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Research Article

Investigation into the Potential of Dry Mango Leaves Powder as Eco-Friendly Additive in Water-Based Drilling Mud

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Abstract

The drilling process relies on drilling fluids to create a safe, usable and cost-effective wellbore. Many additives used to maintain drilling fluid properties are non-biodegradable and pose environmental and human health risks. This concern has increased interest in exploring eco-friendly materials as additives in water-based mud. This study investigated the impact of Dry Mango Leaves Powder (DMLP), obtained from the Kent Mango Tree, as an additive in water-based mud. DMLP was prepared by crushing and sieving it to a 75-micron size. Five drilling fluid samples were created: four with different DMLP concentrations (1.75 g to 7.0 g) and one control without DMLP. The samples were aged for 16 hours at room temperature before assessing the mud weight, pH, and filtration characteristics at room temperature and rheological properties at 77 ℉ (25 ℃), 120 ℉ (48.8 ℃) and 150 ℉ (65.5 ℃). The properties were determined by following the standards of the American Petroleum Institute. The results demonstrated that DMLP effectively reduced alkalinity by 25.2% at a concentration of 7.0g. Rheological values and plastic viscosity decreased with increasing DMLP concentration at 77 ℉, 120 ℉ and 150 ℉, though there were no significant changes in the yield point. The addition of DMLP improved gel strengths with the difference in the final and initial gel strength staying below lb/100ft ^{2}at all concentrations and temperatures, except for a concentration of 1.75 g at 77 ℉. The addition of 7.0 g of DMLP reduced the fluid loss by 22.4%. Although DMLP showed potential in improving gel strength and fluid loss, its effectiveness as a weighting agent remains limited. This study demonstrates the potential of DMLP as an eco-friendly additive to enhance certain properties of water-based mud, making it a promising alternative for sustainable drilling operations.

Keywords

Dry Mango Leaves Powder, Filtration, Mud Density, pH, Rheology

1. Introduction

The oil and gas industry comprises a series of processes, necessitating the adoption of various methods to ensure safe environmental operations. One of these processes is drilling, which involves creating boreholes in the earth to access hydrocarbon reservoirs. Drilling an oil and gas well requires the use of drilling fluids, making it vital in the discovery of oil and

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gas. Also known as drilling mud, these fluids serve several functions, including controlling subsurface pressures, supporting and stabilising the wellbore, transporting cuttings, transmitting hydraulic horsepower to the bit, and cooling and lubricating the bit [1, 2]. Drilling fluids are typically composed of solids, liquids, chemicals, and sometimes gases, and are often defined as liquid compositions aiding the drilling process of petroleum wells [3]. While drilling fluids provide significant advantages in the exploration and production industry, the combination of additives and chemicals can harm the environment and human health. This concern has led to a growing preference for water-based drilling fluids over oil-based ones [4. 5]. Many conventional chemical additives are non-biodegradable and pose environmental hazards, including toxic heavy metals, synthetic polymers, and harmful chemicals. Consequently, global concern for protecting the environment from harmful chemicals and non-biodegradable materials is increasing [6-8]. As a result, the industry is focused on optimizing drilling fluid formulations to develop safer and more environmentally friendly alternatives.

Researchers have explored numerous biodegradable materials as drilling mud additives to address environmental concerns linked with conventional additives. Zhang et al. [9] explored pomelo peel powder as an environmentally sustainable additive for water-based drilling fluids to inhibit shale hydration swelling. Their analysis showed that fresh pomelo peel powder contains active substances that reduce mud filtration, enhance rheological properties, and prevent clay hydration and expansion. Researchers have investigated various food waste materials as drilling fluid additives, including banana peels, potato peels, sugarcane, tamarind gum, coconut coir, peach pulp, soybean peels, olive pulps, and pomegranate peels [10-15]. Okon et al. [16] studied rice husk as an eco-friendly additive for filtration control. They found that a rice husk concentration of 20 ppb reduced fluid loss by 65% compared to a 10 ppb concentration of carboxymethyl cellulose (CMC). However, while rice husk effectively controlled fluid loss, it had undesirable effects on plastic viscosity. In 2015, Adebowale and Raji studied banana peel ash as an alternative drilling mud additive and found it improved pH and controlled corrosion.

Nyeche et al. [17] examined potato starch mixed with Polyanionic cellulose (PAC) to enhance mud properties, noting a decrease in filtration but a negative impact on rheological properties. Moslemizadeh and Shadizadeh [18] investigated henna extract in water-based muds as an eco-friendly shale inhibitor, finding it reduced shale swelling and improved lubricity, with a 10 ppb addition showing slight fluid loss improvement but also decreasing mud rheological properties. Al-Hameedi et al. [19] investigated the use of Palm Tree Leaves Powder (PTLP) as an eco-friendly mud additive, finding that it reduced pH and fluid loss while enhancing filter cake deposition. PTLP, when finely ground, also lowered viscosity but significantly reduced yield point, indicating its potential as a mud-thinner. Broni-Bediako et al. [6] examined Dry Bamboo Leaves Powder (DBLP) as a water-based mud additive, discovering that it decreased alkalinity, altered yield point and plastic viscosity, and improved gel strengths and filtration characteristics.

Despite ongoing efforts, many biodegradable materials remain underexplored. One such material is the mango leaf from the Kent mango tree, which is abundant and accessible in tropical West and Central Africa. This study investigates the potential of Dry Mango Leaves Powder (DMLP) as an eco-friendly additive to replace harmful chemical compounds in drilling fluids. By evaluating its impact on key drilling fluid properties such as viscosity, yield point, and fluid loss, we aim to contribute to more sustainable and cost-effective drilling operations.

2. Materials and Methods

This section outlines the materials and equipment used for preparing Dry Mango Leaves Powder (DMLP) and formulating the mud samples. It also details the experimental procedures employed to measure the density, pH, rheological and filtration characteristics of the mud samples.

2.1. Preparation of Dry Mango Leaves Powder

The Dry Mango Leaves (DMLs) (Figure 1) were obtained from the Kent mango tree. They were cleaned and exposed to the sun for one day to remove residual moisture. The dry leaves were then milled into smaller particles using a ball mill for 75 minutes (Figure 2). The milled particles were subsequently sieved through a 75-micron screen (Figure 3) to achieve the fine particle size shown in Figure 4.

Figure 1. *Dry Mango Leaves.*

Figure 2. *Ball Mill.*

Figure 3. *75-Micron Screen.*

Figure 4. *Dry Mango Leaves Powder.*

2.2. Formulation of Mud Samples

Five mud samples were prepared by measuring 350 ml of water and labelling them as CF (Control Fluid), A, B, C, and D. To each sample, 22.5 g of bentonite clay was added, followed by specific concentrations of Dry Mango Leaves Powder (DMLP) ranging from 0.5% by weight of water (%w/w) to 2%w/w except for the CF (Table 1). The concentration of DMLP used was based on studies conducted by Medved et al. in 2022 and Al-Hameedi et al. in 2019 [20, 21]. The samples were mixed with a mud mixer and aged at room temperature for 16 hours under static conditions for the drilling mud to develop its rheological and filtration characteristics fully. According to Al-Hameedi et al. [19], 16 hours is usually enough for drilling fluid to develop its properties fully. After ageing, the density, pH and filtration properties were assessed at room temperature, and the rheological properties were examined at 77 ℉ (25 ℃), 120 ℉ (48.8 ℃), and 150 ℉ (65.5 ℃). Figure 5 displays the mud balance used for measuring the weight of the materials.

Table 1. *Composition of the Mud Samples.*

Mud Samples	CF	A	B	C	D
Water (ml)	350	350	350	350	350
Bentonite (g)	22.5	22.5	22.5	22.5	22.5
DMLP (% w/w)	0	0.5	1	1.5	2.0
DMLP (g)	0	1.75	3.5	5.25	7.0

Figure 5. *Electronic Balance.*

2.3. Laboratory Testing

To assess the impact of various DMLP concentrations on the Control Fluid (CF), full-set measurements were first recorded for the CF. Afterwards, tests were conducted for CF mixed with multiple concentrations of DMLP. The experiment was repeated once for each concentration of DMLP to ensure the data's validity.

2.3.1. Density

The density of the mud samples was measured using a mud balance (Figure 6), a highly sensitive and accurate field instrument for determining the density or specific gravity of drilling fluids. The mud cup was filled with mud and the lid of the cup was placed firmly on the cup to expel excess mud through a hole in the lid. The arm of the mud balance was then placed on the base with the knife edge on the fulcrum, and the rider was adjusted until the arm was level, as indicated by the level vial. The density was read at the point where the slider weight stabilized.

Figure 6. *Mud Balance.*

2.3.2. Rheology

The rheological properties of the mud samples were measured using a rheometer (Figure 7), which characterizes the viscous behaviour of fluids. The sample was poured into the rheometer's cup, which was then positioned correctly by aligning with the base plate. The sample was stirred at various speeds, with dial readings recorded after stabilization at each speed. For the temperatures of 120 ℉ and 15 ℉, a thermo-cup was used to heat the mud samples before the readings were recorded. The rheometer was also used to determine the gel strength of the mud samples at 10 seconds and 10 minutes. After the mud had remained static for some time (10 secs) the rotor was set at a low speed (3 rpm) and the deflection was reported as the initial or 10-second gel. The same process was repeated after the mud remained static for 10 minutes, to determine the 10-minute gel. The dial readings were employed to calculate the plastic viscosity (PV) and yield point (YP) of the drilling fluid using Eqs. 1 and 2 respectively [22, 23].

$$PV,\ cP = \theta_{600} - \theta_{300} \tag{1}$$

$$YP,\ lb/100\ ft^2 = \theta_{300} - PV \tag{2}$$

where, θ_{300} and θ_{600} are the dial reading at 300 and 600 rpm, respectively.

Figure 7. *Rheometer.*

2.3.3. pH

The pH of the mud samples was measured using a pH meter (Figure 8). This measurement was achieved using a glass electrode and a reference electrode. The glass electrode was immersed in each mud sample to record the pH values.

Figure 8. *pH Meter.*

2.3.4. Filtration

The filtration test for each mud sample was performed using a filter press (Figure 9). The filtration process began by placing a rubber gasket and a screen in the base cap with the filtrate tube. Then a filter paper was carefully positioned on the screen inside the base cap, followed by a rubber gasket on top of the filter paper. The mud cup was then firmly locked on the base cap. The mud sample was poured into the mud cup and secured with a rubber tube and the top cap. A graduated cylinder was set up under the screen to collect the filtrate. The filtration test was initiated by applying a pressure of 100 psi for 30 minutes, after which the filtrate volume was measured in millilitres (ml). Following the test, the pressure was gradually released, the cell was opened, and the filter paper was removed. The thickness of the filter cake was then measured with a vernier calliper.

Figure 9. *Filter Press.*

3. Results

The results from the mud density, rheology, filtration, and pH tests are presented in this section for further discussion.

3.1. Mud pH and Results

The results for the pH and mud density of the mud samples are illustrated in Table 2.

Table 2. *Results for pH and Density of Mud Samples.*

Mud Samples	CF	A	B	C	D
pH	10.25	9.01	8.30	7.95	7.67
Density (Ib/gal)	8.50	8.50	8.50	8.50	8.50

3.2. Rheology Results

The results from the rheological tests conducted at various temperatures are presented in Tables 3 to 5.

Table 3. Rheological Properties of WBM with Varying Concentrations of DMLP at 77 °F.

Mud Samples	Dial Readings						Gel Strength (Ib/100ft^2)	
	θ_{600}	θ_{300}	θ_{200}	θ_{100}	θ_6	θ_3	*Initial 10 sec.*	*Final 10 min.*
CF	26	20	18	15	14	14	9	35
A	25	19	17	14	11	12	16	27
B	23	18	16	14	12	13	15	25
C	22	17	15	13	12	13	15	23
D	20	16	13	12	10	11	13	22

Table 4. Rheological Properties of WBM with Varying Concentrations of DMLP at 120 °F.

Mud Samples	Dial Readings						Gel Strength (Ib/100ft^2)	
	θ_{600}	θ_{300}	θ_{200}	θ_{100}	θ_6	θ_3	*Initial 10 sec.*	*Final 10 min.*
CF	28	20	18	16	14	15	19	32
A	23	18	15	14	13	14	18	21
B	21	16	15	13	13	14	15	21
C	20	16	15	13	13	14	15	20
D	20	15	14	13	13	13	14	18

Table 5. Rheological Properties of WBM with Varying Concentrations of DMLP at 150 °F.

Mud Samples	Dial Readings						Gel Strength (Ib/100ft^2)	
	θ_{600}	θ_{300}	θ_{200}	θ_{100}	θ_6	θ_3	*Initial 10 sec.*	*Final 10 min.*
CF	32	26	24	22	23	27	23	20
A	24	19	17	15	14	16	15	17
B	22	17	16	15	15	16	15	16
C	20	16	14	13	14	15	14	15
D	18	15	14	12	12	13	13	13

3.2. Filtration Results

Tables 6 and 7 present the results of the filtrate volume and filter cake thickness from the filtration test of all five mud samples.

Table 6. Filtrate Volume of WBM with Varying Concentrations of DMLP.

Title 1	Filtrate Volume (ml)				
	CF	A	B	C	D
1	0.2	0.4	1	1.4	0.8
2	1.6	2	2.6	2.4	2.2
3	3	3.2	3.6	3.6	3.4
5	4	5.2	5.4	5.2	5.4
7	6.6	6.6	6.8	6.6	6.8
9	7.6	7.8	8	7.6	8
10	8.4	8	8.4	8.2	8.4
11	9	9	9.2	8.8	9
12	9.6	9.6	9.4	9.2	9.4
13	10	10.2	10	9.6	9.8
15	11	11.2	10.6	10.4	10.6
17	12	12	11.2	11.2	10.8
19	12.8	12.8	12	11.8	11.2
20	13.2	13.2	12.4	12.2	11.4
21	13.6	13.6	12.6	12.6	11.8
22	14	14	12.8	12.8	12
23	14.4	14.2	13.6	13.2	12.2
25	15.2	15	13.8	13.6	12.4
27	16	15.6	14	14.2	12.8
29	16.8	16.4	14.6	14.6	13
30	17	16.8	15	14.8	13.2

Table 7. Filter Cake Thickness.

CF	A	B	C	D
3 mm	3 mm	3 mm	3 mm	3 mm

4. Discussion

4.1. Effect of DMLP on Mud Density

The density of drilling mud must be adequate to ensure that the mud column's hydrostatic pressure prevents the fluid flow from formation into the wellbore [24-26]. The appropriate drilling mud density is determined by subsurface formation pressures. If the mud density is higher than necessary to control formation pressures, it can decrease the drilling rate, increase differential pressure sticking, fracture the formation leading to possible loss of circulation, raise mud costs, and thus increase overall well costs [6, 27-29]. Figure 10 illustrates the impact of DMLP on the density of water-based mud. As shown, the mud density remained the same with increasing concentrations of DMLP compared to the Control Fluid (CF) which had no DMLP. The lack of change in mud density with increasing DMLP concentrations suggests that DMLP does not influence the hydrostatic pressure of the mud column. This indicates that DMLP cannot be used as a weighting material but may still offer benefits in other areas such as rheology and filtration.

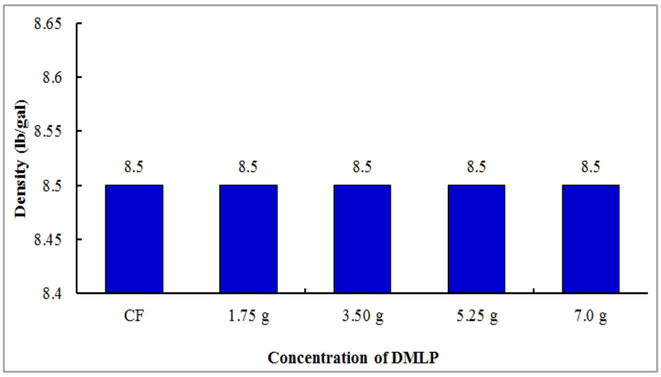

Figure 10. Effect of DMLP on Mud Density.

4.2. Effect of DMLP on pH

The pH of drilling mud plays a crucial role in the drilling process. An acidic drilling mud is undesirable in the drilling process as it can cause corrosion of drilling equipment and potentially lead to hazardous incidents [6]. Therefore, engineers need to maintain an optimal pH range. Typically, water-based mud performs best within a pH range of 8.0 to 10.5. Figure 11 illustrates the impact of DMLP on the pH of water-based mud. It was noticed that the pH of the mud decreased as the concentration of DMLP increased. The addition of DMLP reduced the alkalinity of all the drilling mud compared to the Control Fluid (CF). Higher concentrations of DMLP resulted in a greater reduction in the alkalinity of the mud samples. The pH of the samples decreased by 12.1%, 19.0%, 22.4%, and 25.2% at concentrations of 1.75 g, 3.50 g, 5.2 5g and 7.0 g respectively, compared to the CF. The reduction in pH with increasing DMLP concentrations indicates that DMLP can serve as an effective pH reducer in drilling operations. This property could be particularly advantageous in wellbore environments where lowering alkalinity is necessary, such as in cementing jobs or when drilling through formations prone to high calcium concentrations. This phenomenon aligns with findings from studies conducted by Broni-Bediako et al. [6] and Al-Hameedi et al. [19] which evaluated the use of waste materials such as bamboo leaves, and palm tree leaves.

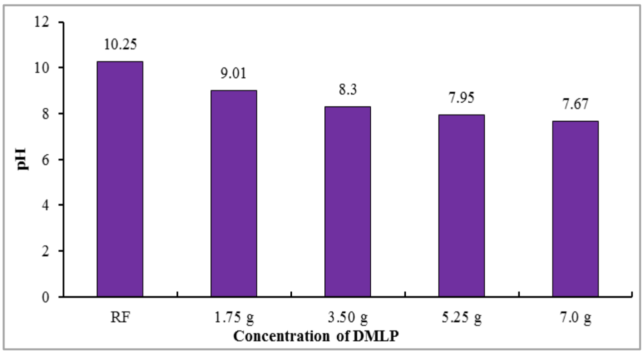

Figure 11. *Effect of DMLP concentration on pH.*

4.3. Profile of Shear Stress and Shear Rate

Figures 12 and 13 illustrate the behaviour of shear stress and shear rate of the drilling mud at various DMLP concentrations at 77 ℉ and 150 ℉, respectively. The results suggest that higher concentrations of DMLP in the samples caused a reduction in rheological values at a high shear rate, from 200 rpm to 600 rpm. The curves demonstrate a similar increasing profile for the shear-stress shear-rate behaviour at 120 ℉, as shown in Table 4.

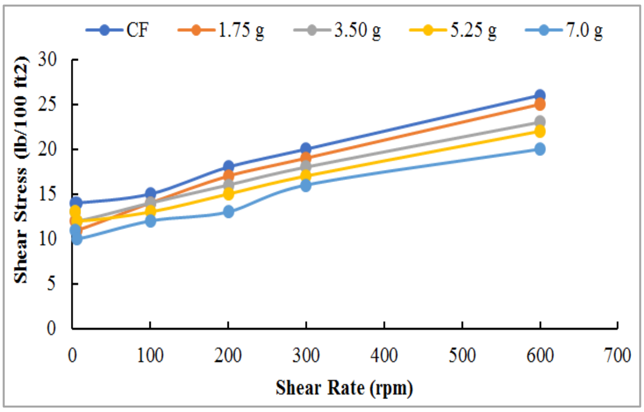

Figure 12. *Shear Stress and Shear Rate Behaviour at 77 °F.*

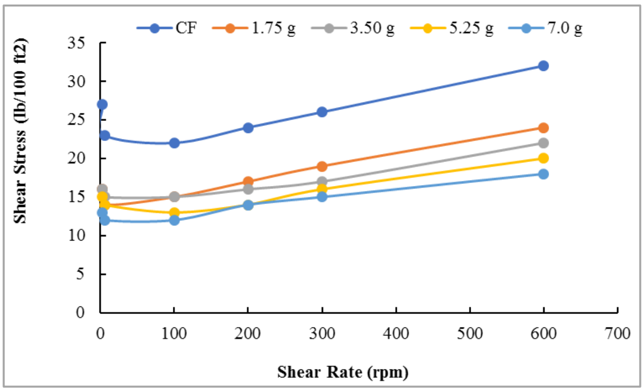

Figure 13. *Shear Stress and Shear Rate Behaviour at 150 °F.*

4.4. Effect of DMLP on Rheological Properties

The rheological properties of drilling mud describe how it flows and deforms when subjected to external forces [30]. Optimal rheological properties enable the swift removal of bottomhole cuttings, improve the rate of penetration, lower power consumption, ensure drilling safety, and enhance economic benefits [31]. This section examines the effect of Dry Mango Leaves Powder (DMLP) on the plastic viscosity, yield point, and gel strength of water-based mud at various temperatures.

4.4.1. Plastic Viscosity

Plastic viscosity (PV) is an absolute flow property indicating the flow resistances of certain fluids like the drilling mud. The viscosity of the base fluids and the solid content influence it [32]. Drilling mud with a high PV is unwanted as it reduces the rate of penetration [28]. Additionally, fluids with high plastic viscosity can result in increased equivalent circulating density because higher pump pressures are needed to circulate the fluid in the wellbore [33]. High PV results from increased mud weight or solid content in the drilling mud. As illustrated in Figure 14, increasing the concentration of DMLP from 1.75 g to 7.0 g resulted in a reduction in the plastic viscosity of all mud samples compared to the CF.

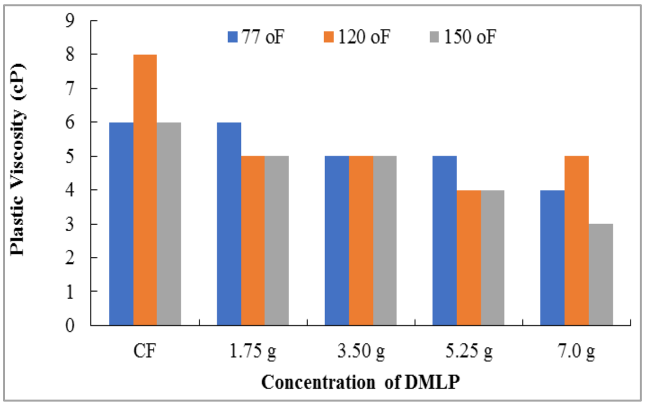

Figure 14. *Effect of DMLP Concentrations on Plastic Viscosity.*

4.4.2. Yield Point

The yield point is the initial resistance to flow caused by electrochemical attractive forces within the mud under flowing conditions [24]. It signifies the stress needed to initiate fluid movement [34]. A higher yield point leads to increased frictional pressure losses and a rise in the Equivalent Circulation Density (ECD). Figure 15 illustrates that there is no significant difference in the yield point between the CF and the drilling fluid with DMLP concentrations ranging from 1.75 g to 7.0 g at temperatures of 77 ℉ and 120 ℉. However, at 150 ℉, the yield point decreased with increasing concentrations of DMLP compared to the CF.

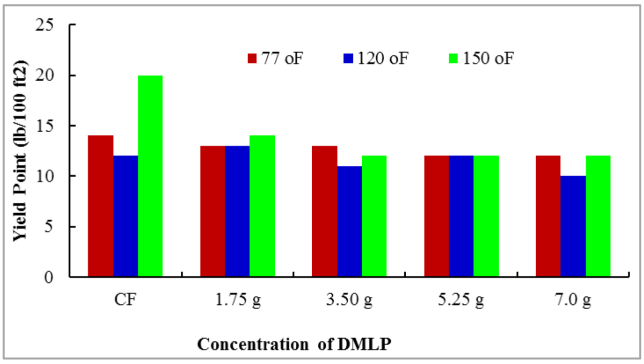

Figure 15. *Effect of DMLP Concentrations on Yield Point.*

4.4.3. YP/PV Ratio

The cutting carrying capacity of the drilling mud samples was examined using the YP/PV ratio. According to Bageri et al. [35], the cutting carrying capacity of the drilling fluid increases with increasing YP/PV ratio. As indicated in Figure 16 the YP/PV ratio for all the samples tested at 77 °F and 120 °F increased with increasing concentration of DMLP compared with the CF except for 1.75 g at 77 °F. This suggests that the addition of DMLP improved the cutting carrying capacity of the mud. At 150 °F, the carrying capacity was improved at a concentration of 7.0 g.

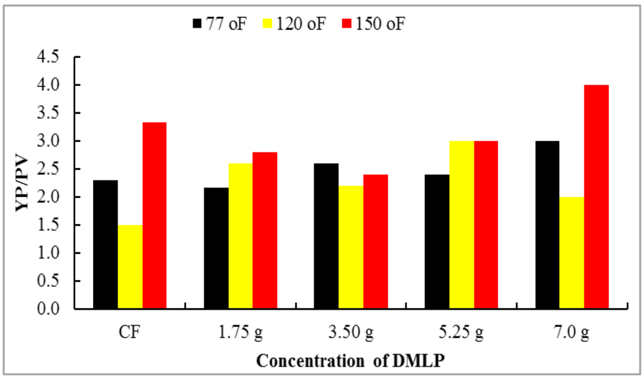

Figure 16. *Effect of DMLP Concentrations on YP/PV Ratio.*

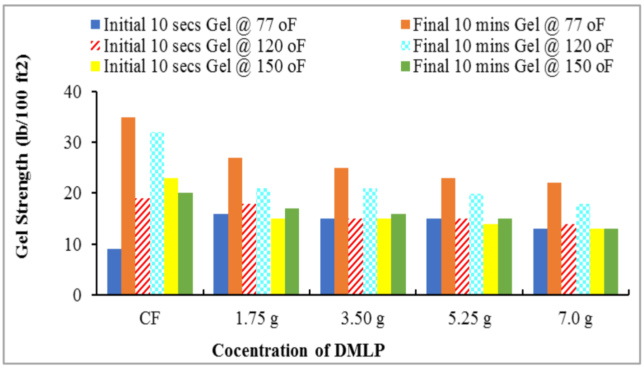

Figure 17. *Effect of DMLP on Gel Strength.*

4.4.4. Gel Strength

Gel strength assesses the shear stress of drilling mud at low shear rates, typically measured with a viscometer after the mud has been allowed to sit undisturbed for specific periods-usually 10 seconds, 10 minutes, and 30 minutes, as per the standard API procedure [36]. This measurement indicates how well the drilling fluid can suspend drill cuttings when circulation is paused. The initial (10-second) and final (10-minute) gel strengths provide insight into the degree of gelation that occurs once circulation stops and the mud settles. Higher gelation during these shutdown periods requires increased pump pressure to resume circulation [37, 38]. As depicted in Figure 17, adding various concentrations of DMLP reduced both the initial (10-second) and final (10-minute) gel strengths compared to the CF, except for the initial (10-second) gel strength at 77 °F, which was higher than the CF. The addition of DMLP improved gel strength performance, with the difference between the initial and final gel strengths at all concentrations and temperatures below 10 lb/100ft^2, except for a concentration of 1.75 g at 77 °F, resulting in 11 lb/100ft^2. This indicates that drilling fluids with DMLP concentrations up to 7.0 g will not require additional pressure to transition from pump-off to pump-on conditions, thereby preventing induced fractures in weak formations and maintaining pump efficiency [39].

4.5. Effects of DMLP on Filtration Characteristics

Filtration occurs when mud at a higher pressure than the formation pressure forces filtrate into the rock, making mud solids deposited on the borehole walls. Excessive filtration rates and thick mud cake can lead to formation damage, and differential pipe sticking [40, 41]. Figure 18 displays the results of a static filtration test, including filtrate volume and mud cake measurements.

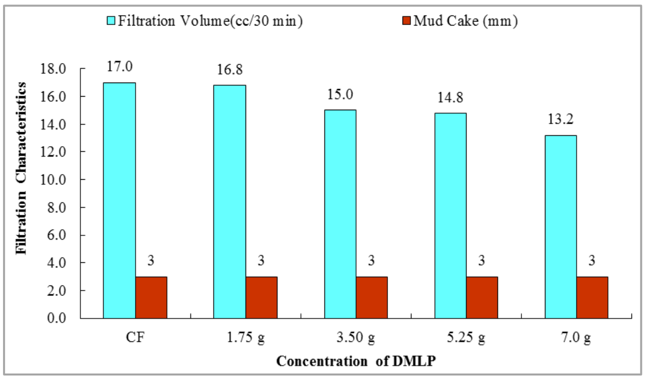

Figure 18. *Effect of DMLP on Filtration Characteristics.*

Figure 18 shows that the filtrate volume decreased with the addition of DMLP compared to the CF. The results indicate that filtration reduced as the concentration of DMLP increased. Specifically, at concentrations of 1.75 g, 3.50 g, 5.25 g, and 7.0 g, the filtrate volume decreased by 5.8%, 11.8%, 12.9%, and 22.4% respectively. However, the mud cake remained consistent at these concentrations. According to Annis and Smith [29], the permeability of the cake is directly proportional to the product of fluid loss and thickness of the mud cake. Consequently, if both fluid loss and cake thickness are low, the permeability of the cake will also be low. The observations from the study indicate that DMLP can serve as a fluid loss control agent.

5. Conclusions

This study was designed to investigate the potential of Dry Mango Leaves Powder (DMLP) from Kent Mango Tree as eco-friendly additive in water-based drilling mud. Four drilling mud samples were prepared with varying concentrations of DMLP, ranging from 1.75 g to 7.0 g, and compared to a Control Fluid (CF) without DMLP. The samples were aged for 16 hours at room temperature. Following this ageing period, density, pH, and filtration properties were assessed at room temperature, while rheological properties were tested at 77 ℉, 120 ℉, and 150 ℉. All experiments were conducted per American Petroleum Institute specifications. The density of the drilling mud with varying concentrations of DMLP consistently measured 8.5 ppg, the same as the density of the CF. The pH of the drilling mud decreased as the amount of DMLP increased. DMLP effectively reduced alkalinity by 25.2% at a concentration of 7.0 g. Therefore, DMLP can be used as an effective pH-reducing agent. The rheological values and plastic viscosity decreased with increasing concentrations of DMLP at 77 ℉, 120 ℉, and 150 ℉. The addition of DMLP concentrations did not result in substantial changes in the yield point between the CF and the drilling fluid with DMLP concentrations ranging from 1.75 g to 7.0 g at temperatures of 77 ℉ and 120 ℉. However, at 150 ℉, the yield point decreased as the concentration of DMLP increased compared to the CF. The addition of DMLP enhanced gel strength performance, with the difference between the final and initial gel strengths staying below 10 lb/100ft^2 at all concentrations and temperatures, except for a concentration of 1.75 g at 77 ℉, which resulted in a value of 11 lb/100ft^2. The amount of filtrate volume decreased as the concentration of DMLP increased, in comparison to the CF. The addition of 7.0 g of DMLP reduced the fluid loss by 22.4%. However, the thickness of the mud cake remained consistent across all DMLP concentrations. These results indicate that DMLP has favourable filtration properties and shows promise as a fluid loss-controlling agent. The study has proved the potential of DMLP as an alternative to other biodegradable materials in enhancing certain properties of water-based drilling fluid while contributing to reducing the ecological risks posed by non-biodegradable additives in drilling fluids.

Abbreviations

API	American Petroleum Institute
CF	Control Fluid
DMLP	Dry Mango Leaves Powder
PAC	Polyanionic Cellulose
PV	Plastic Viscosity
YP	Yield Point

Author Contributions

Eric Broni-Bediako: Conceptualization, Formal Analysis, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing

Daniel Ocran: Supervision, Validation, Writing – review & editing

Kwabena Akorafi Appiah: Project administration, Investigation, Validation

Solomon Okine Charway: Formal Analysis, Investigation, Methodology, Validation

Conflicts of Interest

The authors declare no conflicts of interest.

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