Rheological Behavior of Waxy Crude Oils under Oscillatory Shear and Effect of Plant Seed Oil

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Abstract

Different samples of waxy crude oils were taken before pipeline inlet to field processing facility in the Hadida and Heglig crude pipelines which carrying crude oil from producing oil fields located in the west part of the west Kordofan state, to the costal terminal at Port Sudan. Samples were tested for their flow behavior under superimposed small amplitude oscillatory by dynamic rheometer. The oscillation behavior of the crude oils is measured under dynamic rheological tests for the following parameters: strain sweep, frequency sweep and temperature sweep tests. However, strain sweep was first performed at frequency 10 rad/sec and temperature of 50°C (below wax appearance temperature) to determine linear viscoelastic region. Further, the linear viscoelastic region was calculated as (0.05%) which is used to carry out frequency sweep and temperature sweep tests.

. Moreover, untreated and additive treated crudes with flow improvers (Jatropha Curcas seed oil and Xylene) were used to identify the impact of additives on pour point, wax appearance temperature and flow properties of the crudes.

GC-FID was introduced to perform a composition analysis for untreated and additive treated crudes and average carbon number distribution was identified as C26. In addition, untreated and additive treated crudes were thermal fractionated and their wax appearance temperatures were measured by DSC and the results compared with those obtained from viscometry method. Further, the two crudes show high pour point (33 °C and 33 °C) and high wax appearance temperature (59.88 °C and 59 °C) for Hadida and Heglig crudes respectively, which is essentially required treatment for their storage, production and transportation via pipeline.

Moreover, it was observed that concentration of 5%v/v Jatropha seed oil and xylene capable to reduce Heglig crude pour point from (33 °C to 15 and 18 °C) respectively, on the other hand all pour point depressant used in this study were failed to affect the pour point of Hadida crude, but they affect its viscosity and show improvement in the flow behavior.

However, Hadida and Heglig crudes exhibit a negligible amount of asphaltenes content (0.05) and there may be no problems for the crudes rheology with asphaltenes precipitation.

Furthermore, measured rheological parameters such as storage modulus (G') and loss modulus (G") reveals that, the two crudes exhibit viscoelastic behavior where at low frequencies storage modulus dominate loss modulus indicating solid-like behavior and at high frequencies loss modulus dominate storage modulus indicating liquid-like behavior, also gelling behavior of the crudes was determined by crossover point at which the G' value overlap the G" value and this behavior was confirmed by low tan δ values (i.e. less than one as indicated in Table 4). Furthermore, vegetable seed oil obtained from plant sources such as Jatropha Curcas seed oil could be used as flow improvers for pour point depressant and enhances flow properties of Sudanese waxy crude oils.

Keywords

Waxy crude oils, Chemical additive, Jatropha seed oils, Rheology, DSC, Thermal and Oscillatory Behavior

I. Introduction

Transportation of waxy crude oils via the pipelines passage through temperature zones lower than the pour point of the crude oil affects the flow characteristics of the crudes. Paraffin deposition generally consists of wax, asphaltenes, resin and sands, etc. The high wax contents of the crude cause heavy deposition on the pipeline wall. For efficient operation of a pipeline system, steady and continuous flow without interruption is desirable [1]. However, it is important for pipeline operations to know wax appearance temperature (WAT) of waxy crude oil. Waxy crude oils are difficult to handle [2]. They exhibit non-Newtonian flow behavior at temperatures below the WAT because of wax crystallization. On further cooling and successive crystalized gelling occurs below the critical pour point. Wax precipitated results in handling problems and increased production costs. In addition, some studies have been published on wax related problems [3] and remediation and control techniques [4], [5] and [6].

Furthermore, many methods concerning with wax related problems have been presented to the industry [7], [8] and [9]. These methods fall in two different categories: remedial which involves, thermal, mechanical, and chemical treatment or preventive using dispersants or crystal modifiers [10] or using flow improvers by lowering the pour point and reducing dynamic viscosity and yield stress [11], [12] and [13]. All of these methods have their disadvantages; they all increase operating expenses but preventive procedure have economic advantage over remedial methods. Therefore, it is essential to be able to predict the amount and conditions of wax precipitation in order to reduce operating expenses. In addition, the use of the flow improvers to modify the rheological properties, making the oil suitable for easy transportation have been reported by [14] and [15].

Many works available in the literature for the studies of solvent dilutions have been reported by [16], [17] and [18]. However, a separation of waxes by fractional crystallization at low temperature using different solvents was carried out by [19]. Moreover, some authors were reported a fractionation method using a mixture of solvents (methyl isobutyl ketone and toluene) recovering and crystallizing the soluble fraction at lower temperature [20]. In addition, solvents such as xylene and toluene are used for removal of wax deposits [21].

Furthermore, in recent years, researchers are trying to find more convenient and reliable methods to determine the content of crude oils. DSC technique is well documented as a powerful technique for investigating the characteristic of crude oils. Several studies have evaluated the cloud point of different crudes with additive [22] and without additive [23] and [24]. In addition, some authors were compared the values of WAT obtained by viscometry and DSC. They concluded that the viscometry method underestimates the WAT value [18]. Further, comparisons of WAT for crude oils measured by different techniques have been reported in literature [25] and [26].

Moreover, the effect of composition on rheological behavior of waxy crude oils has been studied by researchers [27], [28], [26], [29], [30], and [31]. Also, Effect of plant seed oils on flow properties of Nigerian waxy crude oil have been investigated by [32].

In this study, the flow behavior of the two Sudanese crudes has been investigated in terms of their thermal, dynamic oscillatory and viscoelasticity behavior. Influence of vegetable seed oil (extracted from Jatropha Curcas seed) and xylene as comparative flow improvers on pour point, WAT, thermal and rheological properties of the crudes have been investigated.

II. Experimental Section

A. Materials

In this study, two crude oils were used one is light waxy crude oil and the other medium crude oil from Hadida and Heglig oil fields respectively; both fields are located in west Kordofan State, Sudan. However, crude oil samples were taken from pipeline inlet (Hadida and Heglig line) of Central Processing Facilities (CPF), because the crude from outlet lines of CPF system almost treated with chemicals i.e. CPF system consists of four parts a) crude oil processing system b) Heating system c) Chemical injection system and d) Firefighting system.

In addition, samples of Jatropha Curcas seed oil (J_2) and Xylene (Xy) as comparative additive were used as flow improvers with concentrations (1%v/v, 3%v/v and 5%v/v). Sets of experiments were performed: composition analysis, thermal fractionation and rheological characterization.

B. Methods

The composition analysis (quantitatively and qualitatively) was performed using GC-FID; WAT was carried out using differential scanning calorimetry (DSC). Further, DSC method covers the determination of temperature at which waxy solids form when crudes are cooled. The cooling rates used were ranging from 0.5 to 2 ^{o}C/min. Pour points were determined accordingly to ASTM method (D-5853). Strain sweep, frequency sweep and temperature sweep tests, at constant shear rate performed using Haake RheoScope1 with cone and plate geometry, gab 0.27 mm.

C. Sample preparation and measurement

Prior to measurements the crude samples untreated and additive treated with (1%, 3% and 5% of pour point depressants) were heated to a temperature of 65 ^{o}C above their WAT for 60 minutes in closed containers and shaken thoroughly to erase any previous thermal history and to ensure complete dissolution of any precipitation solids. Samples were left to cool to room temperature (ambient temperature) and shaken again to homogeneity before samples were taken out and the hot samples were introduced into sealed stainless steel cells and weighed and DSC measurements were conducted. The measurements were performed within the temperature range of 65 ^{o}C to -10 ^{o}C at a cooling rate of 2^{o}C/min. The additive concentrations were (1 v/v%, 3 v/v% and 5 v/v %) for each additive (J and Xy) were examined for the two crudes used in this study.

D. Dynamic Shear Rheology

Dynamic tests were performed for investigations of the rheology of the waxy crude oils under conditions of periodic deformation. Dynamic oscillatory measurements are quite useful for studying processes that involves a change of structure in the sample. All waxy crude oils oscillation tests are carried out under fixed 0.05% strain to make sure that the investigated behavior lies within the linear viscoelastic range (LVER). The elastic and viscous responses of viscoelastic crudes were quantified by using Haake RheoScope 1 Rheometer manufactured by Thermo Scientific Germany, using standard cone-plate geometry with 0.027 mm gab, in which a sample of 0.2 ml is required for each test. Three different oscillatory tests were conducted: 1)- Strain sweep 2)- Frequency sweep and 3)- Temperature sweep test.

a) *Strain Sweep Test*

Strain sweep measurements were carried out on the crudes on Haake RheoScope 1 rheometer to determine the linear viscoelastic range and it was calculated as (0.05%). All subsequent tests were carried out at strain below the critical strain values.

b) Frequency Sweep Test

A frequency (ω) sweep test was also carried out to find the dependence of elasticity and loss modulus on the frequency applied in the linear deformation region. In a frequency sweep, the test frequency is varied to establish the frequency dependence of a material. HAAKE RheoScope1with cone and plate geometry gape (0.027 mm) was used to perform the viscosity versus frequency (0.01 to 100 rad/sec) at constant strain (0.05%), to obtain the viscosity of waxy crude under no flow condition (almost). The two components of the complex dynamic shear modulus (G*) were determined from the frequency sweep test viz. the storage modulus (G') and the loss modulus (G") which characterizes the dissipation losses in the system. Phase angle was measured to identify the amount of elasticity present in a sample.

c) Temperature Sweep Test

Temperature sweeps are useful for measuring the temperature dependence of the viscosity or the thermal transition in waxy crude oil. Temperature is varied from 75 ^{0}C to pour point of the test samples (33^{o}C and 33 ^{o}C) for Hadida and Heglig crudes respectively.

I. Results and discussion

1) Physical properties of the Waxy Crudes

In this study, one additive of green plant origin namely, Jatropha Curcas seed oil (J_2) and xylene (Xy) were used as pour point depressants. The results of the pour point and other physical properties such as density, API gravity, asphaltenes content and water content for untreated and additive treated Hadida and Heglig crude oils are shown in Table 1 and 2. The pour point measurements of the crude oils reveal that as the additive concentration increases there is a maximum depression in pour point.

The physical characteristics of the Hadida and Heglig crude oils indicate that the two crudes exhibit highest pour point (33 ^{o}C and 33 ^{o}C) and light range API gravity (35.15 and 31.12) respectively. Further, API gravity determines the grade or quality of crude oils. Generally, crude oil samples with API gravity greater than (31) are classified as light crude oils, those with API gravity of 22-31 are classified as medium crude, while those with API gravity of 20 and less are referred to as heavy crude oil (API, 2011). Furthermore, from the API gravity results the Hadida and Heglig crudes can be classified as light and medium crude oils respectively. In addition, the two crude oils have negligible amount of asphaltenes (0.05), so there is no problem of asphaltenes precipitation. The rheological behavior is thus free of the effects of the asphaltenes on the gelation of waxy crudes, as reported by [33].

Table 1 Physical Properties of the crude oils

crude Oils	pour point ^{o}C	density g/mL	API	Asphaltene content	Water by distillation
Hadida	33	0.848	35.15	0.05	0.8
Heglig	33	0.879	31.12	0.05	0.8

2) Effect of Additives on pour point (PP.)

The pour point data given in Table 2 indicate that the additives J_2 causes a reduction in the pour point of Heglig crude from (33 ^{o}C to 15 ^{o}C) up to 18 ^{0}C, with 5% J_2 as compare with additives Xy which reduced up to 15 ^{o}C (from 33 ^{o}C to 18 ^{o}C). On the other hand, all of the additives fail to reduce PP of light Hadida crude oil. In addition, it was observed that the crude oils tested responses differently with different additives and they response differently with the same additive at different dosage. Further, pour point depressant (PPDs) may accomplish this task by modifying the size and shape of wax crystals and inhibits the formation of large wax crystal lattices [34]. Generally, the PPDs created barrier to the formation of the interlocking crystal wax network [35]. As a result, the altered shape and smaller size of the wax crystals reduce the formation of the interlocking networks and reduces the pour point [36] by preventing wax agglomeration [37]. However, behavior of the PPDs used in this study to reduce PP suggests that all additives can be effectively used as wax inhibitors.

Table 2 Effect of additive on pour point

Waxy Crude	Blank crude	1%J	3%J	5%J	1% Xy	3% xy	5% Xy
Hadida	33 °C	33	33	33	33	33	33
Heglig	33 °C	27	24	15	30	24	18

3) Gas Chromatography (GC-FID) Analysis

The compositions (amount and type of waxes) of the crude oils were analyzed by GC-FID, for determination of carbon number and average molecular weight distributions. The n-alkane distributions and the content of non-alkanes on the crude oils are plotted in Figures 1, 2, 3 and 4 for Hadida and Heglig crude respectively. The average molecular weight and carbon number distribution for untreated and additive treated Hadida and Heglig crude oils were found in range (C_{10}-C_{40}) as shown in Figures 1, 2, 3, and 4 respectively. It can be observed; the major peaks in the chromatogram for Hadida and Heglig crudes are n-alkanes with carbon number C_{10} to C_{43} for Hadida crude and C_{10} to C_{41} for Heglig crude.

Furthermore, macro-crystalline waxes (C_{18+} to C_{35+} n-paraffins, which consist of straight chain saturated hydrocarbons) were dominant (i.e. 54% for Hadida and 56% for Heglig) while micro-crystalline waxes (C_{35+} to C_{50} n-paraffins, which composed of branched and cyclic hydrocarbons) minor (10% for Hadida crude and 3% for Heglig crude).

However, the relative area under the curve for each n-alkane was converted to the relative abundance of the species. The chromatogram of the treated crude with 5%J_2 presented in Figures 2 and 4 indicates little light ends in the mixture and predominately high normal paraffin content in the sample. In addition, the plot clarifies that the fractions of n-alkanes lighter than C_{20} decreased while the fraction of n-alkanes heavier than C_{20} increased as compared to the untreated crude oils.

It can be noted that a high average carbon number (C_{26}) tends to precipitate suddenly in the form of a solid at fairly high temperature above the PP. It can be noted that, GC-FID analysis of the waxy crude oils reveals that Hadida and Heglig crude highly paraffinic and need wax inhibitor and/or flow improvers to be added during production and transportation.

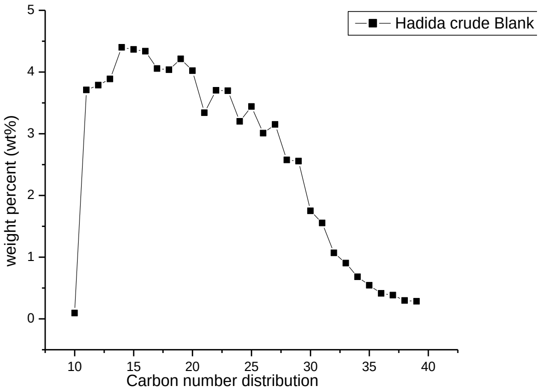


Fig.1 Carbon Number distribution for Hadida Crude Untreated

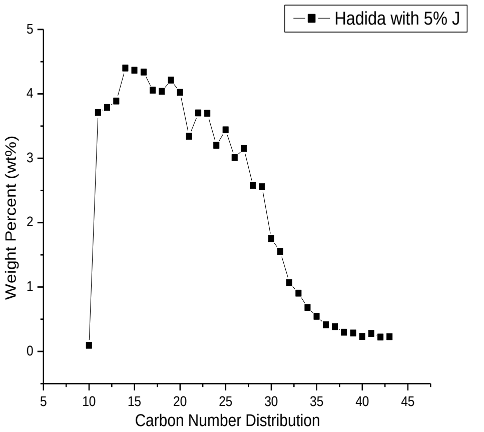


Fig. 2 Carbon Number Distribution for Hadida Crude Treated With 5%J

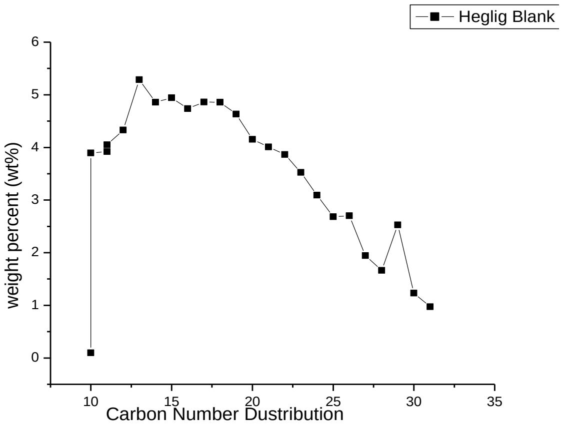


Fig. 3 Carbon Number Distribution for Heglig Crude Untreated

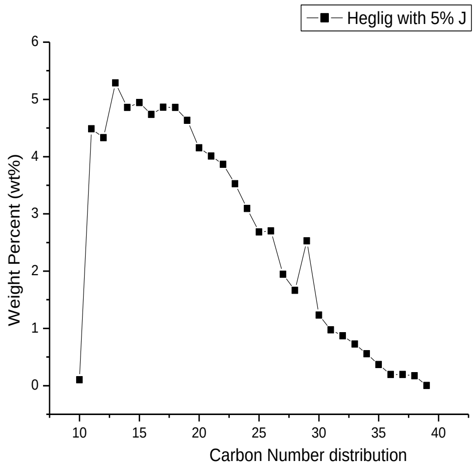


Fig. 4 Carbon Number Distribution for Heglig Crude Treated With 5%J

5) Differential Scanning Calorimetry (DSC)

DSC thermogram of untreated and additive treated Hadida and Heglig crude oils are shown in Figures 5, 6, 7, 8, 9 and 10 respectively. The DSC test was done to prove that the temperatures at the buried pipeline and in the experiments were low enough to have precipitated crystals in these oils. The onset temperature which was determined by the interaction of the inflection line of the peak front with the processing baseline is called WAT. Further, the first peak corresponds to the WAT, while the second one is another crystallization event [38]. Wax appearance temperature for (Hadida =59.88 ^{0}C and Heglig 59 ^{o}C). The high values obtained for the WAT are mainly due to the amount of wax present in the composition of the crude oils [39]. At this temperature the thermal transition from liquid to solid phase had occurred and the first paraffin crystals appeared upon cooling of oil as an effect of the decreased solvating capacity of the oil matrix.

It is observed WATs increase with increasing wax content, in particular with increasing n-paraffin content. Further, it was observed that the oil with higher WAT exhibits higher pour point. These results of WAT were confirmed by rheometric method by plotting (log η vs. 1/T) as shown in Figures 11 and 14. It was found that WAT measured by viscometry for Hadida and Heglig crude oils is around (50 ^{0}C). However, it was found that WAT measured by DSC for all crude oils higher than those obtained by viscometry method. Most DSC curves show the sharp spike of the exothermal peak for waxy crude oils used in this study, except untreated Hadida crude oil Figure 5 and additive treated Heglig crude with 5% J_2 as shown in Figure 9. The exothermal peak corresponds to the crystallization and hence precipitation of solid particles of wax during the cooling process.

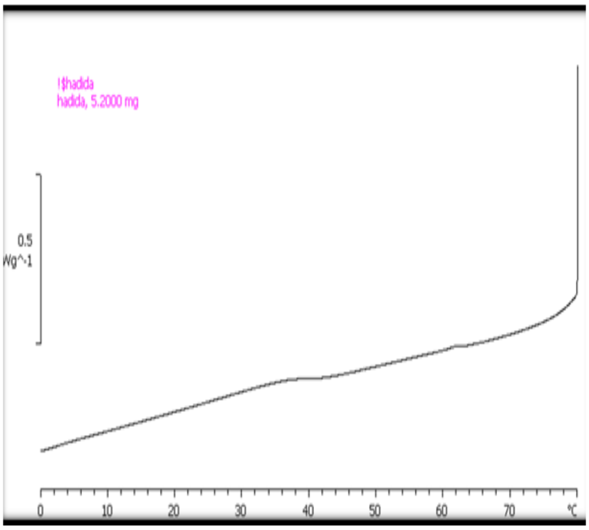


Fig. 5 DSC thermogram of Hadida crude untreated

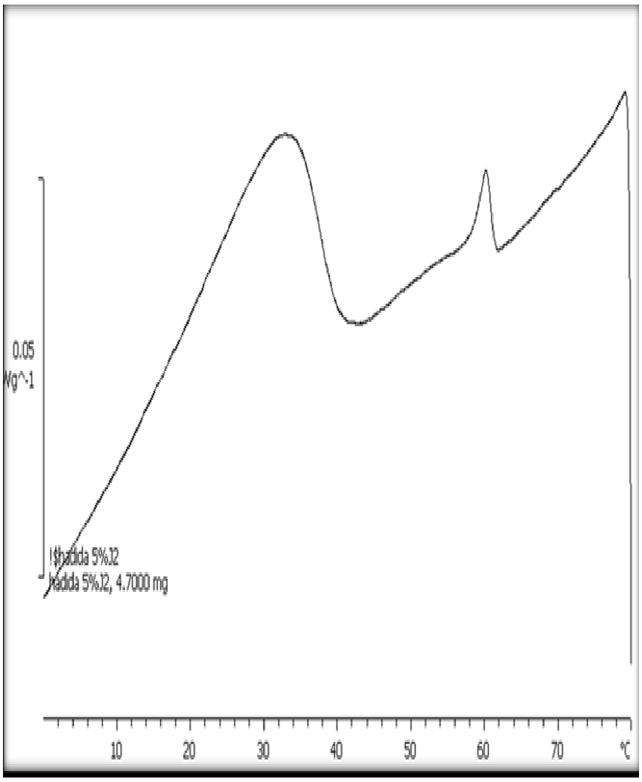


Fig. 6 DSC thermogram of Hadida crude treated with 5% J_2

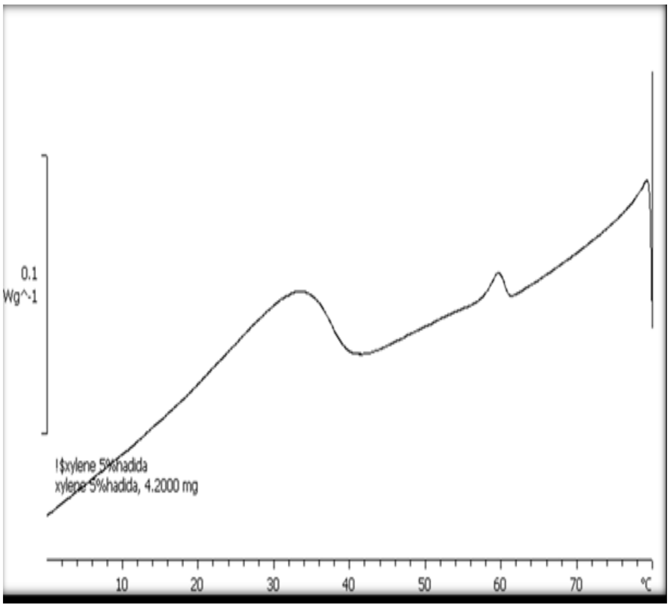


Fig. 7 DSC thermogram of Hadida crude treated with 5% Xy

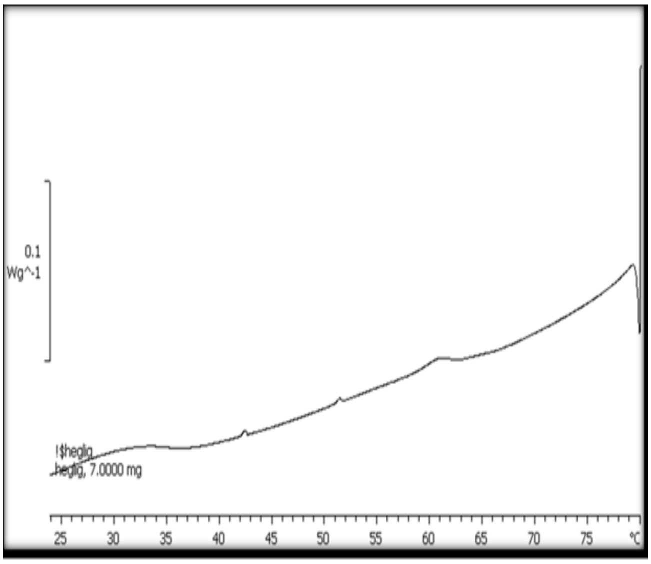


Fig. 8 DSC thermogram of Heglig crude untreated

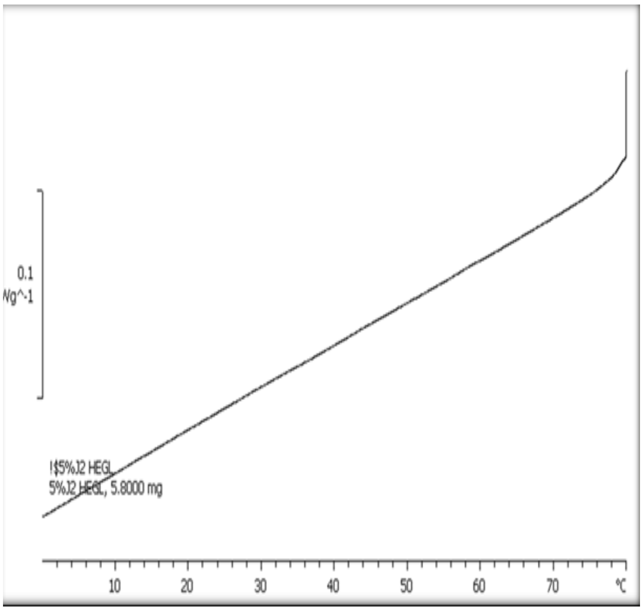


Fig. 9 DSC thermogram of Heglig crude with 5% J_2

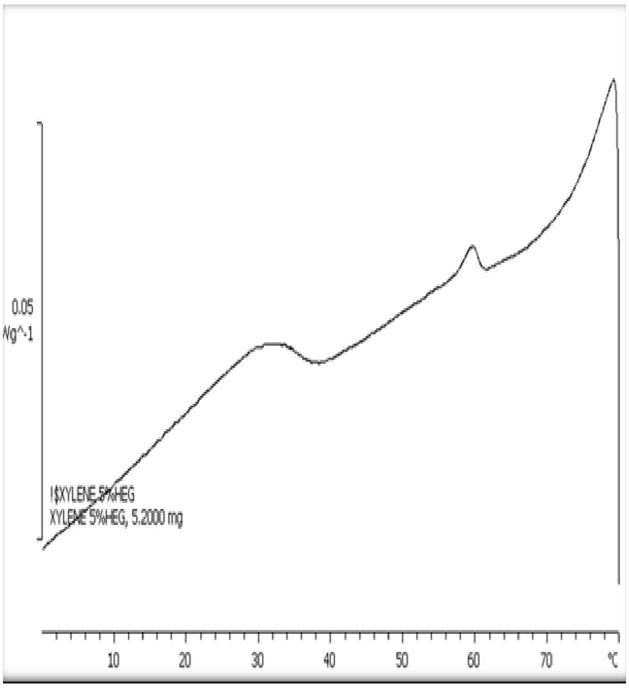


Fig. 10 DSC thermogram of Heglig crude treated with 5% Xy

4) *Viscosity Measurements*

[1] Effect of Temperature

Temperature is varied from 75 ^{0}C to pour point of the test samples (33^{0}C and 33^{0}C) for Hadida and Heglig crude oils respectively. Data collected from measurements of temperature sweep tests (temperature versus viscosity) were plotted in Figures 11, 12, 13 and 14. The dynamic viscosity decreases with increases in temperature in the Newtonian range and can be considered as a simple exponential Arrhenius equation: $\eta = Ae^{Ea/RT}$ Where, η is the Newtonian dynamic viscosity, E is activation energy of viscous flow, A is a constant, R universal gas constant and T is temperature. As shown in Figures 11and 14, WAT of the waxy crude samples were identified by plotting the logarithm of viscosity versus reciprocal temperature. However, this process was used successfully by [26] and [40] to identify WAT of their sample waxy crude oils.

It can be observed, from Figures 11 and 14, the curve of log η versus 1/T shows linear behavior at high temperatures, obeying with Arrhenius equation. First break of the line (first deviate from linearity) can be approximated as WAT (50 ^{o}C). At the point of deviation sufficient wax has crystallized to change the rheology of the crude oil from Newtonian to non-Newtonian. This condition shows that, starting from 50 ^{o}C steep increase of viscosity occurs, which corresponds to the beginning of forming crystals networking for the longest paraffins.

A large increase of the viscosity is observed at 33 ^{o}C, then the rate of increase the viscosity changes again, and then second deviation of curve was observed this correspond to the pour point at (33 ^{o}C) for Figures 11 and 14 respectively, which is well agree with results obtained from ASTM methods Table 2. As the temperature is lowered, the viscosity increases more gently, but due to the shearing, and reaches at the end to the gel point of 25 ^{o}C for Figures 11 and 14 for the two crudes. This gradual change in the rheological properties of oil can be attributed to the strong effect of temperature on viscosity of wax components in the crude oil, as well as to the composition of the crude.

A strong influence of temperature on the rheology is revealed by measured high activation energy. The activation energy of viscous flow, E_a can be obtained from the slope of the linear curve log η versus 1/T. Further, the values of E_a for the three concentrations are in the range 9.8-10.4 KJ/mole and in agreement with the values obtained by [26]. As the temperature drops, solid wax suspends in the oil, the viscosity and E_a increase sharply, characterizing with the large slope of the curve.

It can be noted that, the viscosity values are found to be high at low shear rates, because at low shear rates more time is provided to break the complex chemical structures of the crude oil sample at the corresponding temperature

but at high shear rate an almost constant viscosity was observed with increasing shear rate. This could result from effective dispersion of wax agglomerate in the continuous phase originally immobilized within the agglomerates, after being completely broken down into the basic particles. On the other hand, at higher temperatures where the behavior is Newtonian, the difference between the viscosity values is not significant, this could result from, wax in the crude oil could not agglomerate and aggregates, and hence reducing the oil viscosity. In addition, it is found that measurement of WAT from viscometry method is lower than from DSC. The reason is associated to the condition where the first crystal will be formed once the oil reached WAT. Furthermore, the discrepancy is attributed to the much smaller sample volume and detectable length scales measured using DSC or cross polar microscopy [4].

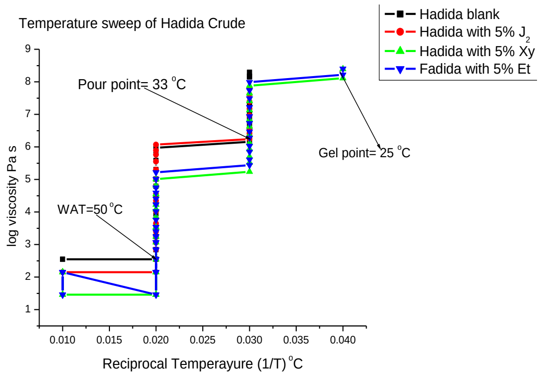


Fig. 11 log η vs. 1/T plot for treated Hadida crude

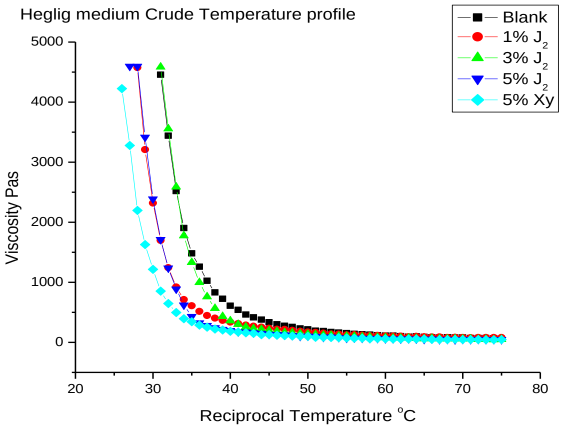


Fig. 12 A Plot of η vs. T for treated Heglig crude

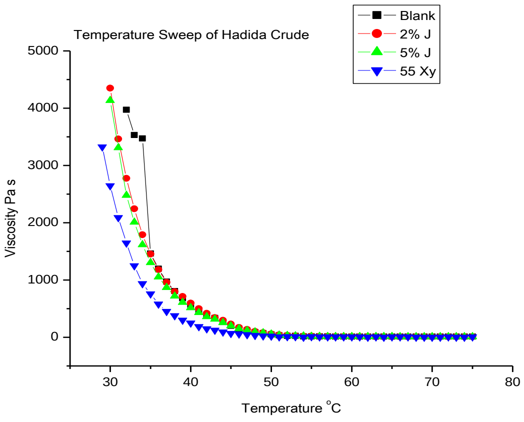


Fig. 13 A Plot of η vs. T for treated Hadida Crude oil

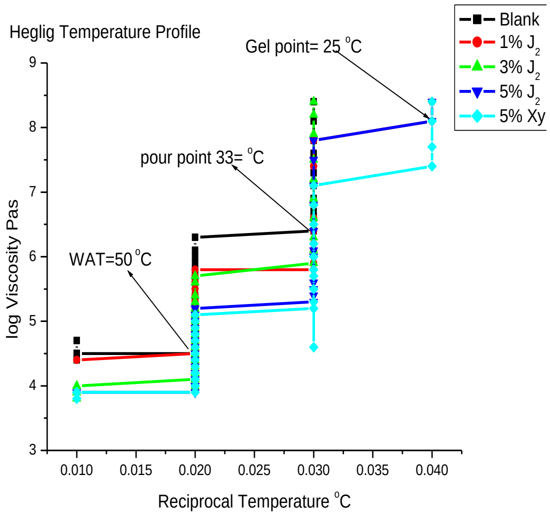


Fig. 14 log η vs. 1/T for treated Heglig crude

[2] Frequency sweep test

Results of the frequency sweep test for untreated and additive treated Hadida and Heglig crudes with different doses of additive concentrations (J_2 and Xy) were presented in Figures (15 to 23) respectively. It can be observed that, at lower frequencies, the storage modulus (G') dominate the loss modulus (G'') indicating predominance of solid-like behavior i.e. the energy, which is reversibly stored by restoring forces. There is a crossover point when storage modulus exceeds loss modulus ($G''= G'$ or tan δ=1 or δ=45) the material behavior changes from elastic to predominately viscous or liquid-like behavior i.e. the energy which irreversibly dissipated due to viscous flow. In addition, a phase displacement angle of θ^o (means elastic behavior) was plotted with G' and G" (Figures 18, 19, 20, 21, 22 & 23) to confirm viscoelastic behavior of the crudes shown in Figures 15, 16 and 17. It can be observed, the phase shift is nearly constant with frequency and the material remains elastic over the complete range. Further, to confirm elastic properties of the crude the dissipation factor (Tan δ) is used to estimate, whether the viscous or elastic behavior is dominating (Tan δ> 1 viscous or Tan δ<1 solid), it can be observed from Table 5, Tan δ values almost lower than unity more "solid" indicating predominance of the elastic behavior.

Moreover, this crossover point is also called the gel point. Furthermore, the crossover of the curves is considered by [42] as the gelation point and the temperatures in which this point takes place are called gel temperatures. In addition, as G'' and G' are the reaction of the sin type stress applied on the structure of waxy crude oil, unlike purely elastic body, the viscoelastic structure cannot respond instantly, at high frequency. Although low frequency is available, yet it will take a very long time to complete an experiment as very high or very low frequency is not suitable for viscoelastic measurement, usually 1 Hz is selected in small amplitude oscillation (SAOS) experiment.

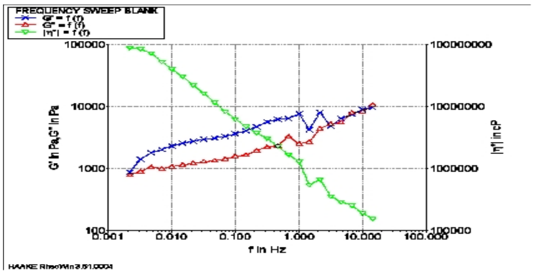
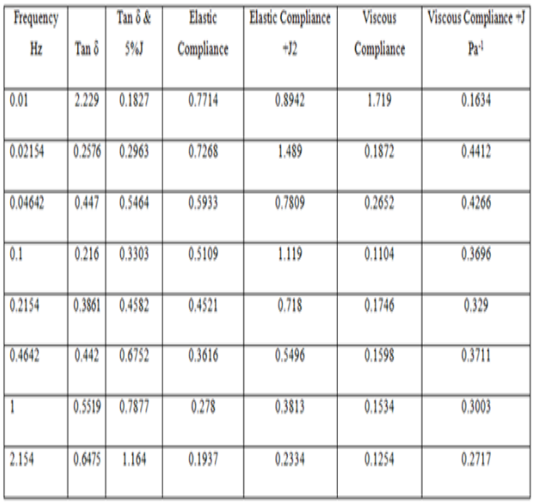


Fig. 15 Frequency Sweep of Untreated Hadida Crude

Table 5 Tan δ and compliance for the treated crude



Frequency Hz	Tan δ	Tan δ & 5%J	Elastic Compliance	Elastic Compliance +J2	Viscous Compliance	Viscous Compliance +J Pa^{-1}
0.01	2.229	0.1827	0.7714	0.8942	1.719	0.1634
0.02154	0.2576	0.2963	0.7268	1.489	0.1872	0.4412
0.04642	0.447	0.5464	0.5933	0.7809	0.2652	0.4266
0.1	0.216	0.3303	0.5109	1.119	0.1104	0.3696
0.2154	0.3861	0.4582	0.4521	0.718	0.1746	0.329
0.4642	0.442	0.6752	0.3616	0.5496	0.1598	0.3711
1	0.5519	0.7877	0.278	0.3813	0.1534	0.3003
2.154	0.6475	1.164	0.1937	0.2334	0.1254	0.2717

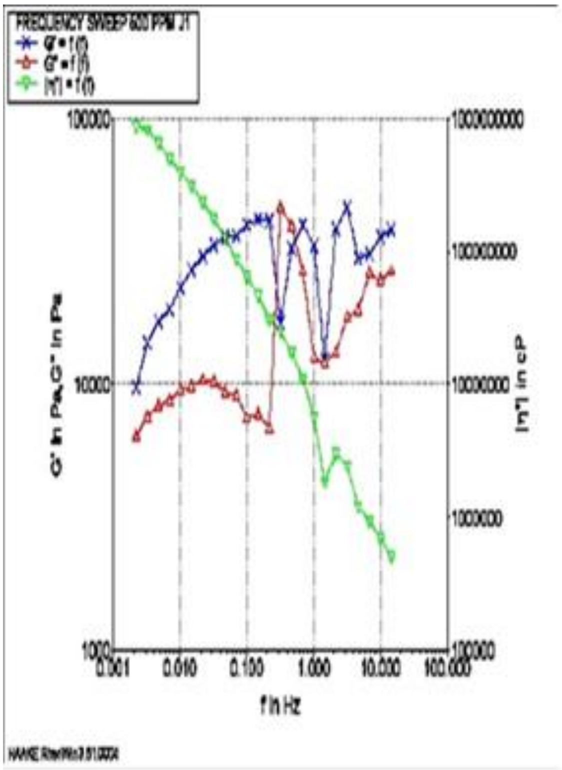


Figure 16 Frequency Sweep of Hadida with J_2 500 ppm

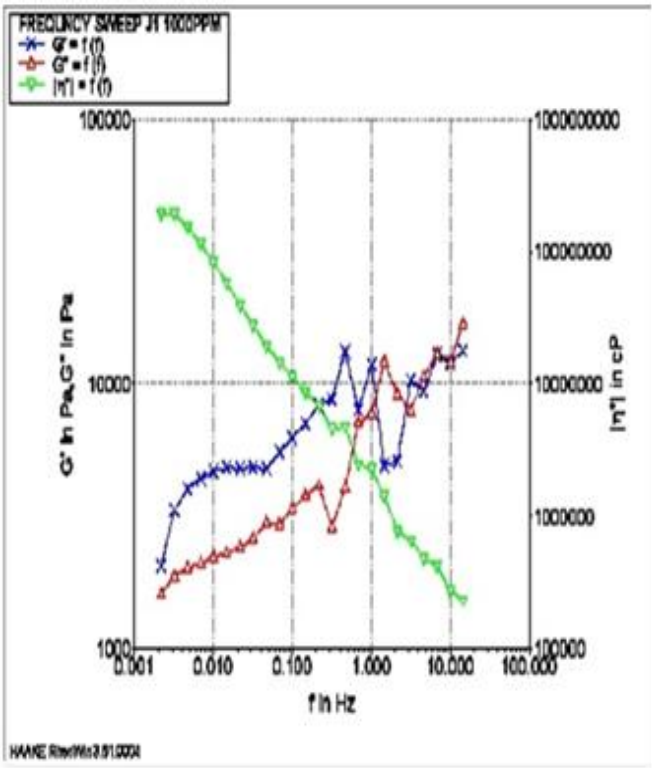
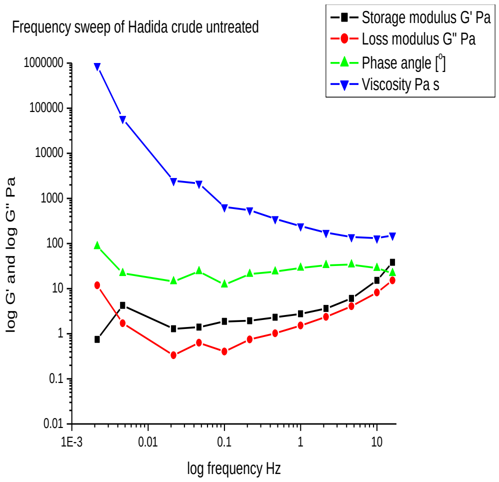


Figure 17 Frequency Sweep of Hadida with J_2 1000 ppm



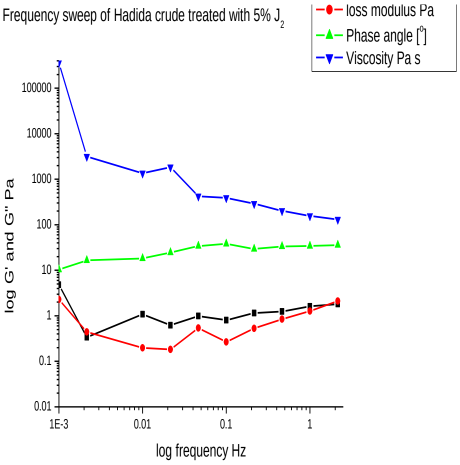


Fig. 18 Frequency Sweep of Hadida Crude untreated

Fig. 19 Frequency Sweep of Hadida Crude treated with 5% J_2

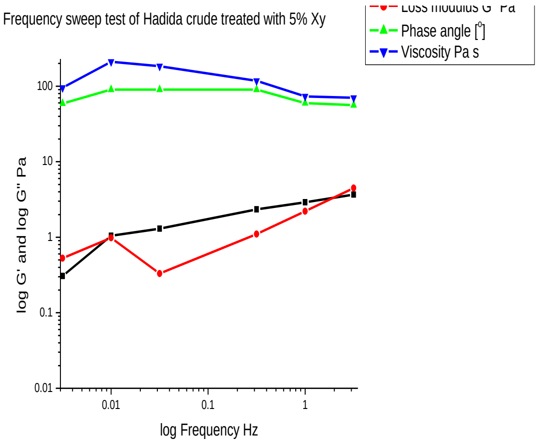


Fig. 20 Frequency Sweep test of Hadida Crude Treated with 5% Xy

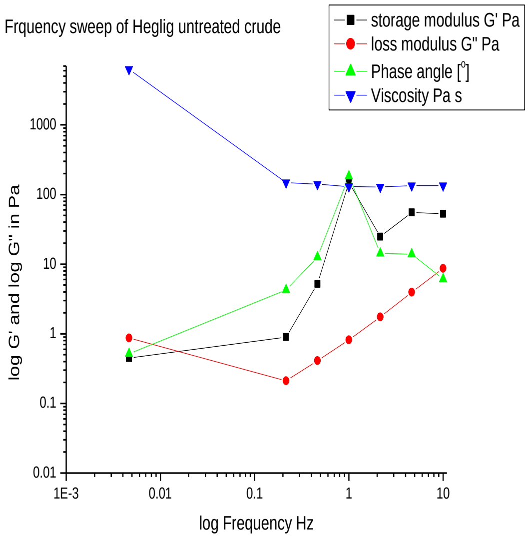


Fig. 21 Frequency Sweep of Heglig Crude untreated

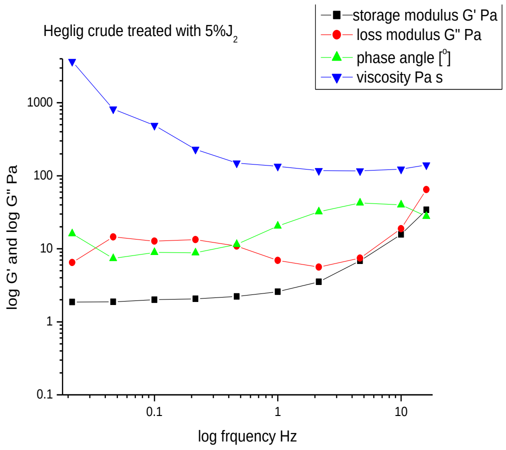


Fig. 22 Frequency Sweep of Heglig Crude treated with 5% J_2

[3] Strain Sweep Oscillation test

Strain sweep experiment was carried out to determine the linear deformation region. During the strain sweep test, the frequency is held constant at 10 rad/s and the amplitude of the deformation signal or the strain signal is varied. This measurement range is called linear viscoelasticity region (LVER). In addition, for shear strain within the LVER was calculated as 0.05% for Hadida and Heglig crude oils. In this case, most of the waxy in the crude oil has crystallized and the structure formed by waxy crystals is very strong. Similar to frequency sweep test at low strain, G' is greater than G" and G* is very close to G", which means that elastic behavior's is dominant (G' and G") are almost the same. This means the structure of waxy crude oil is not destroyed.

Furthermore, these behaviors agree with those obtained from frequency sweep test, that the crude shows viscoelastic behavior, at lower rate of measurements, the crude solid-like behavior are dominant while at high rate of measuring parameters (strain and frequency sweep tests) liquid-like behaviors were dominant.

CONCLUSIONS

- Sudanese waxy crude oils have been characterized using chemical additives and measured WAT is used as criteria to determine flow properties.
- Effect of additives with different concentrations showed that the concentration of 5% is the optimum and capable of lowering the

pour point and wax deposition potentials of the crude samples.

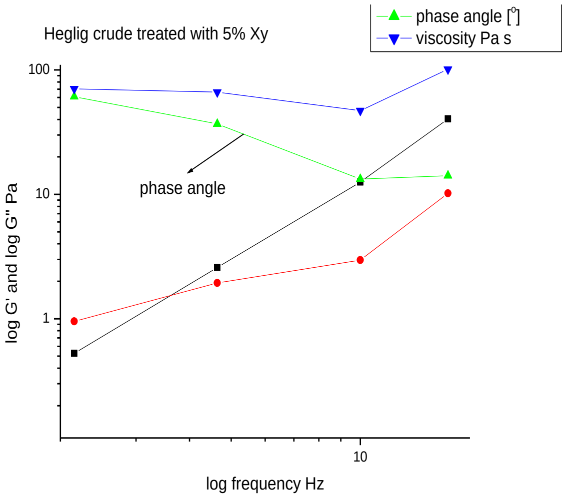


Fig. 23 Frequency Sweep test of Heglig Crude Treated with 5% Xy

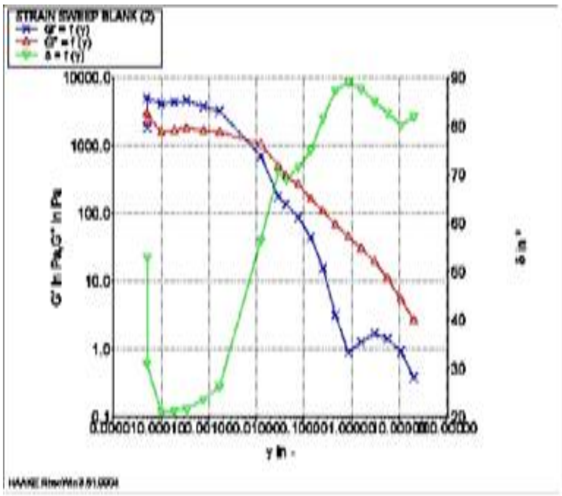


Fig. 24 Strain Sweep Oscillation of Hadida Crude Untreated

- All additives used show effectiveness in depressing pour point and reduction of viscosity of Heglig crude oil, on the other hand they fail to reduce Hadida crude oil pour point but they affects its viscosity and show improvement in the flow behavior.

- Gel point of the crude at 25 ^{0}C which confirmed by constant shear, and temperature sweep experiment under oscillatory shear can be used to study storage stability for different waxy crude oils.
- The two crude oils were wax-rich oils which certainly will need treatment with inhibitors and/or improvers during production and transportation. Further, crude oils exhibit a negligible amount of Asphaltene content and there may be no problems for the crudes with Asphaltene precipitation.
- The two crudes used in this study show a viscoelastic behavior.
- Natural seed oil obtained from plant sources such as Jatropha Curcas seed could be used as flow improvers for pour point depressant and reduction of viscosity for Sudanese waxy crude oils.
- Biodiesel derived from Jatropha Curcas seed oil can be utilized to produce water to grow Jatropha and used the biodiesel as a solvent (Integrated green solutions with positive economic impact on the community).

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