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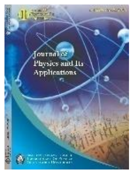

# Laboratory Evaluation of Sugarcane Bagasse as a Sustainable Additive of Loss Circulation Material in 7% KCl-PHPA Water-Based Mud

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ABSTRACT

Loss circulation is one of the main problems in drilling operations that can cause loss of cost, time, and safety risks. One of the methods of countering it is by adding Loss Circulation Material (LCM). This study aims to evaluate the use of sugarcane bagasse, a fiber-rich sugar industrial waste, as an environmentally friendly LCM in drilling mud based on 7% KCl Polymer PHPA. Variations of the addition of 0, 2, 4, and 6 grams of bagasse were tested on a laboratory scale to see their effect on the properties of the sludge, including density, Plastic Viscosity ($\mu_p$), Yield Point ($\tau_0$), gel strength (10 seconds and 10 minutes), pH, and API filtrate loss. The results showed that the addition of up to 6 grams of bagasse increased Plastic Viscosity ($\mu_p$) from 16 to 22 cP, Yield Point ($\tau_0$) from 22 to 27 lb/100 ft$^2$, and 10-minute gel strength from 15 to 16 lb/100 ft$^2$, while decreasing API filtrate loss from 5.6 to 5.1 mL. These quantitative improvements indicate a good bridging ability in the loss zone. This research confirms that bagasse can act as an alternative LCM that is environmentally friendly, supporting the principle of circular economy and biomass waste reduction.

## 1. Introduction

Drilling mud plays a crucial role in the success of drilling operations, both in controlling formation pressure, lifting cutting, and protecting productive formations. One of the problems that often occurs is the loss of sludge into the formation (loss circulation), which can cause stuck pipes, non-productive time (NPT), and increased operating costs. Conventional circulation loss management is carried out by adding LCM based on granular, flaky, and fibrous materials such as mica, walnut shell, or calcium carbonate [1]. However, the plugging efficiency of granular materials like walnut and marble heavily depends on their particle size distribution, which can degrade under high mechanical shear during circulation. While traditional chemical plugging materials and granular LCMs are effective for low to medium fluid losses, severe or cavernous loss circulation often requires physical plugging tools or mechanical interventions to prevent repeated fluid invasion [2], [3].

Conventional LCMs such as CMC (Carboxymethyl Cellulose) are widely used for their ability to control filtration loss and form a thin, dense mud cake [4]. However, CMC prices are relatively expensive and dependent on imports. Therefore, the selection and development of effective and environmentally friendly lost circulation material (LCM) additives is an important focus in current drilling fluid research. CMC is produced from plant cellulose substances. Cellulose produces alkaline and carboxymethyle substances that are soluble in fluids [5], [6]. Recent developments have shown that extracting CMC directly from agricultural waste, such as sugarcane bagasse, can yield a high-purity product that effectively maintains mud density and reduces filtration loss to acceptable standards. Furthermore, utilizing organic biomass materials as drilling fluid additives aligns with the global push for carbon neutrality, offering renewable, biodegradable, and cost-effective alternatives to petroleum-derived chemicals [7], [8].

Wheat nano-biopolymers can improve the rheological and filtration properties of mud, but do not specifically address circulation loss [9]. The use of coffee waste and watermelon peel to reduce fluid loss, but studies are limited to a simple laboratory scale [10]. Various biomasses such as mica, wheat straw, oak bark, and bagasse or sugarcane fibers are mixed and evaluated for their performance on drilling fluids, but these biomasses are not used as the main material [11].

Peanut shells were also studied as LCMs, but in this study did not attribute their application to reactive clay formations [12]. The use of orange peel as an additive, but the concentration tested was very low (≤0.5% w/w) and only emphasized the filtration aspect [13]. Wider evaluations of natural fibers have confirmed their strong impact on enhancing the plastic viscosity, yield point, and gel strength of water-based muds while simultaneously acting as fluid loss agents. Specific studies on sugarcane fiber biomass reveal that its addition to water-based systems securely increases fluid density and significantly boosts the yield point without causing environmental harm [14], [15].

To further combat fluid loss without harming the environment, the industry is shifting toward sustainable and bio-based additives derived from organic materials like cellulose, starch, and lignin. These organic materials are highly effective at sealing the borehole wall because their flexible particles can adapt to different pore sizes and build a tight filter cake. For example, lignin-based materials can penetrate fractures and establish strong physical and chemical bonds with the rock surface, providing a highly stable cementing layer that significantly reinforces wellbore stability. Specifically, lignin-derived adhesives and cross-linked networks can act as high-performance wellbore strengthening agents by filling micro-fractures and forming a dense interphase under thermal curing. Organic bridging materials made from flexible cellulose particles also rapidly migrate to the borehole wall under pressure differentials to form an impermeable and highly adaptable filter cake. Proper particle size selection of these cellulose-based fibers ensures that an external filter cake forms efficiently, which greatly limits the internal invasion of polymers and solids into the formation and prevents irreversible permeability damage [16]–[18].

Studies on sugarcane bagasse (SCB) have begun to be carried out, but there are still gaps. SCB can reduce filtration loss by up to 39.6%, but it is only tested at a temperature of ≤80 °C under simple laboratory conditions [4]. Comparison of banana peels and SCB, showed that banana peels were superior, but in the study SCB was not evaluated as a single material with particle size and concentration optimization [19].

Based on this literature, there are several research gaps that need to be filled. First, most studies have focused on filtration properties and rheology, but have not comprehensively examined the mechanism of plugging in heavy circulation loss scenarios. Second, bagasse is often only positioned as an additional material, even though its high fiber properties of cellulose have the potential to provide better plugging performance than other biomass. Third, there has been no study that specifically assesses the performance of bagasse as a single LCM in KCl/PHPA-based sludge that is widely used in the Indonesian field.

The specific novelty of this study lies in evaluating bagasse as a standalone LCM applied directly into a 7% KCl-PHPA polymer system. This approach aims to observe the actual synergistic effect between the natural SCB fibers and synthetic polymers (PAC-LV, XCD, and PHPA) in controlling fluid loss and rheology, specifically targeting reactive shale zones like the Korinci and Binio formations.

To achieve this, this research evaluates how different concentrations of bagasse affect the mud's rheological properties, filtration, and bridging potential. Ultimately, the findings are expected to support the development of eco-friendly, locally sourced LCMs that fit practical drilling conditions in Indonesia.

## 2. Materials and Methods

This study uses water-based mud (WBM) formulated referring to the API Recommended Practice 13B-1 standard with the main ingredients in the form of fresh water as a continuous phase, bentonite as much as 25 grams per 350 mL of water as a viscosity-forming material, 7% KCl as a shale inhibitor, PHPA (Partially Hydrolyzed Polyacrylamide) as a rheological control polymer and shale stabilization, barite as much as 130 grams per 350 mL of water to increase the weight of the drilling mud, and NaOH as much as 1 gram per 350 mL of water for pH regulation. As the main test material, milled dried bagasse is used with variations of adding 2 grams, 4 grams, and 6 grams to 350 mL of mud. The addition of 2, 4, and 6 grams to the 350 mL mud volume was selected to simulate field concentrations of 2, 4, and 6 pounds per barrel (ppb), providing an empirical baseline to observe rheological changes. The following is the table 1 of the formulation of WBM KCL PHPA mud in this study:

**Table 1:** WBM KCL 7% PHPA Formulation

| Material | S.G | Conc.(ppb) | Mix Time |
|---|---|---|---|
| Fresh Water | 1 | 306 | - |
| Bentonite | 2.6 | 2.25 | 10 |
| KOH | 2 | 0.5 | 1 |
| SODA ASH | 2.5 | 0.15 | 1 |
| Starch | 1.5 | 2 | 8 |
| PAC-LV | 1.5 | 0.35 | 8 |
| PAC-R | 1.5 | 0.5 | 8 |
| XCD | 1.5 | 1.15 | 10 |
| KCL | 1.99 | 25.6 | 5 |
| PHPA powder | 1 | 0.25 | 5 |
| Barite | 4.2 | 113.58 | 5 |

Sugarcane Bagasse is obtained from local sugarcane mill waste. Before use, the bagasse is washed with water to remove any remaining sap and dirt, then dried in the sun for approximately 48 hours until the moisture content is significantly reduced. After drying, the bagasse was mechanically ground using a manual coffee grinder. While a full particle size distribution analysis was not conducted, the material was physically constrained to a maximum particle size of strictly < 1 mm. Therefore, all bagasse particles used in this formulation are < 1000 μm (equivalent to passing an 18-mesh sieve). Determining the specific size distribution curve remains an important aspect for future optimization.

The laboratory testing was systematically conducted across based mud or basic mud without the addition of bagasse as a control and three different bagasse concentrations (2 grams, 4 grams, and 6 grams) to evaluate their respective impacts on the mud properties. The best result was determined by identifying the specific concentration that successfully reduced filtration loss while maintaining the rheological parameters ($\mu_p$, $\tau_0$, and Gel Strength) within the required operational specifications of the target well.

Testing of the properties of the WBM is carried out using several standard instruments. WBM density is measured by mud balance, while WBM pH is measured using a digital pH meter. The rheological properties of the sludge were tested with the Fann Viscometer Model 35 at speeds of 600, 300, 200, 100, 6, and 3 rpm to obtain the parameters of Plastic Viscosity ($\mu_p$), Yield Point ($\tau_0$), apparent viscosity ($\mu_a$), and gel strength at intervals of 10 seconds and 10 minutes according to the API RP 13B-1 method.

The filtration test was performed with the Low Pressure Low Temperature (LPLT) Filter Press at a pressure of 100 psi for 30 minutes to measure the volume of the filtrate and the thickness of the mud cake. The test results data were then analyzed comparatively to evaluate the effect of variations in bagasse concentration on the rheological properties and filtration of drilling mud, and compared with the findings of previous research as the basis for discussing the novelty of this study. The research flowchart is shown in Fig. 2.

PAC LV, PHPA, and XCD in table 1 of the drilling mud formulation are the ingredients used as Fluid Loss Reducers. The basic formulation in this study replicates the operational conditions commonly used in the field, namely sludge that already contains PAC-LV, PHPA, and XCD as a fluid-loss reducer. The purpose of the study was not to replace PAC-LV, PHPA, and XCD but rather to evaluate whether the addition of bagasse (SCB) could act as a complementary LCM that improves the bridging/plugging mechanism and decreases the need for synthetic additives.

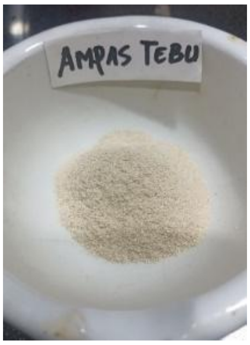


**Fig. 1:** Processed Sugarcane Bagasse

The mud formulation in samples 1, 2, 3, and 4 was adjusted to the conditions of the target well. In this study, the target depth of the well as the basis for making mud formulations is at a depth of 2100 ft or about 640.08 meters. The current laboratory evaluation was conducted at 120°F and low pressure. This condition closely simulates the target depth. The rock formations in this study target are the Korinci formation and the Binio formation. In Fig. 3 about the stratigraphy of the well rocks targeted by this study, it can be seen that the Korinci formation and the Binio formation have an intermittent rock structure between sandstone and shale. This is the target of this study, because this sandstone has cracks in the rock structure so that it causes loss of circulation in the WBM drilling mud used.

## 2.1. Rheology Drilling Mud

Drilling mud rheology describes the behavior of fluid flow to *shear stress* and *shear rate*. Understanding rheological characteristics is very important because it determines the ability of sludge to lift drilling powder (*cuttings*), maintain well stability, and control loss *circulation* and filtration.

In general, drilling mud is not a Newtonian fluid, but rather follows the plastic Bingham fluid model. The relationship between shear stress (τ) and shear rate ($\dot{\gamma}$) is stated as follows [4]:

$$\tau = \tau_0 + \mu_p \tag{1}$$

where τ is shear stress $\left({}^{lb}/_{ft^2}\right)$, $\tau_0$ is Yield Point (YP) or minimum volume $\left({}^{lb}/_{100\,ft^2}\right)$, $\mu_p$ (PV) is Plastic Viscosity (cP), and γ is shear rate ($s^{-1}$).

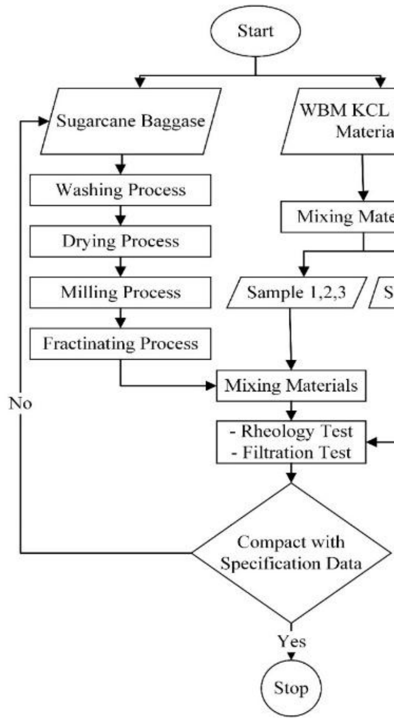


**Fig. 2:** Flowchart of the proposed algorithm.

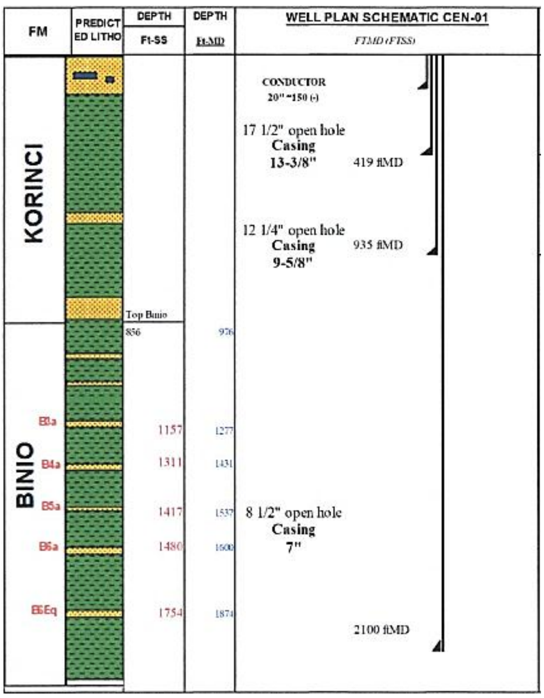


**Fig. 3**: Stratigraphy and Well Plan Schematic.

The rheological parameters of the sludge are calculated from the reading of the viscometer dial at a given speed (API RP 13B-1, 2009):

a. Plastic Viscosity ($\mu_p$)
Plastic Viscosity ($\mu_p$) describes the resistance of mud flow due to friction between solid particles in a fluid. The value of $\mu_p$ is influenced by the concentration of dispersed solids, particle size, and interactions between particles. $\mu_p$ is calculated from the difference in the reading of the viscometer dial (θ) at 600 rpm and 300 rpm according to API RP 13B-1 standard (2009). Too high a $\mu_p$ can increase *the equivalent circulating density* (ECD) and cause *lost circulation*, meanwhile the $\mu_p$ that is too low can reduce the mud suspension ability [4], [12].

$$\mu_p = \theta_{600} - \theta_{300} \tag{2}$$

b. Yield Point ($\tau_0$)
Yield Point ($\tau_0$) is the minimum shear force required to start a mudflow. $\tau_0$ reflects the electrostatic and mechanical ability of particles to interact with each other, thus relating to the ability of mud to lift cutting to the surface. $\tau_0$ is calculated by subtracting $\mu_p$ from the viscometer dial reading (θ) at 300 rpm. A high enough $\tau_0$ value is desirable for the mud to be able to carry cutting efficiently, but too high a value can increase the risk of excess pressure in the annulus [4], [12].

$$\tau_0 = \theta_{300} - \mu_p \tag{3}$$

c. Apparent Viscosity ($\mu_a$)
Apparent Viscosity ($\mu_a$) is the effective viscosity of the mud at a given shear speed and is calculated as half of the viscometer reading (θ) at 600 rpm. $\mu_a$ provides an overview of the sludge's resistance to flow under operating conditions. Optimal $\mu_a$ values are important for maintaining hydraulic stability in the borehole [4], [12].

$$\mu_a = \frac{\theta_{600}}{2} \tag{4}$$

d. Gel Strength
*Gel Strength* is a measure of the strength of the mud structure to maintain cutting in a stationary state. This value is measured from the viscometer reading after the sludge is left for 10 seconds (initial gel strength) and 10 minutes (final gel strength). The appropriate gel strength ensures that the cutting does not settle when the mud circulation stops. Gel strength values that are too high can cause difficulties in restarting circulation (*surge pressure*), while values that are too low result in cutting deposits (API RP 13B-1, 2009).

### 2.2. Filtration and Mud Cake

In addition to rheology, the filtration properties of drilling mud are also important parameters that determine the success of drilling operations. Filtration is the process of drilling fluid exiting into the formation due to a pressure difference between the mud column and the formation, while solid particles are trapped on the surface to form a layer called *a mud cake* (API RP 13B-1, 2009).

Polymer additives such as PAC-LV work by forming a thin film on a dense, impermeable cake filter surface, thereby reducing the permeability of rocks interacting with drilling mud and lowering the volume of filtrate. However, PACs do not directly provide the bridging effect of large particles.

**Table 2:** Rheology WBM 7% KCL Polymer PHPA Test Results

| Mud Properties | | Specification | 7% KCL PHPA |
|---|---|---|---|
| Mud Weight | ppg | 11 ppg | 11 |
| 600 | | | 54 |
| 300 | | | 38 |
| 200 | | | 30 |
| 100 | | | 22 |
| 6 | | | 10 |
| 3 | | | 9 |
| $\mu_p$ | cP | 10 – 18 | 16 |
| $\tau_0$ | lb/100 ft$^2$ | 18 – 24 | 22 |
| Gel Strength 10 Sec | lb/100 ft$^2$ | 5 – 9 | 9 |
| Gel Strength 10 Min | lb/100 ft$^2$ | 10 – 15 | 15 |
| API *filtrat* | ml/30 min | <6 cc/30 min | 5.6 |
| pH | | 8.5 - 9.5 | 9 |

**Table 3:** Rheology WBM 7% KCL Polymer PHPA Test Results with Variety of Bagasse Pulp Mass.

| Mud Properties | | Specification | SCB 2 gr | SCB 4 gr | SCB 6 gr |
|---|---|---|---|---|---|
| Mud Weight | ppg | 11 ppg | 11 | 11 | 11 |
| 600 | | | 56 | 64 | 71 |
| 300 | | | 38 | 42 | 49 |
| 200 | | | 32 | 36 | 41 |
| 100 | | | 24 | 28 | 31 |
| 6 | | | 10 | 11 | 12 |
| 3 | | | 9 | 10 | 10 |
| $\mu_p$ | cP | 10 – 18 | 18 | 22 | 22 |
| $\tau_0$ | lb/100 ft$^2$ | 18 – 24 | 20 | 20 | 27 |
| Gel Strength 10 Sec | lb/100 ft$^2$ | 5 – 9 | 9 | 10 | 10 |
| Gel Strength 10 Min | lb/100 ft$^2$ | 10 – 15 | 15 | 15 | 16 |
| API *filtrat* | ml/30 min | <6 cc/30 min | 5.4 | 5.3 | 5.1 |
| pH | | 8.5 - 9.5 | 8.5 | 8.5 | 8 |

### 3. Results and Discussion

Tables 2 and 3 are the results of testing the properties of 7% KCl-PHPA base mud and after the addition of sugarcane bagasse (SCB) in variations of 2 grams, 4 grams, and 6 grams. The parameters tested included density, $\mu_p$, $\tau_0$, gel strength (10 seconds and 10 minutes), pH, and API filtrate loss.

As shown in Table 2, the based mud formulation already exhibits a strong fluid loss control (5.6 mL) prior to the addition of SCB. This baseline performance is primarily provided by synthetic polymers such as PAC-LV, XCD, and PHPA, which function by forming a thin, impermeable chemical film on the filter paper.

In the Table 3, the API filtrate volume of the mud which is added with the SCB is further reduced, reaching 5.1 mL at the 6 grams concentration. This additional improvement highlights a complementary physical mechanism rather than a chemical synergy. While the existing polymers chemically coat the formation surface, the fibrous structure of the bagasse physically bridges and plugs the larger micro-fractures or pores. Therefore, the sugarcane bagasse acts specifically as a physical Loss Circulation Material (LCM) that mechanically reinforces the polymer-based mud cake, preventing severe fluid invasion without disrupting the chemical balance of the base mud.

### 3.1. Influence on rheological properties

The addition of SCB increases the $\mu_p$ and $\tau_0$ values compared to the WBM formulation. At a concentration of 2 grams, the increasing in $\mu_p$ is still moderate (+12.5%) and $\tau_0$ up about 8%. At a concentration of 4 grams, the increase was more significant, indicating the interaction of SCB fibers with mud particles that strengthened the suspension network. The concentration of 6 grams yields the highest $\mu_p$ and $\tau_0$, which indicates increased viscosity and the ability of the mud to lift cutting (Fig. 4 and 5). Increased Plastic Viscosity ($\mu_p$) is caused by an increase in the concentration of solids in the sludge [20].

In Fig. 6, gel strength increases with SCB concentration. In 6 grams of bagasse, the gel strength of 10 minutes exceeds the specified value in table 3. In 4 grams and 6 grams bagasse, the value of 10 seconds of gel strength exceeds the specified value in table 3. In bagasse, 2 grams show the ability of SCB to form a strong suspension structure when circulation stops. This condition is important to keep the cutting suspended, but gel strength that is too high can make it difficult to pump start-up (surge pressure).

From the result of the rheology tests are important to note that the target specification for the well requires a Plastic Viscosity ($\mu_p$) between 10-18 cP and a Yield Point ($\tau_0$) between 18-24 lb/100 ft$^2$. The addition of 4 grams and 6 grams caused the rheological parameters to exceed these safe operational limits. This indicates that excessive bagasse can negatively impact pump pressure and ECD. Thus, the 2 grams concentration provides the most optimal balance.

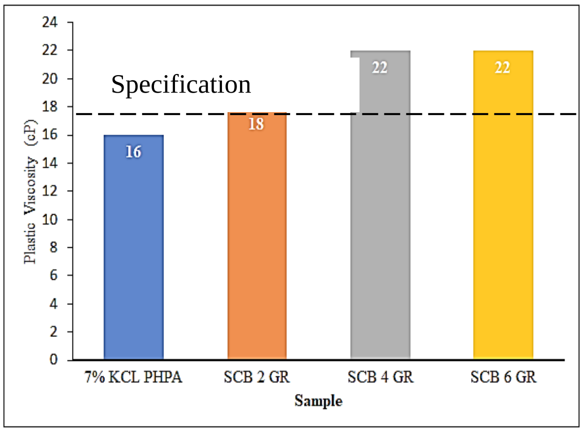


**Fig. 4**: Effect of sugarcane bagasse (SCB) concentration on the Plastic Viscosity ($\mu_p$) of the drilling mud.

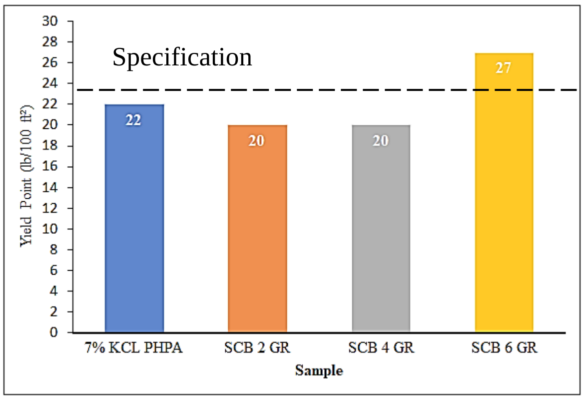


**Fig. 5:** Effect of sugarcane bagasse (SCB) concentration on the Yield Point ($\tau_0$) of the drilling mud.

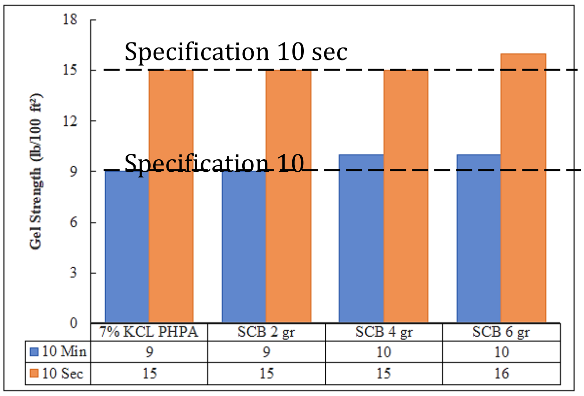


**Fig. 6:** Effect of sugarcane bagasse (SCB) concentration on the 10-second and 10-minute Gel Strength of the drilling mud.

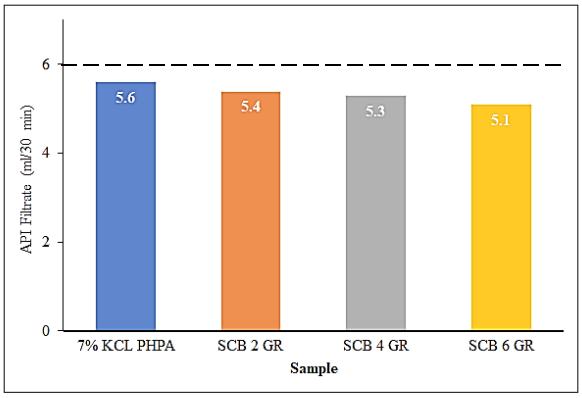


**Fig. 7:** Effect of sugarcane bagasse (SCB) concentration on the API Filtrate volume of the drilling mud.

### 3.2. Filtration

Filtrate loss is significantly reduced with the addition of SCB. Base mud yielded 5.6 mL of filtrate (30 minutes), while with SCB 6 grams reduced this value to 5.1 mL, indicating an approximate 9% reduction. This result confirms that SCB fibers contribute to the bridging effect on the filter paper without disrupting the primary function of the existing fluid loss reducers in the mud system. These findings are in line with previous research that fibrous biomass waste can reduce filtrate loss by up to 40% [12].

The laboratory results show that SCB has the potential to be an environmentally friendly, cheap, and abundantly available alternative LCM in Indonesia. In addition to reducing the need to import synthetic additives (e.g. CMC), the use of SCB also supports the principle of circular economy through the reduction of biomass waste from the sugar industry. The application of the KCl-PHPA system is very relevant because this system is widely used in shale drilling in Indonesia. Nonetheless, the study was limited to laboratory conditions with a temperature of 120°F and low pressure. Further evaluation is needed on HPHT (high pressure high temperature) conditions as well as artificial fracture simulation tests to validate the performance of SCB plugging in severe loss circulation conditions.

### 3.3. Quantitative Comparison with Previous Studies

To explicitly highlight the unique contribution of this research, Table 4 provides a quantitative comparison between the present research and previous works utilizing sugarcane bagasse as a lost circulation material.

**Table 4:** Quantitative comparison of sugarcane bagasse performance with previous studies.

| Study / Reference | Base Mud System | SCB Concentration | PV ($\mu_p$) Change | YP ($\tau_0$) Change | API Filtrate Reduction |
|---|---|---|---|---|---|
| Present Research | 7% KCl-PHPA | 2 to 6 grams | +12% to +37% (16 to 22 cP) | -9% to +22% (22 to 27 lb/100 $ft^2$) | ~9% (5.6 mL down to 5.1 mL) |
| Terakulsatit [2] | Water-Bentonite | 1% to 5% (w/v) | Increased | Increased | 39.6% (24.0 mL down to 14.5 mL) |
| Akmal et al. [9] | WBM (Xanthan-Barite) | 0.1 to 0.6 g/mL | +150% (10 to 25 cP) | +288% (9 to 35 kg/$m^2$) | ~42% (19.0 mL down to 11.0 mL) |
| Khalid et al. [10] | Water-Bentonite | 1 to 2.5 grams | +72% (11 to 19 cP) | +127% (11 to 25 lb/100 $ft^2$) | 13% (10.7 mL down to 9.3 mL) |

Table 4 quantitatively summarizes the performance of sugarcane bagasse (SCB) across different studies. While previous research [4], [19] reported massive fluid loss reductions of 39.6% and 42% respectively, it is crucial to note that their conventional base muds had very poor initial filtration control (yielding 19.0 to 24.0 mL of filtrate). Furthermore, in previous studies experienced extreme spikes in rheological parameters (up to 288% increase in YP and 150% in PV) upon adding SCB, which could severely disrupt drilling hydraulics [19], [20].

In contrast, the present study utilizes an advanced 7% KCl-PHPA system that already possesses excellent baseline filtration (5.6 mL). Achieving an additional 9% reduction (down to 5.1 mL) demonstrates that SCB effectively provides a physical bridging mechanism that perfectly complements the synthetic polymers. More importantly, the SCB in our formulation kept the Plastic Viscosity ($\mu_p$) about +37% and Yield Point ($\tau_0$) about +22% increments at manageable levels, proving its superior practical applicability in field operations compared to simple water-bentonite systems.

## 4. Conclusion

The addition of sugarcane bagasse to WBM 7% KCl Polymer PHPA has been proven to improve rheological properties, especially plastic viscosity, yield point, and gel strength, while reducing filtrate loss. This shows the effectiveness of bagasse as *a natural loss circulation material* that is able to improve the performance of drilling mud. In addition to providing technical benefits, the use of biomass waste also supports sustainability and circular economy aspects in oil and gas drilling operations in Indonesia.

However, this research has several limitations. The evaluation was limited to basic laboratory conditions at a temperature of 120°F without high-pressure simulation. Additionally, the exact particle size distribution of the mechanically ground bagasse was not precisely measured. For further studies, we highly recommend conducting High-Pressure High-Temperature (HPHT) tests to observe any potential thermal degradation of the natural fibers. Future research should also perform a detailed sieve analysis to determine the exact optimal mesh size and perform the bridging mechanism through experimental evidence (e.g., SEM images, mud cake morphology, fracture-plugging tests, or permeability measurements), ensure the moisture content of the bagasse is strictly controlled below 15%, and utilize a permeability plugging apparatus with a gravel pack or silica sand bed to better simulate real downhole fracture sealing.

## 5. Acknowledgments

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