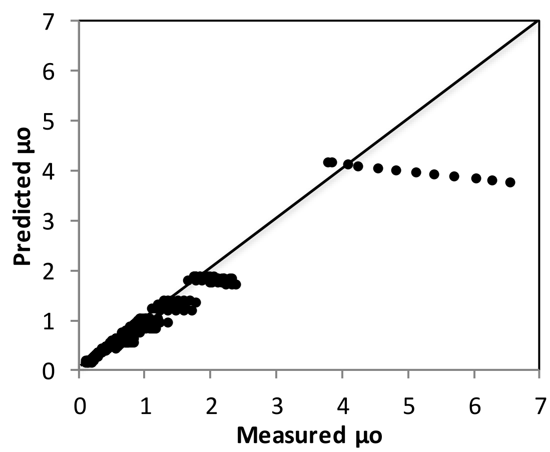

Figure C.6. Kartoatmodjo and Schmidt (1994)

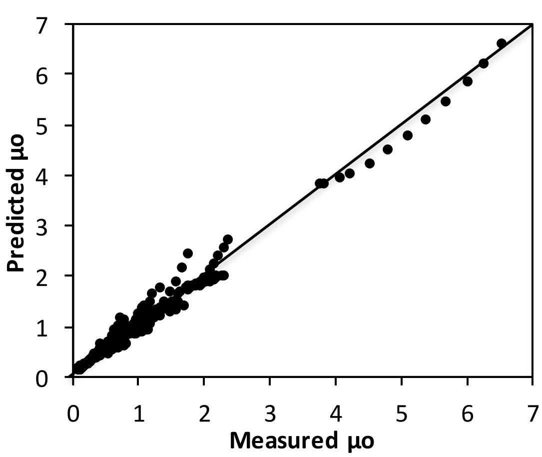

Figure C.5. Khazam *et al*. (2016)