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COMPARATIVE FLOW BEHAVIOR OF OIL SLUDGE AND CRUDE OILS FROM ALGERIAN STORAGE TANKS

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ABSTRACT. This study investigates the flow behavior of tank bottom sludge and two crude oil samples by analyzing the variation of viscosity and shear stress with shear rate and temperature. The flow curves reveal that all samples exhibit non-Newtonian, shear-thinning behavior characterized by a distinct yield stress, particularly prominent in the sludge due to its high content of heavy fractions such as asphaltenes, resins, and solid particulates. Viscosity and shear stress consistently decrease with increasing temperature, a result of the thermal disruption of intermolecular forces and breakdown of microstructural networks. At low shear rates, sludge displays more pronounced shear-thinning behavior than crude oils, while at high shear rates, all samples approach Newtonian flow regimes due to molecular alignment and structural degradation. Model fitting shows the Herschel-Bulkley model best describes the sludge's rheology, whereas the Casson model better fits the crude oils under specific temperature conditions. Temperature sensitivity analysis (10–40 °C) indicates that crude oils experience greater viscosity reduction than sludge, with crude 1 showing the highest response due to its thermally labile composition. Yield stress also diminishes with temperature, reflecting the weakening of internal structural rigidity. These findings underscore the critical influence of composition and temperature on the flow properties of petroleum-derived fluids, with implications for pipeline transport and sludge management.

Keywords: *Crude oil, flow behavior, Sludge, temperature, viscosity, yield stress.*

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INTRODUCTION

Crude oil remains a cornerstone of the global energy supply, with demand significantly rising in the early years of the 21st century compared to the latter part of the 20th century [1]. Given this persistent and growing demand, crude oil is expected to continue serving as a primary energy source in the foreseeable future. Ensuring the safe and efficient transport of crude oil from subsurface reservoirs to surface facilities is a critical aspect of flow assurance. Among available methods, pipeline transportation stands out as the most economical and efficient means for delivering crude oil and its derivatives. A key factor in the successful transport of petroleum fluids is their rheological behavior. Rheological properties, such as viscosity, play a central role in governing flow dynamics and directly impact the design and operation of pipeline systems [2]. Effective management of these properties allows oil companies to optimize the use of existing pipeline infrastructure while minimizing technical challenges. Crude oil is a complex mixture composed of various hydrocarbon fractions, including saturates, aromatics, resins and asphaltenes. Viscosity, in particular, is influenced by the chemical nature and relative concentrations of these components. Heavy crude oils, characterized by high viscosity, are especially prone to pressure drops during long-distance pipeline transport. This increased flow resistance results in elevated energy consumption for pumping operations [3]. The molecular structure of crude oil constituents has a profound impact on viscosity. Non-polar components such as saturates and aromatics tend to reduce viscosity, whereas polar components such as resins and asphaltenes tend to increase it. Asphaltenes are highly polar due to the presence of heteroatoms and metallic elements. They are prone to self-association, forming viscoelastic nanoaggregates. When their concentration exceeds a critical threshold, these aggregates interact with other polar compounds, leading to a dramatic rise in viscosity [4].

Crude oil often separates into heavier and lighter fractions during storage, with the heavier components settling at the bottom of tanks as sludge. This sludge, a complex mixture of oil, sediment, heavy metals, paraffin, and water, can form a stable water-in-oil emulsion. It causes issues like corrosion, reduced storage capacity, and blocked discharge lines, requiring periodic removal [5]. However, it is valuable due to its high oil content, which can be recycled to improve energy resources. Oil sludge composition varies, but typically contains 4-7% solid sediment and has a higher aliphatic (40-60%) than aromatic (25-40%) content. Technologies like solvent extraction, centrifugation, and microwave irradiation have been developed to treat sludge [6-7]. The stability of sludge, caused by oil adsorption on solid particles and the presence of polar fractions like resins and asphaltenes, increases its viscosity [8].

Rheology, which studies how a material deforms under shear stress, is crucial for understanding oil sludge flow. Oil sludge, with its high solid and water content, exhibits complex rheological behavior. It can be pseudoplastic (shear-thinning) and behave differently based on temperature, shear rate, and chemical additives. Research has shown that surfactants, solvents, temperature, and pressure can significantly reduce sludge viscosity, making it easier to handle and pump. Rheological studies, including those by Hassanzadeh et al. [9] and Jie et al. [10], help optimize the management and treatment of tank bottom sludge.

The purpose of this article is to investigate and compare the flow behavior of oil sludge and various Algerian crude oils under different thermal and shear conditions, with particular focus on their rheological properties such as viscosity, shear stress, and yield stress. Understanding these properties is critical for optimizing the handling, transport, and processing of petroleum products, especially in storage tank management where sludge accumulation presents operational and environmental challenges. By modeling the variation of viscosity and shear stress with both temperature and shear rate, this study aims to offer practical insights into flow improvement strategies and sludge remediation. The comparative nature of this study is especially important for identifying how sludge behavior deviates from that of standard crude oils, thus guiding the development of more efficient mechanical or chemical treatment methods and contributing to enhanced operational efficiency and reduced maintenance costs in the petroleum industry.

RESULTS AND DISCUSSION

Variation of viscosity and shear stress with shear rate at various temperatures

Over extended storage periods, the physicochemical properties of crude oil undergo significant alterations due to factors such as reservoir depletion, pressure fluctuations, temperature variations, climatic conditions, and microbial activity, including the presence of oxidizing bacteria and fungi. Moreover, the volatilization of lighter hydrocarbon fractions leads to compositional changes that affect the polarity, solubility, and density of the crude oil, as well as the ratio of saturated to aromatic hydrocarbons. These transformations promote the sedimentation of heavier constituents such as paraffins, asphaltenes, resins, and inorganic solids at the bottom of storage tanks [9]. Consequently, the flow behavior of the resulting high-viscosity sludge is modified due to structural rearrangements in asphaltene and wax crystal networks, which can form gel-like matrices, particularly at lower temperatures. A comprehensive understanding of the parameters influencing the rheological behavior of these materials is essential for accurate flow modeling, the characterization of complex flow phenomena, and the design of pipelines and treatment equipment. Such insights are critical for optimizing energy consumption, enhancing operational safety, and achieving economic and processing efficiency within the petroleum industry.

The flow behavior of the oil sludge and crude oil samples, characterized by the variation of viscosity and shear stress as a function of shear rate at selected temperatures (10 °C and 20 °C), is illustrated in Figures 1 and 2. The shear stress versus shear rate plots reveal the existence of a distinct yield stress, below which no flow occurs. Beyond this yield point, a linear relationship emerges, indicating a non-Newtonian, pseudoplastic behavior. This suggests that a finite shear stress is required to overcome internal structural resistance and initiate flow. Experimental observations further show that with increasing temperature, shear stress, viscosity, and yield stress decrease. This reduction is attributed to the thermal weakening of intermolecular interactions, consistent with previous findings [11].

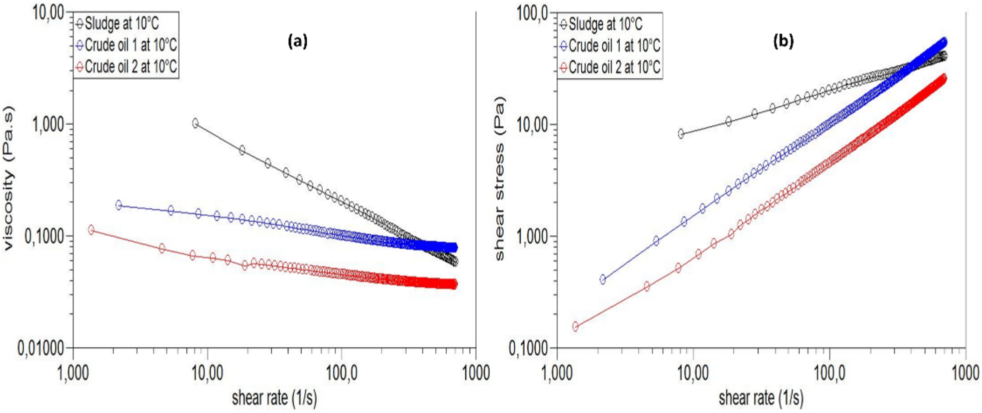

Figure 1. Flow curves of sludge and crude oils at a temperature of 10 °C: (a) viscosity versus shear rate, (b) shear stress versus shear rate.

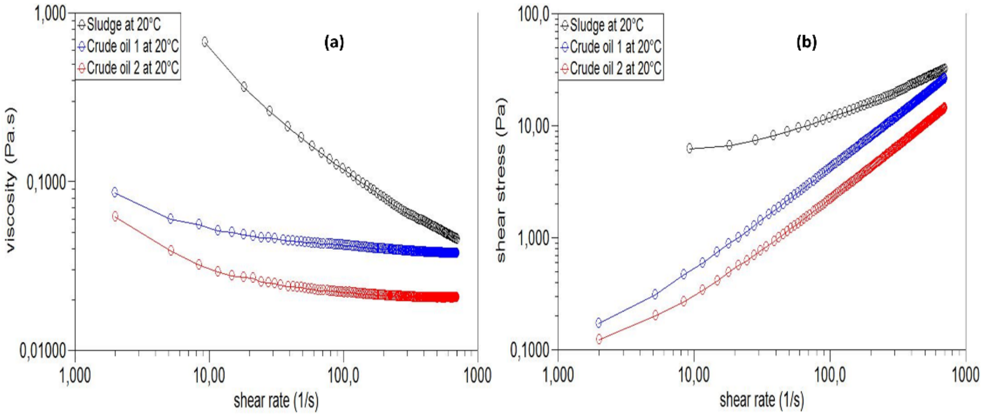

Figure 2. Flow curves of sludge and crude oils at a temperature of 20 °C: (a) viscosity versus shear rate, (b) shear stress versus shear rate.

The viscosity profiles of the sludge and both crude oils reveal two distinct rheological regimes. At low shear rates, the sludge exhibits pronounced non-Newtonian shear-thinning behavior, markedly more significant than that observed in the crude oils. Conversely, at high shear rates, the viscosity curves for all samples converge toward Newtonian behavior, indicating a transition in flow characteristics. Notably, shear rate exerts a substantial influence on viscosity, particularly under low-temperature conditions. This flow behavior can be attributed to compositional differences among the samples and their temperature-dependent structural responses. At elevated temperatures, the samples behave as homogeneous, isotropic Newtonian fluids, where viscosity is primarily governed by temperature. A reduction in temperature increases viscosity at a given shear rate due to decreased molecular mobility. Further cooling promotes the formation of a weak gel network structure, which contributes to a progressive rise in viscosity due to the presence of a nascent dynamic gel phase. Under applied shear, the mechanical energy disrupts this gel network, leading to its deformation and eventual breakdown. This structural degradation under shear results in reduced viscosity, especially at higher shear rates. As illustrated in Figures 1 and 2, viscosity is significantly elevated at low shear rates but stabilizes as shear rate increases. This behavior is attributed to the irreversible disruption and alignment of heavier molecular components, which dominate the rheological response at elevated shear conditions [12].

According to Jie et al. [10], the shear-thinning behavior of tank bottom sludge is more pronounced than that observed in crude oil, primarily due to the sludge's distinct compositional characteristics. As indicated in Table 5, the sludge contains elevated levels of heavy fractions such as asphaltenes and resins, as well as a substantial amount of solid particulate matter. These components significantly influence the system's rheological properties. An increase in solid particle concentration enhances the shear-thinning response. In water-in-oil (W/O) emulsion systems, strong interactions among particles and between particles and oil molecules lead to the formation of a continuous, space-filling network. This interconnected structure, combined with aggregates formed by high molecular weight substances, contributes to the sludge's elevated viscosity. Upon the application of shear stress, these structural networks begin to break down. As the shear rate increases, the extent of structural breakdown becomes more substantial, resulting in a marked reduction in viscosity. Beyond a certain shear rate, a dynamic balance is established between the rates of structural breakdown and reformation, and molecular alignment along the shear direction leads to a stabilization of viscosity at a constant level [13].

To characterize the flow behavior of various non-Newtonian fluids under diverse flow conditions, numerous rheological models have been developed and reported in the literature. Nonetheless, specific laboratory and field investigations indicate that empirical correlations derived from curve-fitting techniques are sometimes necessary to accurately capture the complex rheological behavior of certain fluids [14]. In this study, four rheological models, namely the Bingham model, the Casson model, the power-law model, and the Herschel-Bulkley model, were evaluated using Equations 1 through 4 to determine the most suitable model for representing the observed experimental data.

$$\tau = \tau_0 + \mu\dot{\gamma} \quad (1)$$

$$\sqrt{\tau} = \sqrt{\tau_0} + \sqrt{\mu\dot{\gamma}} \quad (2)$$

$$\tau = K\dot{\gamma}^n \quad (3)$$

$$\tau = \tau_0 + K\dot{\gamma}^n \quad (4)$$

Where: τ is shear stress (Pa); τ_0 is apparent yield stress (Pa); μ is apparent viscosity (Pa. s); K is the consistency index (Pa.s^n); $\dot{\gamma}$ is shear rate (s^{-1}) and n is the flow behavior index.

The rheological models described earlier were applied to fit the shear stress data obtained at different shear rates for each sample examined in this study. Both the shear stress values predicted by the models and the experimentally measured values were used to compute statistical error parameters. To evaluate the predictive accuracy of the rheological models, the standard error (SE), a statistical measure quantifying the deviation between predicted and observed values, was calculated following the approach outlined by [15]:

$$SE = \left[\frac{\left[\frac{\sum_{i=1}^{n} (x_m - x_c)^2}{n-2} \right]^{\frac{1}{2}}}{X_m^{max} - X_m^{min}} \right] \times 1000 \tag{5}$$

The term x_m represents the observed or measured value, x_c indicates the computed or theoretical value, and n refers to the total count of data points.

Table 1. Standard error values of shear stress for various rheological models.

Sample	Temperature, °C	Bingham (Eq.1)	Casson (Eq.2)	Power law (Eq.3)	Herschel-Bulkley (Eq.4)
Sludge	10	49.17	26.73	8.28	**8.13**
	20	24.20	5.83	20.36	**5.04**
Crude oil 1	10	8.06	**2.10**	5.27	3.15
	20	3.52	**1.31**	2.49	1.71
Crude oil 2	10	6.78	**1.84**	4.14	2.65
	20	1.88	2.32	3.28	**1.80**

The findings from the modeling study, as shown in Table 1, along with the corresponding minimal standard errors, indicate that the Herschel-Bulkley model most accurately characterizes the flow behavior of sludge over a defined range of shear rates and temperatures. For crude oil 1, the flow behavior is best represented by the Casson model. In the case of crude oil 2, the Casson model is the most suitable for describing flow at 10°C, while the Herschel-Bulkley model provides a better fit at 20°C.

Variation of viscosity and shear stress with temperature and variable shear rate

Table 2 presents the relationship between apparent viscosity and shear stress of samples as a function of temperature across various shear rates, highlighting their non-Newtonian behavior. In pipeline systems, pressure drop refers to the energy loss resulting from frictional interactions between the fluid and the pipe walls. This pressure drop is inversely related to viscosity; lower viscosities correspond to reduced energy losses, while higher viscosities are associated with increased friction and consequently greater pressure drops and energy dissipation. Shear stress, which is closely dependent on the viscosity of fluid, reflects the fluid’s resistance to deformation under flow conditions, particularly in regions near the pipe wall where frictional forces are most prominent [16]. It can also be interpreted as an analogue to the pressure required to initiate or maintain the flow of fluid within the pipeline.

The sludge and crude oil samples exhibited the highest sensitivity to thermal variation, particularly within the temperature range of 10°C to 40°C. Within this interval, a pronounced decrease in both apparent viscosity and shear stress was observed, indicating substantial improvements in the flow properties due to temperature elevation.

Table 2. Effect of temperature on the rheological behavior of samples under different shear rates.

		Temperature, °C					
		10°C		**20°C**		**40°C**	
Type	**Shear rate, S^{-1}**	**Viscosity, mPa.s**	**Shear stress, Pa**	**Viscosity, mPa.s**	**Shear stress, Pa**	**Viscosity, mPa.s**	**Shear stress, Pa**
Sludge	100	204	20.16	118.8	11.74	85.51	8.417
	200	130.5	25.9	80.36	15.95	54.93	10.94
	300	97.54	29.19	64.62	19.34	44.5	13.3
	400	81.42	32.49	57.97	23.13	39.13	15.6
	500	71.56	35.68	52.74	26.3	35.82	17.88
	600	64.28	38.46	48.57	29.06	33.33	19.96
	700	58.2	40.68	45.46	31.78	31.44	21.96
Crude oil 1	100	100.9	9.903	42.04	4.119	16.7	1.637
	200	88.96	17.7	39.84	7.92	16.17	3.214
	300	83.7	24.96	38.7	11.53	15.99	4.767
	400	81.11	32.36	38.21	15.24	16.01	6.387
	500	79.48	39.6	37.85	18.85	16.11	8.022
	600	77.86	46.64	37.67	22.56	16.17	9.684
	700	77.26	53.94	37.57	26.22	16.2	11.31
Crude oil 2	100	45.31	4.485	22.08	2.164	10.64	1.05
	200	40.98	8.122	21.12	4.197	10.26	2.03
	300	38.39	11.64	20.79	6.196	10.18	3.04
	400	37.87	15.08	20.59	8.211	10.15	4.039
	500	37.18	18.49	20.45	10.18	10.24	5.106
	600	36.75	21.99	20.5	12.27	10.23	6.117
	700	36.58	25.51	20.51	14.32	10.32	7.209

To quantitatively assess the extent of improvement in flow behavior, specifically the reductions in viscosity and shear stress, the Average Degree of Reduction (DAR) is introduced. The DAR is calculated using the following equation:

$$(\mathrm{DAR})\% = \frac{1}{\mathrm{n}}\sum_{\mathrm{i}=1}^{\mathrm{n}}\left[\frac{\text{initial value} - \text{final value}}{\text{initial value}}\right] \times 100 \quad (6)$$

The data presented in Table 3 demonstrate that increasing the temperature from 10°C to 40°C significantly reduced the initial viscosity and shear stress at the fluid–pipe wall interface for sludge and crude oils 1 and 2 by approximately 52%, 81%, and 74%, respectively, indicating a substantial improvement in flow behavior. When the temperature was increased from 10°C to 20°C, viscosity and shear stress reductions of 31%, 54%, and 46% were recorded for sludge, crude 1, and crude 2, respectively. Further heating from 20°C to 40°C resulted in additional reductions of 31%, 58%, and 51% for the same samples.

Table 3. Percent decrease in viscosity and shear stress of samples with increasing temperature.

		Temperature, °C					
		10°C - 20°C		20°C - 40°C		10°C - 40°C	
Type	**Shear rate, S^{-1}**	**% Viscosity reduction**	**% Shear stress reduction**	**% Viscosity reduction**	**% Shear stress reduction**	**% Viscosity reduction**	**% Shear stress reduction**
Sludge	100	41.76	41.77	28.02	28.30	58.08	58.25
	200	38.42	38.42	31.65	31.41	57.91	57.76
	300	33.75	33.74	31.14	31.23	54.38	54.44
	400	28.80	28.81	32.50	32.56	51.94	51.99
	500	26.30	26.29	32.08	32.02	49.94	49.89
	600	24.44	24.44	31.38	31.31	48.15	48.10
	700	21.89	21.88	30.84	30.90	45.98	46.02
Crude oil 1	100	58.33	58.41	60.28	60.26	83.45	83.47
	200	55.22	55.25	59.41	59.42	81.82	81.84
	300	53.76	53.81	58.68	58.66	80.90	80.90
	400	52.89	52.90	58.10	58.09	80.26	80.26
	500	52.38	52.40	57.44	57.44	79.73	79.74
	600	51.62	51.63	57.07	57.07	79.23	79.24
	700	51.37	51.39	56.88	56.86	79.03	79.03
Crude oil 2	100	51.27	51.75	51.81	51.48	76.52	76.59
	200	48.46	48.33	51.42	51.63	74.96	75.01
	300	45.85	46.77	51.03	50.94	73.48	73.88
	400	45.63	45.55	50.70	50.81	73.20	73.22
	500	45.00	44.94	49.93	49.84	72.46	72.39
	600	44.22	44.20	50.10	50.15	72.16	72.18
	700	43.93	43.87	49.68	49.66	71.79	71.74

These findings reveal that while all three fluids exhibit a strong temperature-dependent decrease in viscosity, the extent of this response is governed by their compositional characteristics. Crude 1 showed the greatest reduction, suggesting a higher concentration of thermally sensitive constituents such as waxes and low molecular weight asphaltenes.

Crude 2 also responded significantly to temperature, although to a slightly lesser degree, indicating a somewhat more stable molecular composition. The sludge sample exhibited the lowest total reduction, with identical decreases of 31% observed over both the 10°C to 20°C and 20°C to 40°C intervals. This uniform reduction implies that the sludge contains a broader distribution of heavy components, with viscosity loss occurring more gradually across the full temperature range. Unlike crude oils, where most structural breakdown occurs rapidly at lower temperatures, the sludge matrix may contain a wider range of molecular weights, causing continuous disaggregation and viscosity reduction over both intervals.

The decrease in viscosity across all samples can be attributed to thermal effects on the fluid microstructure. Heating disrupts intermolecular forces within high molecular weight compounds such as waxes and asphaltenes, promoting molecular mobility and reducing resistance to flow. This effect is particularly pronounced between 20°C and 40°C, where wax dissolution typically occurs [17]. Additionally, increased temperature enhances the Brownian motion of dispersed particles, contributing to the breakdown of structured aggregates and further lowering viscosity [10,18]. The differences observed among the samples underscore the influence of composition and molecular architecture on thermal response, with crude oils exhibiting sharper declines in viscosity compared to the more compositionally heterogeneous sludge.

Yield stress

The yield stress represents the critical shear stress at which a material transitions from an elastic (solid-like) response to plastic (flow) behavior. Below this threshold, deformation is primarily reversible and the sample behaves elastically due to its internal structure. Once the applied stress exceeds the yield point, irreversible deformation occurs, initiating flow [19]. Yield stress is typically determined either by extrapolating flow curves to zero shear rate or by fitting data to non-linear rheological models. In the present study, yield stress measurements were conducted under controlled shear rate conditions at two different temperatures, 10°C and 20°C. This method is widely accepted for characterizing yield stress, particularly in complex fluids with non-Newtonian behavior such as sludge and crude oils.

Table 4. Measurement of the yield stress of samples as a function of temperature.

	Yield stress, Pa		
Temperature, °C	**Sludge**	**Crude oil 1**	**Crude oil 2**
10	8.18	0.404	0.153
20	6.22	0.171	0.123

The results in Table 4 demonstrate a pronounced temperature dependence in all samples, reflecting the influence of fluid microstructure on flow initiation. At 10°C, the sludge exhibited a substantially higher yield stress (8.18 Pa) compared to both crude oil 1 (0.404 Pa) and crude oil 2 (0.153 Pa), suggesting a significantly more rigid structure likely dominated by higher contents of heavy components such as asphaltenes and resins. When the temperature increased to 20°C, the sludge yield stress decreased to 6.22 Pa, and corresponding reductions were also observed in crude oil 1 and crude oil 2, with values declining to 0.171 Pa and 0.123 Pa, respectively. This consistent decrease across all samples with rising temperature indicates a reduction in internal resistance to flow, attributed to the thermal softening of structural components, which facilitates molecular mobility and disrupts the elastic network. The comparative analysis reveals that sludge maintains a significantly higher resistance to flow under both thermal conditions, underscoring its more complex or aggregated microstructure, whereas the much lower yield stress values in crude oils 1 and 2 reflect less structural rigidity and a greater intrinsic ability to flow, even at lower temperatures. These findings align with the general rheological understanding that the flow behavior of complex fluids is strongly influenced by the presence and thermal responsiveness of heavy fractions.

CONCLUSIONS

The rheological investigation of sludge and crude oil samples under varying shear rates and temperatures reveals complex, non-Newtonian flow behavior that is highly dependent on both composition and thermal conditions. A key finding is the presence of yield stress in all samples, with sludge exhibiting significantly higher values due to its dense, structured matrix enriched with asphaltenes, resins, and particulate matter. This indicates a strong internal network that must be disrupted to initiate flow.

Shear-thinning behavior dominates across the samples, particularly in sludge, where viscosity decreases markedly with increasing shear rate. This is due to the progressive breakdown of microstructural networks and molecular alignment under applied stress. At low shear rates, the sludge behaves as a structured gel-like material, while at higher rates, its behavior transitions toward Newtonian as viscosity stabilizes. Crude oils demonstrate similar transitions but with less pronounced structural resistance.

Temperature plays a critical role in modulating rheological properties. As temperature increases, shear stress, viscosity, and yield stress all decline substantially, driven by the weakening of intermolecular interactions and breakdown of structured aggregates. The most significant viscosity reductions occur between 10°C and 40°C, particularly in crude oils, where thermally sensitive components like waxes and low molecular weight asphaltenes contribute to sharper transitions in flow properties. Sludge, with its broader molecular weight distribution, shows a more gradual response to thermal changes.

Modeling results confirm the suitability of the Herschel-Bulkley and Casson models in capturing the observed flow behavior, with the Herschel-Bulkley model best describing sludge rheology across temperature ranges. These insights underscore the importance of compositional and structural factors in determining the flow characteristics of heavy petroleum residues and highlight the critical role of temperature in optimizing their handling and transport.

EXPERIMENTAL SECTION

The oily sludge used in this study was sourced from the bottom of a crude oil storage tank at an oil refinery located east of Algiers, which processes crude oil from various regions of the Algerian desert. Following collection, the viscous sludge was stored in a sealed glass container at ambient temperature. Prior to testing, the sludge was manually stirred and subsequently homogenized using a Heidolph MR 3001k incubator shaker at 250 rpm for 15 minutes at 20 °C to prepare 20 mL samples. Key properties of the sludge are presented in Table 1. Crude oil samples were also obtained from two separate tanks in the Tin Fouye Tabankort (TFT) field in southern Algeria. At 20 °C, the densities of crude oil 1 and crude oil 2 were 840 kg/m³ and 825 kg/m³, with corresponding API gravities of 37 and 40, respectively.

The flow behavior of all samples was assessed using an AR-2000 rheometer (TA Instruments) equipped with a Couette geometry featuring a 14 mm diameter and a 1 mm gap [20-24]. Measurements were conducted at 10, 20, and 40 °C, with temperature control maintained via an external water bath and a cover to limit evaporation. Data were acquired and analyzed using the Rheology Advantage software. The rheometer operated in various modes including controlled rate (CR), controlled stress (CS), and oscillatory (OSC) testing. Before measurements, samples were subjected to a 30-second pre-shear at 100 s^{-1} to ensure homogenization, followed by a one-minute rest period. Shear rate sweeps were performed across a range from 0.01 to 700 s^{-1}.

Table 5. Characteristics of the sludge sample used in this study [25].

Characteristics	Amount
oil (wt %)	75
water (wt %)	19
solid particles (wt %)	6
Saturates	52.10
Aromatics	25.90
Resins	15.50
Asphaltenes	6.50

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