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Improvement of rheological and filtration characteristics of water-based drilling fluids using naturally derived henna leaf and hibiscus leaf extracts

Abdul R. Ismail[1,2] · Noorul M. N. A. Mohd[1,2,3] · Nurul F. Basir[1,2] · Jeffrey O. Oseh[1,2,4] · Issham Ismail[1,2] · Shafeeg O. Blkoor[1,2]

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Abstract

Biodegradable additives are required to minimize the environmental hazards from drilling fluid wastes. This study explores the feasibility of the applications of henna leaf extracts (HLE) and hibiscus leaf extracts (HBLE) as ecological benign products in water-based drilling fluids (WBDFs). Rheological and filtration characterizations were carried out on the WBDFs to detect the effects of different concentrations (1, 2, 10, 20, 30, and 40 g) of these plant extracts at 78 and 300 °F. The results of 1 and 2 g of the plant extracts were compared with those of low-viscosity polyanionic cellulose (PAC LV). Compatibility test was carried out using 25 g/L of the green additives on base fluid (A-0), and the swelling rate of sodium bentonite in distilled water was also considered using 1, 10, and 20 g of the green additives. The findings showed that HLE and HBLE significantly reduced the filtrate loss between 62% and 67% and between 64% and 76%, respectively, and improved the rheological characteristics of the WBDF system between 10 and 40 g. PAC LV showed a greater effect on the rheological properties than the green additives in equal amounts (1 and 2 g), but it exhibited flat high and progressive gels which can lead to mechanical pipe sticking. The test data also showed that the inclusion of HLE and HBLE in the WBDF demonstrated larger impact on the mud cake than PAC LV. The cake thickness of the WBDF was reduced in the following order: 30–32% (by HLE), 32–33% (by HBLE), and 24–27% (by PAC LV). This interprets the outstanding filtration characteristics of green additives. Further, compatibility test data confirmed that the green additives are compatible with the other base fluid additives and the swelling behavior of sodium bentonite verified that the green plants are effective in inhibiting bentonite swelling. Here, the Henna extracts displayed higher inhibition property than the Hibiscus product. Notwithstanding, both products showed excellent inhibition property and a strong viscosity enhancing effect on the WBDF system.

Keywords Filtrate loss volume · Henna leaf extracts · Hibiscus leaf extracts · Rheological properties

Abbreviations

10 s GS	Initial gel
10 min GS	10 minutes gel
AHR	After hot rolling
API FL	Filtrate loss volume at 100 psi pressure and 78 °F
API MCT	Mud cake thickness at 100 psi pressure and 78 °F
API	American petroleum institute
AV	Apparent viscosity
BHR	Before hot rolling
CMC	Carboxyl methylcellulose
FL	Filtrate loss volume
GS	Gel strength
HBLE	Hibiscus leaf extracts
HLE	Henna leaf extracts

✉ Noorul M. N. A. Mohd
anam@utm.my

[1] Department of Petroleum Engineering, School of Chemical and Energy Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Malaysia

[2] Malaysia Petroleum Resources Corporation Institute for Oil and Gas (MPRC–UTM), Universiti Teknologi Malaysia, 81310 Johor Bahru, Malaysia

[3] Advanced Membrane Technology Research Center (AMTEC), Universiti Teknologi Malaysia, 81310 Johor Bahru, Malaysia

[4] Department of Chemical and Petroleum Engineering, College of Engineering, Afe Babalola University, P.M.B. 5454, Ado-Ekiti, Ekiti State, Nigeria

HPHT FL	Filtrate loss volume at 500 psi pressure and 300 °F
HPHT MCT	Mud cake thickness at 500 psi pressure and 300 °F
HPHT	High-pressure high-temperature
KCl	Potassium chloride
LCMs	Lost circulation materials
MCT	Mud cake thickness
MW	Mud weight
NaOH	Sodium hydroxide
OBDFs	Oil-based drilling fluids
OX-SCAV	Oxygen scavenger
PAC LV	Low-viscosity polyanionic cellulose
PHPA	Partially hydrolyzed polyacrylamide
PV	Plastic viscosity
ROP	Rate of penetration
WBDFs	Water-based drilling fluids
YP	Yield point

Introduction

It is often difficult to locate and develop new petroleum fields in challenging drilling environments, such as deeper offshores, geothermal wells, or high-pressure high-temperature (HPHT) environments. Improving field techniques, including multipurpose, cost-saving, environmentally accepted, and more efficient drilling fluids, have made the drillings of longer-reach wells, deeper wells, and more complicated wells possible. Such fluids, however, should be built to work efficiently and not to cause damage to the formation (Zhong et al. 2019; Oseh et al. 2019a, b). Oil-based drilling fluids (OBDFs) and water-based drilling fluids (WBDFs) are the most widely used drilling fluids for hydrocarbon productions. OBDFs have been the drilling fluid of choice in unforgiving and complex drilling formations for many years, largely for their high-temperature resistance up to 500 °F, high lubricity, superb salt tolerance, high rate of penetration (ROP), and efficient carrying capacity of cuttings (Amani et al. 2012; Nanthagopal et al. 2019). However, environmental regulations have increased the restrictions on their applications since the 1980s because of their harmful drilling wastes (Nanthagopal et al. 2019; Oseh et al. 2019c, d). Also, high expense and negative impacts on the well cementing pose some drawbacks on applying OBDFs because of weak adhesion between the casing and the formation (Sayindla et al. 2017). The use of WBDFs is an attractive alternative from an economic and environmental perspective. Nonetheless, it also has some flaws, such as low lubricity, low ROP, and increased contact with the formation of hydrophilic clay, which causes wellbore instability due to problems with dispersion and swelling of the clay (Ismail et al. 2015; Xu et al. 2018). Therefore, different additives for WBDFs are constantly being developed to achieve OBDF-like properties (Sayindla et al. 2017; Fujii 2017).

Bentonite-based WBDF system is still the most preferred fluid system in the field to drill oil and gas wells (Choo and Bai 2015). The basic design criteria for WBDFs applied in HPHT wells include Wyoming bentonite (high purity and quality sodium montmorillonite) at low concentrations and fluid additives with only one primary function (Choo and Bai 2015). In freshwater or low salt-water fluids, bentonite is added to provide viscosity required to suspend drilled cuttings and barite (Caenn et al. 2017). At higher salinities, bentonite no longer hydrates and at high temperatures exceeding 300 °F, the clays in the fluid need special attention owing to a gelation process (Kelessidis 2017; Darjani et al. 2017, 2019). The gelation leads to undue fluid viscosity, especially for high-density drilling fluids, and result in increased filtrate flux and unstable wellbore (Saboori et al. 2018). Maintaining wellbore stability is an important function of drilling fluids, which is strongly affected by rheology, filtration control, and filter cake thickness (Saboori et al. 2018; Oseh et al. 2020a, b). The intrusion of water into permeable formation weakens the stability of the wellbore and causes serious drilling problems, such as tight holes, pipe stuck, and wellbore collapse, which hampers the drilling program severely (Saboori et al. 2018; Oseh et al. 2020a, b). Therefore, rheology and filtration control properties of WBDFs are two critical parameters that are optimized to achieve a successful drilling operation.

The common practice in the petroleum industry is to use viscosity modifiers, fluid loss control additives, or even lost circulation materials (LCMs), such as bentonite, barite, graphite, and calcium carbonate to formulate conventional WBDF system. Quite often, commercial macro-polymers, such as partially hydrolyzed polyacrylamide (PHPA), starch, guar gum, xanthan gum, cellulose derivatives, and carboxyl methylcellulose (CMC), are also incorporated to improve the overall properties of the WBDF system (Choo and Bai 2015). This is because these products form hydrogen bonds with water molecules. The bond formation increases the strength of the intermolecular forces that govern the viscosity of the liquid phase (Oseh et al. 2019c, d). Also, polymer, such as polyanionic cellulose (PAC) acts as a fluid loss reducing agent which minimizes the flow of fluid to form a thin cake with low permeability (Luz et al. 2017). It can also improve the viscosity of the drilling fluids depending on its molecular weight and chemical structure (Al-Hameedi et al. 2020). These additives are large size diameter chemicals and are chemically processed. Also, they are non-biodegradable and can present severe harm when exposed to living things. Therefore, the need for ecologically benign materials that will contribute to the regulation of mud properties with an increase in performance without causing environmental hazards could be essential. World concerns about environmental protection from the adverse effects of non-biodegradable products and chemicals are increasing daily. Such concerns are pushing the petroleum industry in the production of safe, cost-effective, sustainable, and environmentally benign drilling fluids from naturally occurring plant extracts.

Recently, the development of locally derived Henna Leaf Extracts (HLE) as a viscosity modifier (Oseh et al. 2019a), filtration control agent (Moslemizadeh et al. 2015), and clay swelling inhibitor (Moslemizadeh et al. 2016) has caught the attention of researchers. HLE is a naturally occurring plant that came from the family of Lythraceae. It is mostly grown in dry tropical and subtropical zones, including Morocco, Yemen, Iran, Nigeria, Iraq, India, Sri Lanka, Afghanistan, Pakistan, and Egypt (Gozubuyuk et al. 2014; Oseh et al. 2018). It is a low-cost and environmentally friendly material that is readily soluble in water. It can act as anti-corrosion in various metallic mediums (Ostovari et al. 2009).

Hibiscus leaf extracts (HBLE) are another natural product that originated from the Malvaceae family. It is a flowering, perennial, woody ornamental shrub widely found in the tropical region. It has been well proven to be medicinal in different studies. It provides an effective antidote to skin rashes and allergies (Obi et al. 1998; Sharada et al. 2012). Sharada et al. (2012) reported that HBLE showed antioxidant properties by producing flavonoids and other phenolic compounds that minimized the harmful effects of UV (ultraviolet) radiation. Fresh hibiscus leaves are typically composed of about 85% moisture content. Others of their components are ash, fat, phosphorus, fiber, calcium, and thiamine. The chemical components of the leaves are isoamyl alcohol, anisaldehyde, methanol, benzyl alcohol, malic acid, niacin, isopropyl alcohol, and 3-methyl-i-butanol (Choo and Bai 2015). Hibiscus leaves are highly economical, devoid of side effects, biocompatible, biodegradable, renewable, and environmentally friendly (Obi et al. 1998; Sharada et al. 2012). The green HBLE as a viscosifier and filtrate loss reducing agent in drilling operations have not been reported in open literature, and this study, therefore, presents its effect in a complex WBDF system.

Typically, industrial-grade low-viscosity PAC (PAC LV) is a very popular chemical used in the field to prevent water leakage into the drilled formation and its characteristics are well documented in several studies. PAC LV is an anionic cellulose ether, soluble in water, and is synthesized using alkali-catalyzed process. It has a high degree of substitution and purity. It also has exceptional features, comprising excellent salt resistance, good temperature stability (stable up to 300 °F), and strong antibacterial activity (Thomas 1982; Balestrini et al. 2009). However, being a chemical additive, the indiscriminate discharge of its effluents into the environments can be harmful to human health and aquatic lives.

There are rather few studies in open literature regarding the effect of locally derived green additives on the rheological and filtration characterizations of WBDFs (Al-Sehaibani 2002; Sharada et al. 2012; Abdollahi and Shadizadeh 2012; Wei 2013; Omotioma and Ejikeme 2014; Gozubuyuk et al. 2014; Samaravati et al. 2014; Moslemizadeh et al. 2015, 2016). Considering economic, sustainability, and environmental factors, as well as the need to promote the local content initiative, development of naturally derived plant-based polymers, such as HLE and HBLE, might improve the rheological and filtration characteristics of WBDFs. These plant extracts are low-costs, biodegradable, non-toxic, and ecologically benign and could be effective in enhancing the physicochemical properties of the complex WBDF system. Therefore, in this study, locally derived green additives (HLE and HBLE) were processed and applied to enhance the rheological and filtration characteristics of the WBDF system. To determine their suitability as filtrate loss control agents and possible applications in the field, their rheological and filtration properties were compared with those of the commonly used industrial-grade PAC LV at 78 °F and a high temperature of 300 °F. Furthermore, the compatibility of these products with some common WBDF additives was assessed and their swelling inhibiting impact of sodium bentonite was evaluated.

Experimental

Materials

The chemicals applied in this study are potassium chloride (KCl), caustic soda (NaOH), bentonite, PHPA, oxygen scavenger (OX-SCAV), barite, sodium chloride (NaCl), and PAC LV. The industrial-grade PAC LV served as filtration control and viscosifier. The green leaf extracts of henna and hibiscus were supplied by a local commercial store (Johor, Malaysia), and they are shown in Fig. 1.

Formulation of drilling fluids

The green leaves (HLE and HBLE) were dried separately in an oven for 48 h at 160 °F to remove moisture. The dried green leaves were crushed into powder form using a grinder. They were filtered to their finest form to reduce the solute content and were stored in a sealed plastic bag at room temperature before their applicability in the WBDF system. The WBDF was formulated in ascending order according to Table 1 with four different concentrations (10, 20, 30, and 40 g) of each of HLE and HBLE products. The formulation of the fluids shown in Table 1 was carried out to study the effects of the green additives (HLE and HBLE) in the complex WBDF system. To evaluate the filtration control performance of these green additives and compare them with a commercial PAC LV, two lower concentrations (1.0 and

2.0 g) of each of the HLE, HBLE, and PAC LV were added into the WBDF after the inclusion of barite. A representation of this formulation is depicted in Table 2.

General testing program of drilling fluids

The properties of the formulated fluid samples were examined using the recommended American Petroleum Institute (API) testing standards (API RP 13B-1 2017). For the tests of mud properties, different fluid samples were formulated. Tests were conducted on the fluids before hot rolling (BHR) and after hot rolling (AHR) at 78 °F and 300 °F, respectively. The fluids were hot-rolled at 300 °F for 960 min in an aging steel cell using a model-35 Fann viscometer. The pH of different concentrations (10, 20, 30, and 40 g) of the green additives was determined using the pH meter at 78 °F to evaluate the sensitivity of the pH of the green additives on the aqueous (WBDF) system. The mud weight (MW) was measured using the fluid balance at 78 °F and 300 °F. Equations (1–3) were used to calculate the plastic viscosity (PV in cP), yield point (YP in lb/100ft^2), and apparent viscosity (AV in cP). The gel strength (GS) was measured by shearing the fluid at 10 s (initial GS) and then letting it rest for 10 s. The maximum shear stress value at 3 rpm was recorded after the rest time as initial GS. The same procedure was followed for the 10 minutes (10 min) GS, but in this case, the samples were rested for 10 min. After the samples were hot-rolled at 300 °F for a continuous 16 h, the same procedures were used for all the measurements of rheological properties. The API fluid loss (API FL) investigation was executed at 78 °F and 100 psi pressure after a continuous 30-min test period and thereafter the API mud cake thickness (API MCT) was measured using a Fann supplied ruler. HPHT filter press was introduced to test for the HPHT FL at 300 °F (heating temperature) at a differential pressure of 500 psi, and the resulting MCT was measured again. All the tests were done thrice, and the average readings were registered.

Fig. 1 Leaf extracts and powder after processing **a** henna and **b** hibiscus

Table 1 Components of WBDF, HLE, and HBLE drilling fluids

Component	Function	WBDF	HLE	HBLE
Water (ml)	Base fluid	320	320	320
Bentonite (g)	Viscosifier and filtrate loss reducer	25	25	25
NaOH (g)	pH control	0.2	0.2	0.2
PHPA (g)	Filtrate loss reducer and viscosifier	1.0	1.0	1.0
OX-SCAV (g)	Corrosion inhibitor	1.5	1.5	1.5
KCl (g)	Clay swelling inhibitor	25	25	25
Barite (g)	Weighing agent	125	125	125
WBDF + HLE	Viscosifier and filtration control	–	10, 20, 30, and 40 g	–
WBDF + HBLE	Viscosifier and filtration control	–	–	10, 20, 30, and 40 g

Table 2 Components of WBDF with 1.0 and 2.0 g each of HLE, HBLE, and PAC LV

Fluid	PAC LV		HLE		HBLE	
	1.0 g	2.0 g	1.0 g	2.0 g	1.0 g	2.0 g
WBDF	–	–	–	–	–	–
WBDF + PAC LV	1.0	2.0	–	–	–	–
WBDF + HLE	–	–	1.0	2.0	–	–
WBDF + HBLE	–	–	–	–	1.0	2.0

$$AV = \theta 600/2 \tag{1}$$

$$PV = \theta 600 - \theta 300 \tag{2}$$

$$YP = 0.511(\theta 300 - PV) \tag{3}$$

Compatibility and permeability tests

Another important factor that is always considered before introducing any additive for drilling formulation is the compatibility of such additive with other fluid additives. Hence, the compatibility test was conducted to inspect the compatibility between the common WBDF additives and the evaluated green additives (HLE and HBLE). This aspect of the investigation was accomplished by adding 25 g/L of the green additives (HLE and HBLE) into test fluid A−0 (base fluid) (Table 3). The fluids were subjected to an aging cell in a dynamic rolling oven for 4 h at 221 °F, and the changes in their dial readings and filtrate losses were measured before and after introducing the green additives. After the measurement of the filtration properties, the permeability of the mud cake was determined at this HPHT condition. The investigation was carried out by the filtration rate through the mud cake based on Darcy's law according to the reports of Elochukwu et al. (2017). Darcy's law is defined by Eq. (4).

$$\frac{dv}{dt} = \frac{KA\Delta P}{\mu h} \tag{4}$$

where dv/dt is the filtration rate, K is the cake permeability, A is the area of cross-section, ΔP is the pressure differential, μ is the viscosity of the fluid, and h is the mud cake thickness achieved from Eqs. (5 and 6).

$$h = \frac{V_f}{A\left(\frac{f_{sc}}{f_{sm}} - 1\right)} \tag{5}$$

where f_{sc} is the volume fraction of deposited solids in the mud cake, f_{sm} is the volume fraction of the solids in drilling fluids, and t is the time of the filtration experiment. It can be noted that the cross section of the mud cake was kept constant at 31.2 cm^2 and the filtrate viscosity (V_f) was evaluated at a differential pressure of 500 psi.

$$V_f = A\sqrt{\frac{2K\Delta P}{\mu}\left(\frac{f_{sc}}{f_{sm}} - 1\right)} \times \sqrt{t} \tag{6}$$

Dynamic linear swelling tests

To examine the influence of the green additives on the swelling behavior of sodium bentonite, different concentrations (1, 10, and 20 g) of HLE and HBLE solutions were prepared. Afterward, a dynamic swelling test was carried out by compressing 10 g of sodium bentonite powder in distilled water under a pressure of 5900 psi (40 MPa) for 24 h using hydraulic compactor according to the works of Moslemizadeh et al. (2015) and Darjani et al. (2017; 2019) with some changes. The tests were conducted at a temperature of 78 °F and atmospheric pressure conditions.

Results and discussion

Effects of HLE and HBLE on the rheological and filtration properties of WBDF

The effects of different concentrations (10, 20, 30, and 40 g) of the locally-derived green additives in a conventional WBDF system are tabulated in Tables 4 and 5 at 78 °F and 300 °F, while the pH of different concentrations of the green additives is presented in Fig. 2.

pH observation

Drilling fluid additives are developed to be mixed with water with a pH level from 8.5 to 10 for the needed chemical reaction to occur and to provide a proper yield (Gamal et al. 2019). After mixing and preparing the WBDF system, the mud pH was measured at 78 °F and the results are presented in Fig. 2. According to Fig. 2, there were changes in the mud pH with the inclusion of HLE and HBLE products at different concentrations. For the HLE product, the pH of the WBDF system at 9.3 decreased with an increase in HLE concentration (between 4.86 and 4.72), while the reverse was the case when HBLE (between 5.84 and 7.47) was introduced into the WBDF system. The data of the pH of

Table 3 Designed compatibility tests fluids

Test fluids	Compositions
A−0 = Base fluid	50 g/L KCl + 100 g/L + NaCl + 7.0 g/L PAC LV + 2.0 g/L PHPA
A−1 = A−0 + 25 g/L HLE	320 ml distilled water + 50 g/L KCl + 100 g/L + NaCl + 7.0 g/L PAC LV + 2.0 g/L PHPA + 25 g HBLE
A−2 = A−0 + 25 g/L HBLE	320 ml distilled water + 50 g/L KCl + 100 g/L + NaCl + 7.0 g/L PAC LV + 2.0 g/L PHPA + 25 g/L HBLE

Table 4 The measured mud properties at different concentrations

Before hot rolling tests (78 °F)

Properties	Units	WBDM	HLE (g)				HBLE (g)			
			10	20	30	40	10	20	30	40
MW	ppg	11.5	11.5	11.4	11.4	11.4	11.4	11.3	11.3	11.3
AV	cP	23	71	96	86	101	78	132	152	165
PV	cP	12	52	64	56	66	53	75	87	70
YP	lb/100ft^2	22	38	65	60	71	51	114	130	190
Initial GS	lb/100ft^2	6.0	16	20	18	24	17	36	41	53
10 min GS	lb/100ft^2	9.0	20	25	21	29	26	50	61	72
API FL	ml	9.7	3.7	3.4	3.7	3.2	3.5	3.1	2.3	2.6
API MCT	mm	3.77	1.90	1.75	1.86	1.64	1.78	1.68	1.44	1.54

Table 5 The measured mud properties at different concentrations

After hot rolling tests (300 °F)

Properties	Units	WBDM	HLE (g)				HBLE (g)			
			10	20	30	40	10	20	30	40
MW	ppg	11.4	11.4	11.4	11.4	11.4	11.3	11.3	11.3	11.3
AV	cP	21	39	51	50	71	77	120	127	140
PV	cP	11	23	29	27	45	41	70	75	66
YP	lb/100ft^2	20	33	44	45	52	73	100	104	148
Initial GS	lb/100ft^2	5.0	12	15	17	20	14	23	36	40
10 min GS	lb/100ft^2	8.0	15	17	20	23	24	30	41	52
HPHT FL	ml	10.1	6.2	5.1	5.9	4.5	5.6	3.4	3.1	3.7
HPHT MCT	mm	3.86	2.55	1.92	2.16	1.72	1.77	1.71	1.62	1.73

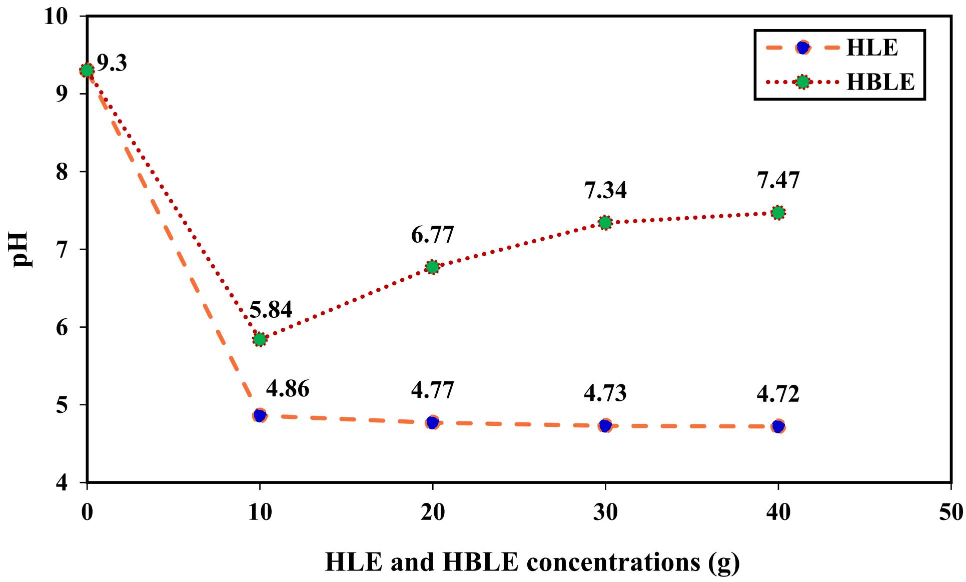


Fig. 2 pH of different concentrations of HLE and HBLE in WBDF system

the HLE product corroborated the reports of Moslemizadeh et al. (2015) in that Henna leaf extracts are acidic in aqueous solution, while Hibiscus leaf is slightly acidic between the pH of 5.5 and 7.5 (Gamal et al. 2019). It is generally believed that Henna extracts solution in water removes the hydrogen atoms from the chemical structure of its constituents, resulting in a consequent reduction of the pH of the solution (Gamal et al. 2019).

Mud weight

The weight of a drilling fluid is a key parameter in drilling operations. The fluid MW is an important factor in drilling operations and its output. The majority of problems faced during rotary drillings are related to the weights of drilling fluids (Fattah and Lashin 2016). To effectively determine the influence of HLE and HBLE on the fluid loss, fluid cake thickness, and formation damage, the MW is the first property to investigate. Typically, how stable is a fluid is governed by its uniformity after aging for a long time. As presented in Tables 4 and 5, there is no considerable variation in the MW of the fluids. The drilling fluids showed a very narrow range of variation. However, after hot rolling experiments at 300 °F, the MW of the fluids reduced slightly which is not high enough to result in damage to the formation (Fattah and Lashin 2016).

Apparent viscosity

Tables 4 and 5 illustrate that the AV of the different fluid systems containing plant extracts (HLE and HBLE) was increased significantly with an increase in concentration over that of the WBDF system. This increase can be detrimental to drilling operations in terms of lost circulation, excess pump power requirement, equivalent circulating density, etc. According to both Tables 4 and 5, the plant extracts need a lower range of concentration to achieve an effective removal of drilled particles and successful drillings without causing harm to the formation. Observation at these tables showed that with 30 g HLE, the AV values were reduced to 86 cP from 96 cP (Table 4). For 20 g, it reduced to 50 cP from 51 cP (Table 5) but started increasing again after the 30 g concentration. A similar trend of reduction in AV was noticed in the AV of the HBLE from 20 g to 30 g after aging (Table 5). The AV of the HBLE exhibited higher values as compared to those of HLE at both temperature conditions. The increase in AV of the WBDF with HLE and HBLE at 10 g is about thrice greater than that of the WBDF at 78 °F and even quadrupled with 20 g HLE and sixfold with 20 g HBLE (Table 4). At a higher temperature of 300 °F, the AV of the WBDF reduced slightly compared to that of HLE which exhibited higher reductions. Also, the HLE samples from 10 to 40 g showed a higher drop in AV than those of HBLE samples. This result implies that the molecules of henna are more sensitive to high temperatures than those of HBLE and the additives that make up the WBDF.

Plastic viscosity

The PV is an indicator of the viscosity of the high shear rate and is dependent on the liquid phase viscosity and the amount of solids in a liquid. The PV is improved by adding solid additives and can be further enhanced by solids, such as clays, which are swelled by taking in water (Annis and Smith 1996). The rheometric PV data presented in Tables 4 and 5 revealed that as the HLE and HBLE increase in concentration, a larger PV is seen in all cases over that of the WBDF system. For the PV of the base fluid, the water was easily adsorbed by sodium bentonite and it swelled quickly. This led to achieving the separation of individual unit layers and a resultant increase in the PV (Moslemizadeh et al. 2015). Also, the interaction of other additives in the base fluid such as PHPA with bentonite can induce bridging which yielded the solution viscosity (Oseh et al. 2019a, b, c). A higher viscosifying effect for both HLE and HBLE is confirmed at both 78 °F and 300 °F. This feature can be linked to the presence of hydrogen bonds in both HLE and HBLE that interacted with the hydrogen ions of water molecules. It can also be linked to the branched molecular chains of the HLE and HBLE products (Moslemizadeh et al. 2016).

According to Table 4, the inclusion of HLE and HBLE has great increasing effects in the PV of the WBDF with increasing concentration. This same effect can be observed after the aging tests (Table 5). Nonetheless, the observed decrease in the AV of HLE from 20 to 30 g was also observed in the PV of the HLE at the same concentrations. A similar trend of results in terms of PV also occurred in the HBLE fluid samples from 30 to 40 g at both temperatures. The inclusion of 40 g concentration of HBLE in the WBDF system reduced the PV by 19.5% from 30 to 40 g (Table 4) and 12% from 75 to 66 cP (Table 5). The decrement of the AV and PV values of the two plant extracts fluid samples can be related to the reduction of the fluids gelation caused by a decrease in the interaction of the molecules (Oseh et al. 2020b, c). This action can also be due to a decrease in the adherence between the hydrogen ions of water molecules and the hydrogen bonds present in the plant extracts (Moslemizadeh et al. 2015). The HBLE fluid samples have a larger PV than those of HLE at the two temperature conditions considered. These data reported in Tables 4 and 5 suggest a great viscosifying power of the plant extracts. However, their potential benefits in a WBDF system could depend on their concentrations and other additives in the fluid.

Yield point

Everything causing changes in the viscosity of the low shear rate is expressed in the YP. The YP indicates that clay strata are susceptible to joining up and creating a flocculated structure (Annis and Smith 1996). The tabularized depiction of the YP data presented in Tables 4 and 5 as calculated by filling in the dial-reading values into Eq. (3) indicates that the inclusion of HLE and HBLE changes the YP of the WBDF. There were significant enhancements in the YP with increasing concentration of the green additives. However, at 30 g

HLE, the YP was reduced to 60 lb/100ft^2 from 65 lb/100ft^2 of 20 g HLE concentration. As observed in both tables, the YP of the HBLE at all concentrations is larger than those of the HLE. The application of HLE and HBLE as additives for drilling fluids might promote local content expansion but their introduction into WBDFs should be painstakingly considered by studying the behavior of the additives that will make up the fluid, especially if higher concentrations are to be used. According to the results depicted in Table 5, an increase in temperature up to 300 °F significantly affects the YP of the fluids in a decreasing manner. Nevertheless, at 10 and 20 g of HBLE, the YP values (73 lb/100ft^2 for 10 g and 124 lb/100ft^2 for 20 g) increased after being subjected to aging treatment over (51 lb/100ft^2 for 10 g and 114 lb/100ft^2 for 20 g) without heat treatments. The HBLE demonstrated the greater enhancement of the YP than the HLE as it does in the PV of the WBDF but could lead to poor circulation rate, decreased ROP, borehole washout, and increased frictional pressure losses.

Gel strength

GS is a measurement of shearing stress needed to start a fluid flow immobile for a long time. It is something that facilitates or prevents contact between clay layers and, therefore, will either increase or decrease the gelling propensity of a dispersion (Luz et al. 2017). The influence of concentration of the locally derived HLE and HBLE on the initial and 10 min gels of the WBDFs is depicted in Tables 4 and 5. In the deficiency of HLE and HBLE in the WBDFs, Tables 4 and 5 portray 6.0 and 5.0 lb/100ft^2 for the initial gel and 9.0 and 8.0 lb/100ft^2 for the 10 min gel, respectively. A very narrow range of variation occurred in both the initial and 10 min gels at both temperatures, indicating low flat gels which are desirable for drillings as it will not lead to stuck pipe (Luz et al. 2017). In the inclusion of different concentrations of HLE and HBLE in the WBDF, both the initial and 10 min gels were increased with an increasing concentration at 78 and 300 °F. At different concentrations of the green additives, the variations in the gels of HLE are less compared to those of HBLE at both temperature conditions. This behavior is similar to the results of AV, PV, and YP reported earlier. In general, HBLE exhibited the highest gels and the variations in both gels (10 s and 10 min) are so large (exceeding 10 lb/100ft^2) that it can cause differential pipe sticking while drilling.

For the results of all the rheological parameters (AV, PV, YP, and GS), the parameters were decreased at the higher temperature of 300 °F. The weakening of molecular attraction forces, which bind liquid molecules together caused this behavior. Consequently, the distance between the molecules increased and the fluid's interaction became reduced (Fattah and Lashin 2016). The rheological data shown in Tables 4 and 5 also demonstrated that the impact of the plant extracts (HLE and HBLE) on the AV, PV, YP, and GS of the WBDFs was gelling with an increasing concentration. This behavior can again be elucidated in the form that the HLE and HBLE unite on the bentonite clay platelets and enhance the attractive forces between the platelets (Aftab et al. 2016). It is, therefore, suggested that a lower concentration of the plant extracts must be used to obtain the desired rheological parameters within the API recommended protocols. Expounding further, given the need to protect the formation from fracture and damage, prevent borehole washout, and avoid excessive frictional pressure losses, a concentration of 10 g of both plant extracts on the rheological data (Tables 4 and 5) can be considered as the optimum concentration for the effective drilling operation.

Filtration control parameters

One of the key properties of drilling fluids is the filtration rate. Strong filtration levels increase the thickness of the fluid, leading to operational problems like pipe sticking and high torque and drag (Al-Hameedi et al. 2019a, b). The measured filtrate losses represented in Tables 4 and 5 verified that the base fluid system with the plant extracts demonstrated a significant reduction in filtrate loss under the API and HPHT conditions with increasing concentration. However, there is an exception to the reduction at the concentrations of 30 g HLE and 40 g HBLE, where the decreasing trend of the filtrate loss does not hold. Clear and significant changes were seen in both the API and HPHT FL of the WBDFs with the inclusion of the green additives. The general trend of the decrement in the API FL of WBDF with HLE is ranged between 61.9 and 67.0% and that of HLBE is ranged between 64.0 and 76.3% against 9.7 ml of WBDF. At HPHT condition, this trend showed a small margin of increment to 10.1 ml using the WBDF alone but decreased to the range between 38.6 and 55.4% with the inclusion of HLE and between 44.6 and 69.3% for the incorporation of HBLE.

The HBLE showed the more improved capacity of decreasing the loss of filtrate of the base fluid system at both temperature conditions than the HLE at all concentrations. This is because HBLE contains humic acid which makes the aqueous medium soluble. The soluble HBLE in WBDF was a deflocculant due to the creation of negative ions (–OH) groups by interacting with bentonite to strengthen the sealing of the mud cake on the wellbore (Sharada et al. 2012). From the study of Oseh et al. (2019a), HLE has superb filtrate loss sealing property at high concentrations due to the high mobility of hydrogen ions that strengthens the sealing capacity of the WBDF. According to Tables 4 and 5, the relatively high volume loss of filtrate of WBDF in comparison with HLE and HBLE suggests that the KCl presence needed for the inhibition of clay swelling and hydration led to a higher volume of filtrate loss of the WBDF than it does in the plant products (Zhong et al. 2011).

The higher the failure of filtrate loss control agents, the thicker the mud cake thickness (MCT). As revealed by Tables 4 and 5, there are appreciable variations in the API and HPHT MCT of the WBDFs with different concentrations of the plant extracts. These results illustrated that WBDFs formulated with the plant extracts exhibited a high decreasing trend of cake thickness under API and bottom-hole conditions with an increasing concentration of 20 g and 30 g for HLE and HBLE, respectively. It can also be seen from these tables that at 30 g HLE, both the API and HPHT MCT are higher than the values of 20 g HLE product. From the rheological and filtration data trend, similar behavior was also observed for 30 g HLE and 40 g HBLE products. Looking at the data presented in Tables 4 and 5, 10 g of both the HLE and HBLE appears to be the optimum concentration of reducing the loss of drilling fluid as it displayed filtrate loss and cake thickness less than 4.0 ml and 2.0 mm, respectively, under the API conditions.

The rheological characteristics of WBDFs investigated with PAC LV and plant extracts

According to the preceding results recounted in Tables 4 and 5, the higher concentrations of the green additives used to enhance the properties of the WBDF demonstrated gelation characteristics of the fluids, which require deflocculant to control the properties. Therefore, to have a meaningful comparison between these green additives and PAC LV for possible improvement in the rheology and filtration properties of the base fluid system, lower concentrations (1.0 and 2.0 g) of each of HLE, HBLE, and PAC LV were compared in this section. The test data of the mud properties at 78 and 300 °F are presented in Figs. 3, 4, 5, 6, 7, and 8.

Beginning with the results of the MW shown in Fig. 3, the 1.0 and 2.0 g concentrations of HLE and HBLE showed no

Fig. 3 Mud weight of drilling fluids

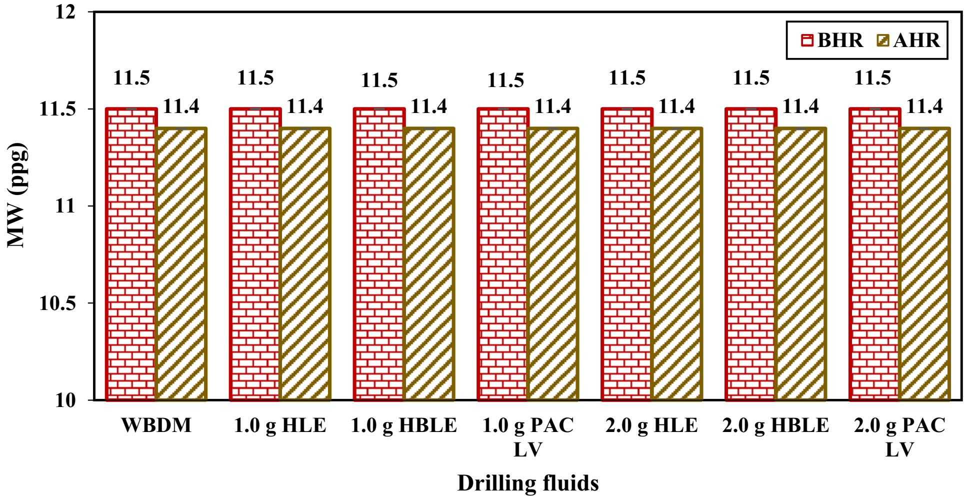


Fig. 4 Apparent viscosity of drilling fluids

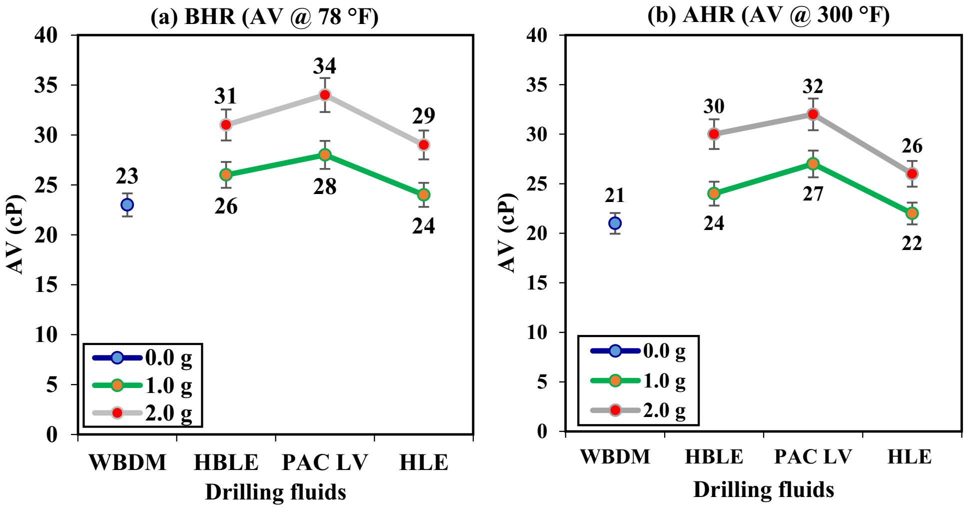


Fig. 5 Plastic viscosity of drilling fluids

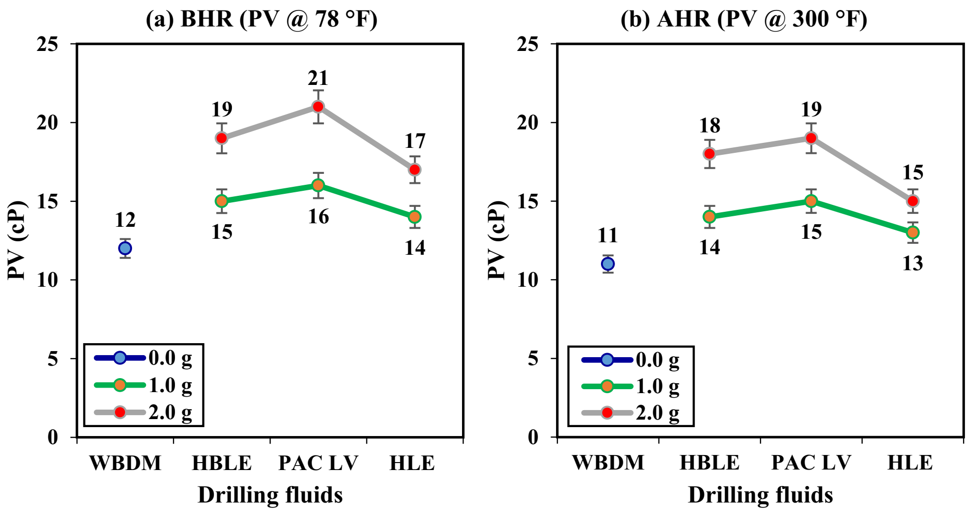


Fig. 6 Yield point of drilling fluids

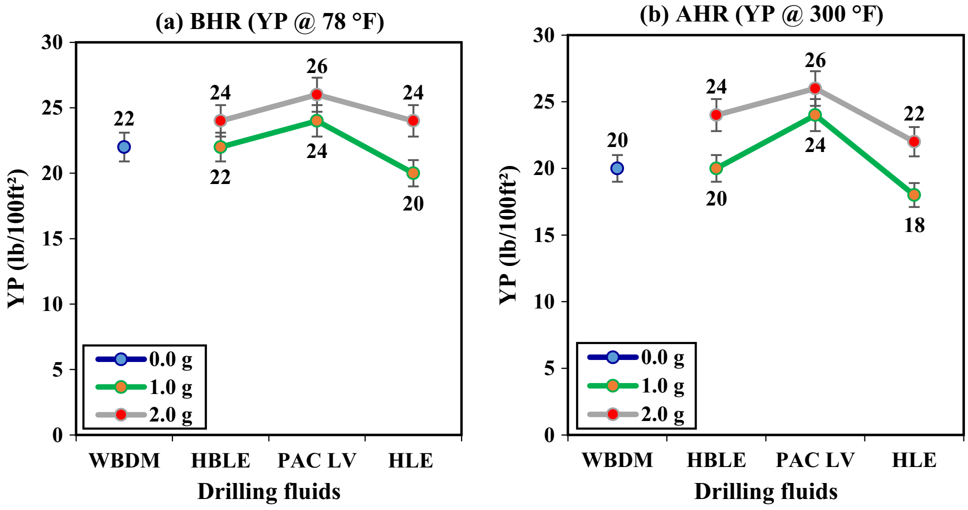


Fig. 7 Initial gel strength of drilling fluids

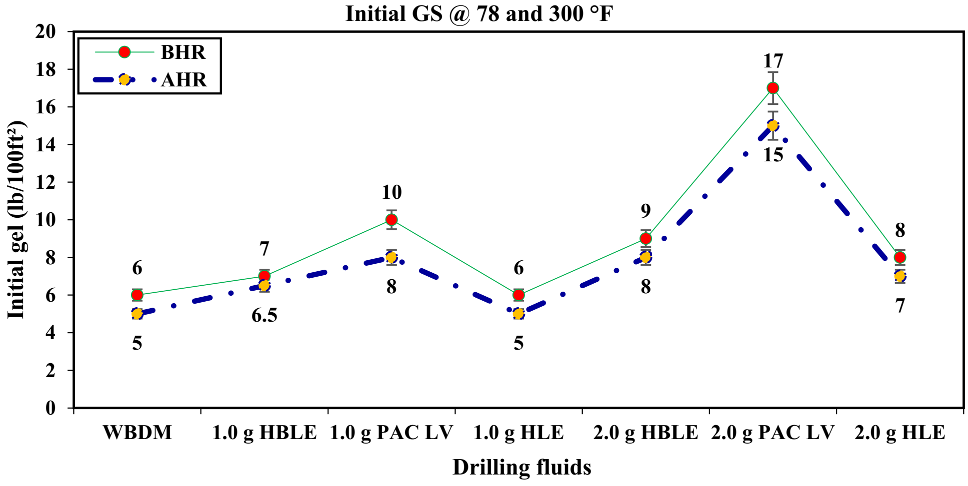
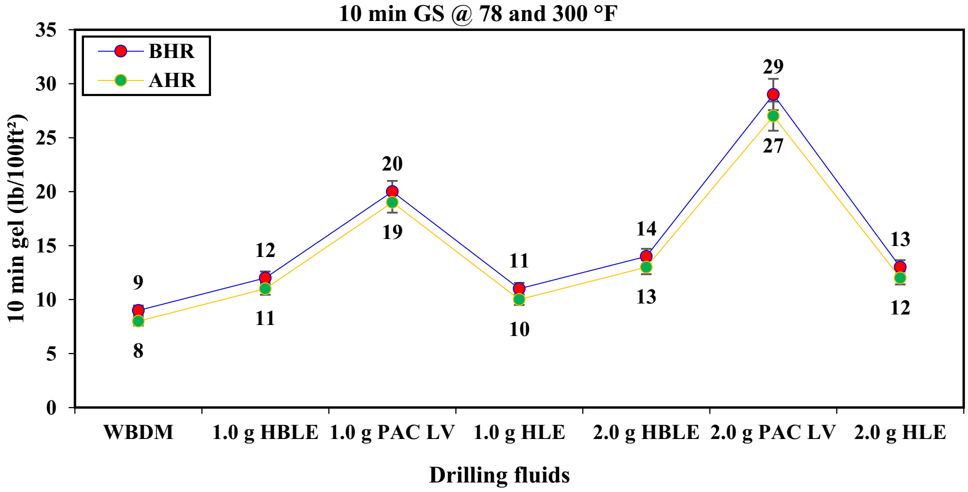


Fig. 8 Gel 10 of drilling fluids



variation in the MW of all the mud systems as it remained constant at 11.5 ppg and 14 ppg before and after hot rolling measurements, respectively. After the aging process (AHR at 300 °F), the MW of the drilling fluids had an insignificant effect. The motive behind this negligible effect was due to the fluid's sensitivity to the higher temperature. It can also be due to the formation of foams in the fluid after aging, as observed in the course of the experiments. Therefore, anti-foaming agents can be suggested to preserve the weight of the fluid if necessary as the drop in the MW is only a little fraction (Iheagwara 2015). For the rheological parameters, the locally derived HLE and HBLE inclusion increased the AV (Fig. 4), the PV (Fig. 5), and the YP (Fig. 6) of the WBDF systems with increasing concentration at both 78 and 300 °F. The increase was more with the concentrations of HBLE than those of HLE. A higher increase in these properties occurred in the WBDFs containing PAC LV more than those of the plant extracts at both temperature conditions. However, these green additives (HLE and HBLE) exhibited strong rheological effects on the WBDF system at the two concentrations of 1.0 and 2.0 g. The values of these fluids will not require extra pressure to pump and circulate. Also, there were no traces of aggregates in these mud systems indicating that the plant extracts are well dispersed and soluble in the mud (Mozaffari et al. 2015, 2017). These results confirm the applicability of these plant extracts as rheological modifiers at concentrations of 1.0 and 2.0 during a typical drilling situation.

Describing further, these plant extracts displayed an excellent suspension ability of drilled particles since the variation of the GS between the10 s and 10 min is not large (not more than 5.0 lb/100ft^2) for both the HLE and HBLE (Figs. 7 and 8). These gels, that are those of the WBDF, HLE, and HBLE, indicate encouraging suspension property and the ability of the gels to break easily when drillings are restarted after a prolonged static condition (Oseh et al. 2020a, b). For PAC LV, it displayed a negative effect on both the 10 s and 10 min gels, especially the 2.0 g concentration and the difference between these gels exceeds 10 lb/100ft^2. This could need extra pump pressure to break the gels when changing from non-flow to flow conditions, which in turn can adversely affect pump efficiency and cause fractures in poor formations (Ismail et al. 2019). It, therefore, holds that, if higher concentrations of PAC LV are introduced into the complex WBDF system as per this study, it might result in flocculation (Oseh et al. 2019c, d).

Additives of PAC are strong chemicals that have been applied in different field applications in drilling operations for many years to increase rheological properties and decrease filtrate loss. In the field, an excess concentration of PAC LV which is equal to the laboratory scale range between 1.2 and 1.8 g per 1000 ml (Al–Hameedi et al. 2020) is normally introduced. In this study, 1.0 g per 350 ml and 2.0 g per 350 ml of PAC LV were added to the WBDF system to have identical concentrations with the plant extracts. In this manner, the rheological parameters were exploited with the inclusion of PAC LV concentrations, as shown in Figs. 4, 5, 6, 7, and 8. Referring again to the rheological behavior of the plant extracts, the results shown in Figs. 4, 5, 6, 7, and 8 and those in the previous section displayed in Tables 4 and 5 verified that HBLE exhibited higher rheological values than HLE product. HLE is a deflocculant as reported by Moslemizadeh et al. (2015) and Oseh et al. (2019a) and can be used to control the fluid's rheological properties, especially the GS and YP which is because of the changes that occur in its composition when it interacts with molecules of water. As the lower concentrations (1.0 and 2.0 g) of HLE got into contact with the molecules of water, hydrogen ions were detached from its structure and negative ions were formed. The positive edge of the clay layers (sodium bentonite) in the fluid became neutralized by the negative ions resulting in a decrease in the GS and YP. However, HLE is inefficient when it comes to reducing the viscosity of the fluid (Moslemizadeh et al. 2015).

The filtration characteristics of WBDFs investigated with PAC LV and plant extracts

The API and HPHT FL was determined at 100 psi and 500 psi differential pressures, respectively, to comprehend the efficiency of HLE and HBLE green additives as fluid loss control agents. Figures 9 and 10 provide the details of these results. The loss of filtrate with both 1.0 and 2.0 g concentrations of plant extracts and PAC LV was found to be outstanding at 78 and 300 °F. The results showed that PAC LV had almost an identical impact with those of the plant extracts in reducing the API and HPHT FL of the WBDF system, but it exhibited a slightly better sealing property than the plant extracts. The API FL of the base fluid was improved with the HLE, HBLE, and PAC LV by 29.9–32%, 31.0–35.1%, and 33.0–37.1%, respectively, from 1.0 to 2.0 g concentrations. After the heat treatment, it increased in the following pattern; 30.7–31.7%, 32.7–33.7%, and 33.7–34.7% for HLE, HBLE, and PAC LV, respectively. Nevertheless, HLE and HBLE exhibited a better enhancement in the API and HPHT MCT of the WBDFs, as compared to the performance of PAC LV presented in Fig. 10. The MCT was reduced with the introduction of HLE by 30.2%, 31.8% by HBLE, and 23.6% by PAC LV at 1.0 g concentration at API conditions. With aging, the HPHT MCT of the base fluid system got reduced by 30.6% for HLE, 33.4% for HBLE, and 27.3% for PAC LV. The decreasing range of the API MCT from

Fig. 9 API and HPHT FL of drilling fluids

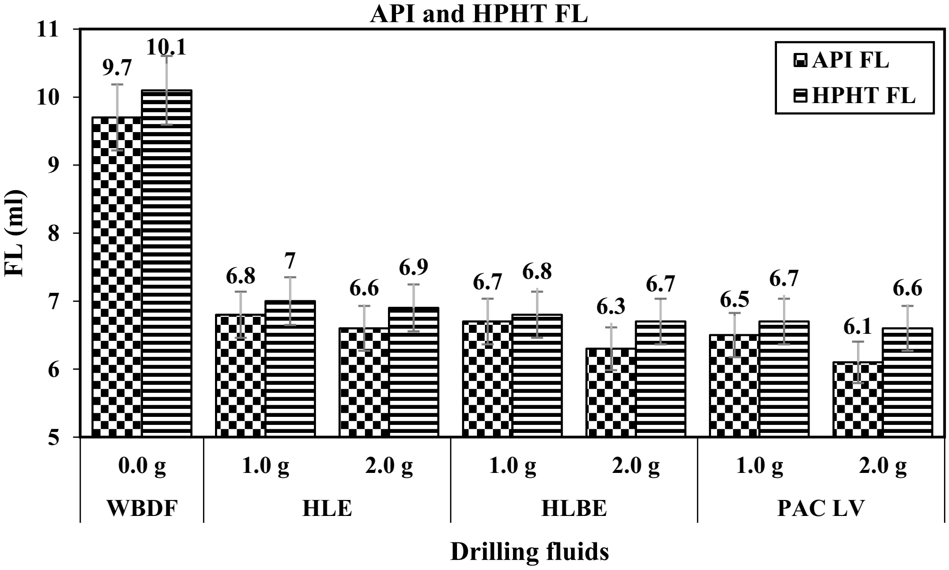
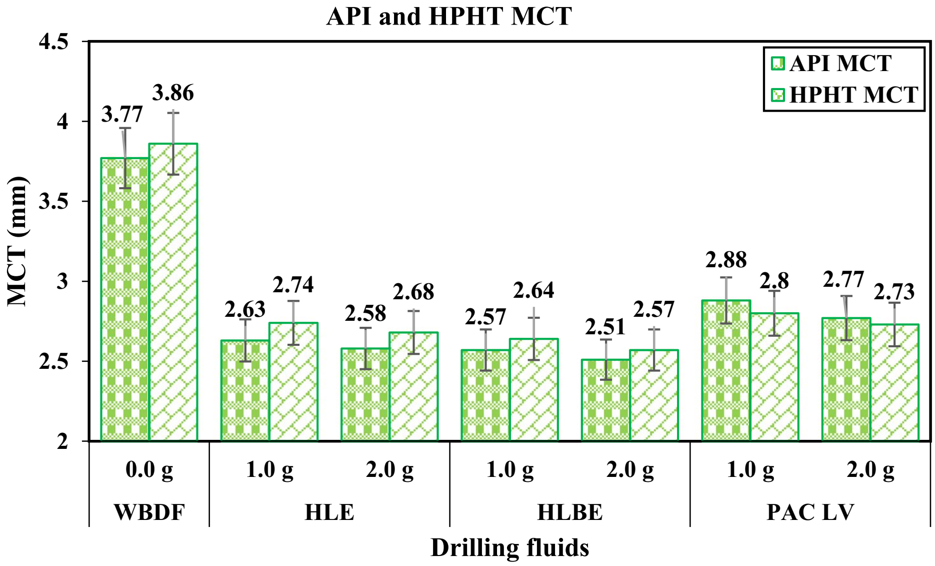


Fig. 10 API and HPHT MCT of drilling fluids



1.0 to 2.0 g concentrations is as follows: 30.2–31.6% for HLE, 31.8–33.4% for HBLE, and 23.6–26.5% for PAC LV. These results suggest that the plant extracts can be used to improve the mud cake before fortifying the drilled formation with casing to prevent any possible mechanical pipe sticking resulting from dense mud cake (Al-Hameedi et al. 2020; Oseh et al. 2020c, d).

Comparison and evaluation of all the fluids performances showed that after 1.0 and 2.0 g concentrations of HLE, HBLE, and PAC LV were applied, the rheology and filtration control parameters of the WBDFs improved. Generally, in the WBDFs, the HLE and HBLE played a significant task in the creation of highly compact mud cake, even at lower concentrations. They performed as efficient viscosifiers and filtration control reducers and compared favorably with the PAC LV, which exhibited higher rheological properties, slightly better sealing property, and less cake thickness. It is hoped that these results can provide more insights into the application of HLE and HBLE as low-cost, sustainable, and ecologically benign ingredients for drilling fluids.

Compatibility test and mud cake permeability observations

The test of compatibility is exceedingly important for the applicability of every drilling fluid additive to assess their interactions with other additives. The data related to compatibility conducted on test fluid A with 25 g/L HLE and HBLE are presented in Fig. 11 (for the rheological properties) and Table 6 (for the filtration properties). The rheological properties, filtrate loss volume, and mud cake thickness measured at 221 °F and 500 psi of the prepared base fluid (A-0) were found to improve after the modification by HLE and HBLE products. The rheological properties of test fluid A-0 were increased by the inclusion of the plant extracts, and these plant extracts also reduced the filtration properties of A-0. This is due to the fine-solubility of the green additives in the mud without aggregates. Aggregation can cause a reduction in the viscosity of drilling muds after a long period (Mozaffari et al. 2015, 2017). To precisely account for the changes that occurred because of the incorporation of the green additives, the percentage of increase or decrease as the case may be was calculated by comparing before and after introducing the green additives. Also, the observed trend of Fig. 11 corroborated that A-2 has better improvement impact on the A-0 properties than A-1. These data are consistent with the previous data reported in Tables 4 and 5, wherein the Hibiscus plant exhibited higher rheological properties and lower filtration properties than the Henna product. It was also found from these tables that at a higher temperature of 300 °F, the reduction in the viscosities (AV and YP) of HLE and HBLE was relatively large owing to the fluid's

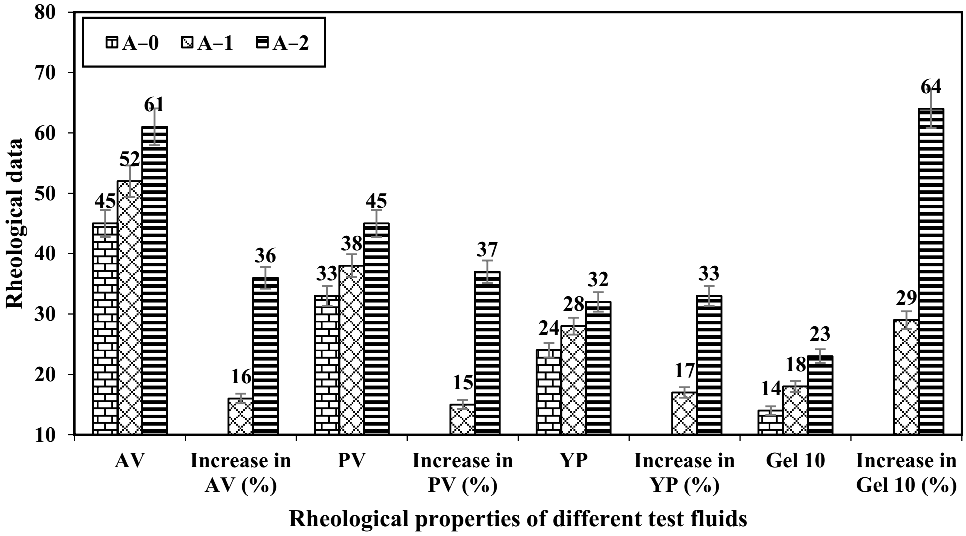


Fig. 11 Compatibility data of different test fluids with changes in their properties

Table 6 HPHT filtrate volume and mud cake thickness of different test fluids

Mud system	Filtrate volume (ml)	Filtrate change (decrease %)	Mud cake thickness (mm)	Change in mud cake thickness (decrease %)	Cake permeability × 10^{-4} (mD)
A−0	11.4	–	3.86	–	2.82
A−1	8.8	22.8	3.42	11.4	2.31
A−2	7.9	30.7	3.24	16.1	2.16

aggregation (Mozaffari et al. 2015; 2017). As no substantial changes were observed with these data (Fig. 11 and Table 6) and those reported in Tables 4 and 5, the compatibility of common WBDF additives with HLE and HBLE was completely obvious.

Table 6 summarizes the filtration behavior of A−0 (base fluid), A−1 (HLE), and A−2 (HBLE) mud systems under the HPHT conditions. It can be observed that the change in the filtrate volume of A−0 with 25 g/L of HLE and HBLE products decreased by 8.8% with A−1 and 7.9% with A−2. In the same vein, the thickness of the mud cake of the A−0 was decreased with the inclusion of the two green additives by 11.4% (with HLE) and 16.1% (with HBLE). The permeability of the mud cake determined as presented in Table 6 displayed a higher permeability for the Henna extracts mud system compared to the Hibiscus leaf extracts but the highest cake permeability was observed in the base fluid. Furthermore, observation of Fig. 12 revealed that the cake thickness of both the HLE and HBLE samples was low and nonerodible with lower permeabilities compared to the base test fluid. Given these data, it can be concluded that the 25 g/L of the plant extracts is compatible with the common WBDF additives and these cake permeabilities are not high to cause damage to the drilled formation.

Linear swelling test observation of sodium bentonite

The linear swelling of sodium bentonite exposed to distilled water and different concentrations of HLE and HBLE aqueous solution at a temperature of 78 °F was examined. The results are shown in Fig. 13. According to Fig. 13, swelling curves of all the mud systems exhibited a like-trend with sharp increases in the first-6 h, which is similar to the swelling character reported by Moslemizadeh et al. (2015) and Darjani et al. (2017, 2019) for montmorillonite in aqueous systems. The sodium bentonite in distilled water was found to follow a constant swelling character within the entire test time of 24 h with the highest swelling level compared to other mud systems. The swelling behavior of the sodium bentonite in any concentration of HLE and HBLE was observed to be considerably lower than in distilled water at each period and after the test completion for 24 h. This translates the attractively benefiting influence that the locally derived green products had on the swelling behavior of sodium bentonite. At the lowest concentration (1.0 g) of each of HLE and HBLE in the distilled water, the sodium bentonite still carries on swelling during the entire test period even if its swelling curve is lower than that in distilled water alone. It was also observed that the introduction of the HLE product in the distilled water displays a higher reduction in the swelling rate of the sodium bentonite at all concentrations than the HBLE product. This interprets the superiority of the HLE in inhibiting the swelling behavior of sodium bentonite over the HBLE product. However, the final regime in which the swelling rate of the sodium bentonite with these two products approaches zero was never realized. In contrast, the swelling curves for higher concentrations (10 and 20 g) of HLE and HBLE show the final regime after about 18 h.

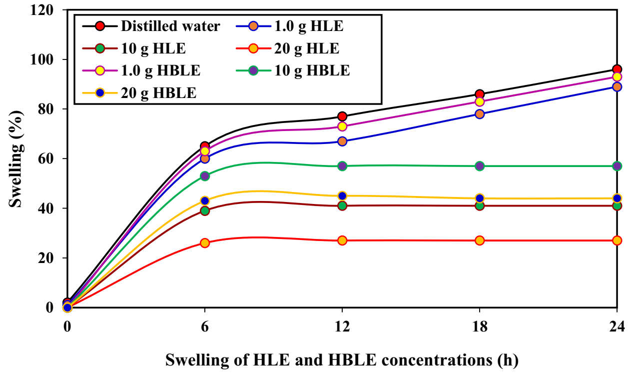


Fig. 13 Swelling data of sodium bentonite in distilled water exposed to different concentrations of HLE and HBLE solutions at 78 °F

Conclusions

In the current study, an all-inclusive set of tests was conducted on a complex WBDF system with different concentrations of two locally derived green additives (Henna leaf and Hibiscus leaf extracts). The results of these plant extracts at 1.0 and 2.0 g concentrations were compared with that of industrial-based PAC LV to investigate their

Fig. 12 HPHT mud cake filtrations for different test fluids


A−0 (K = 2.82 × 10^{-4} mD) A−1 (K = 2.31 × 10^{-4} mD) A−2 (K = 2.16 × 10^{-4} mD)

impacts on the rheological and filtration properties of the WBDF system. Furthermore, swelling inhibitive behavior of sodium bentonite powder with the green additives and the compatibility of these green additives with other additives in the WBDF system was examined. The following conclusions were drawn based on the research goals and the results reached:

1. The inclusion of higher concentrations (between 10 and 40 g) of HLE and HBLE largely enhanced the rheological and filtration parameters of the WBDFs. With lower concentrations (1.0 and 2.0 g) in the WBDFs, the influence of HLE and HBLE was relatively less than that of PAC LV, which showed higher mud's properties.
2. Also, the gels of HLE and HBLE at 1.0 and 2.0 g concentrations showed excellent suspension capacity as the variation between the initial and 10 min gels was not more than 5.0 lb/100ft^2, unlike that of PAC LV that indicated high and progressive gel structure that exceeded 10 lb/100ft^2. This variation can affect drilling operations drastically.
3. The test of compatibility confirmed that the plant extracts are compatible with the common WBDF additives and had an affirmative influence on the filtrate loss volume.
4. The dynamic linear swelling test verified that HLE and HBLE reduced the swelled volume of the evaluated sodium bentonite. To recap, the studied HLE and HBLE demonstrated enhancing effect in the properties of the WBDF system making them suitable agents for WBDF.

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Compliance with ethical standards

Conflict of interest On behalf of all the authors, the corresponding author states that there is no conflict of interest.

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