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Effect of Corn Cob Addition on the Rheological and Filtration Properties of Water Based Drilling Mud

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ABSTRACT - Drilling mud is an essential tool in supporting the success of productive and economical oil and gas well drilling activities. Some chemical additives used to enhance the physical and rheological properties of mud are toxic, non-biodegradable, and have negative environmental impacts. The use of household waste materials such as corn cobs, which can be reused as a natural polymer in drilling mud, presents a promising alternative. The separation of these materials identifies a new polymer candidate, as they contain 41.27% cellulose, 46% hemicellulose, and 7.40% lignin, making them suitable for polymer use. The research involves analyzing the mud rheology, including plastic viscosity, yield point, gel strength, filtration loss, and mud cake, using three water-based mud samples containing 1.5 grams, 3 grams, and 4.5 grams of finely ground corn cobs. The samples are then tested at two different temperatures, 80ºF and 200ºF, to observe the behavior of corn cobs when circulated into the well and entering formations with higher temperatures. The results show that the addition of corncob increases plastic viscosity (13-24 cps), yield point (17-25 lb/100 ft^2), and gel strength (5-17 lb/100 ft^2), while reducing filtration loss (12-7 cc/30 minutes) and mud cake thickness (4-2 mm). Changes in rheological values and filtration loss with each additive addition will serve as indicators of the feasibility of corn cobs as a biodegradable cellulose-containing additive in drilling mud.

Keywords: corn cob, drilling mud, rheology, filtration loss, mud cake.

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1. Introduction

Amid global concern about preserving nature and its surroundings, researchers and professionals in the oil and gas industry are increasingly adopting more environmentally friendly practices. Government regulations aimed at environmental protection motivate the industry to enhance efficiency in drilling operations, particularly in the management and disposal of waste. To minimize environmental impacts, eco-friendly drilling fluids must be used in drilling operations (Kuma et al., 2020). In drilling, a mixture called drilling fluid is a blend of water and clay. It is commonly referred to as drilling mud or just mud. The drilling fluid acts like the bloodstream in the human body during drilling, with the pump functioning as the heart, drilled shales (cuttings) serving as waste, and the mud cleaning system mimicking the kidneys and lungs. Cuttings are removed from the mud cleaning system using sieves and shale shakers (Skalle 2011). The functions of drilling fluid include cleaning the bottom of the hole, lifting cuttings from the borehole to the surface, maintaining formation pressure, and lubricating and cooling the drill bit (Agin et al., 2019).

The oil and gas industry's disposal of spent drilling fluid, produced water, and accumulated drill cuttings poses a constant threat to the environment. Several chemical additives used in traditional water-based mud systems for cost-effectiveness are both harmful and non-biodegradable. Ignoring these issues can result in environmental, health, and safety concerns. Common additives such as potassium chloride, potassium sulfate, sodium hydroxide, polyamines, and chromium-based additives contribute to pollution and are also expensive. Currently, the US Environmental Protection Agency has implemented strict guidelines for water discharge and the disposal of drill cuttings. In response to these regulations, researchers are actively working on developing new additives that are non-toxic, biodegradable, and affordable to promote environmental conservation (Al-Hameedi et al., 2020).

The essential characteristics of drilling fluids are thoroughly outlined in the ANSI/API recommended practice for conducting field tests on water-based drilling fluids, known as 13b-1. The particular attributes of the drilling fluid may vary for each well slated for drilling (Kartini 2014). Several vital properties include rheological characteristics, encompassing plastic viscosity, yield point, gel strength, and viscosity at low shear rate, which facilitate meeting hydraulic requirements, ensuring effective transport of drill cuttings, and suspending drilled solids, goals to be attained during circulation halts. Filtration attributes prevent mud intrusion into formations. Density, or the specific fluid weight, maintains hydrostatic balance in the wellbore column during drilling operations. Inhibition properties enhance penetration rates by upholding wellbore stability and preventing cuttings from adhering to the drill bit. Lubricant features aid in resolving stuck-pipe issues and so forth.

The utilization of persistent additives in controlling drilling fluid properties poses environmental hazards and risks to human safety (Satiyawira et al., 2025). Therefore, there is a demand for alternative additives in drilling fluids to minimize the discharge of persistent waste into the environment.

The majority of traditional chemical additives are persistent compounds that pose various risks when released into the environment (Samura et al., 2025). These additions, such as potassium chloride, potassium sulfate, polyamines, and fluid-loss additives, have detrimental environmental effects. Consequently, there is a need for innovative, environmentally friendly additives that can help manage drilling fluid properties, enhance their effectiveness, and minimize environmental harm. In this regard, bio-products and diverse waste materials are quite beneficial (Le et al., 2025). They offer a comparable range of drilling fluid properties compared to certain established commercial additives. Bio products are readily accessible and cost-effective. Therefore, opting for their use can be a prudent choice to save money, energy, and time (Borah & Das 2022).

Besides bio-products and waste materials, numerous chemical additives and polymers, such as carboxymethyl cellulose, polyanionic cellulose, xanthan gum, and partially hydrolyzed polyacrylamide, stand out as remarkable drilling fluid additives and are also environmentally friendly (Borah & Das 2022).

According to the Environmental Protection Agency, the drilling process produces the second-largest volume of waste to the environment (Onwukwe & Nwakaudu 2012). The selection of drilling mud additives can have an impact on environmental pollution (Miranti et al., 2014). With the development of science, innovations have been made in the field of drilling mud using environmentally friendly natural materials. The advantage of using natural materials, in addition to utilizing household waste, is that they can help prevent pollution during drilling and are readily available in the surrounding environment. The material used in the drilling mud is Corn Cob Powder, and the content contained in the corn cob is based on research.

Several examples of corn waste utilization have been implemented, ranging from use as an alternative fuel for charcoal briquette production to use in drilling and cementing operations. The success of corn cob additive, in the form of Corn Cob Ash, which enhances compressive strength (Adesanya & Raheem 2009) in cement, provides an incentive to explore its impact as an Environmentally Friendly Drilling Fluid Additive for water-based drilling mud. Corn cobs contain cellulose (41.27%), hemicellulose (46%), and lignin (7.40%) (Borah & Das 2022). Considering the high content of cellulose and hemicellulose in corn cobs from a physical and chemical perspective, this locally available and easily accessible material is worthy of testing to evaluate its performance in drilling mud. Natural polymers are those derived from organic monomers such as starch, rubber, chitosan, cellulose, proteins, and lignin (Coniwanti et al., 2015). Cellulose is a polysaccharide naturally formed in plants and is the most abundant natural polymer on Earth (Harsojuwono & Arnata 2015). Meanwhile, hemicellulose and lignin are other components found in plants (Rudin & Choi 2012). Lignin serves as a protector for cellulose and hemicellulose, safeguarding them from chemical and physical damage. A low lignin content will enhance water absorption in corn cob fibers, resulting in smaller filtrate volumes (Nmegbu et al., 2020).

The cellulose nanoparticles presen" in 'orn cobs can enhance the rheological properties of drilling mud, including plastic viscosity (PV), yield point, and gel strength. Rheology, along with filtration loss, is ais a critical aspect in determining the success of drilling operations. Evaluation results for using corn cobs as one of the EFDFA show promising outcomes, with reduced filtrate and mud cake compared with mud without corn cobs (Al-Saba et al., 2018).

The composition of corn compounds can be observed through Energy-Dispersive X-Ray Spectroscopy, a spectroscopic method in which X-rays interact with atoms and molecules. The EDX test results show two chemical elements, namely Carbon at 77.91% and Oxygen at 22.08%. The dominant presence of Carbon indicates the potential of corn cobs to be used as a natural polymer material. Natural polymers typically consist of a main chain of carbon elements. The presence of the two dominant elements, Carbon and Oxygen, indicates that the polymer is a polysaccharide composed of Carbon, Oxygen, and hydrogen atoms.

Corn cobs have the same elemental content and chemical composition as natural polysaccharide polymers. Starch, a type of polysaccharide derived from corn, is primarily used to control filtration without causing mud thinning. In drilling operations, polysaccharide additives are used to control viscosity, PV, YP, and gel strength while reducing drilling mud filtration loss. With this approach, corn cobs are expected to behave similarly and have a positive impact, similar to polysaccharide polymer additives such as starch.

In contrast to previous studies that primarily focus on conventional chemical and commercial polymer additives, this study evaluates the use of corncob waste as an eco-friendly natural polymer additive in a water-based mud system in the laboratory. The expected outcome of this study is to evaluate the feasibility and performance of the corncob additive in improving the rheological properties and filtration characteristics of water-based mud under different temperature conditions.

2. Methodology

This research will be conducted by preparing materials, creating drilling mud samples, testing the samples, and drawing conclusions from physical property tests on the drilling mud samples containing corn cobs, the subject of this study. In the initial stage, corn cobs are processed into small pieces. These pieces are then dried in an oven at 75°C for 30 minutes and left to air-dry in the sunlight for 2 days. The dried corn cobs will be finely ground in a food processor and sifted through a mesh to obtain a powder.

After obtaining the powdered corn cob samples, other materials are needed to support this research. These materials include fresh water, caustic Soda, and bentonite. In the research, three drilling mud samples will be prepared with different corn cob compositions, namely 1.5 grams, 3 grams, and 4.5 grams in each sample. Below is Tables 1 through 3, which depicts the composition of the materials used in each sample.

Table 1.
Sample composition 1

Material	S.G	*Weight* (gram)	Volume (ml)	% Vol (350 ml)
Water	1	343	343	97.95
Caustic Soda	2.13	0,10	0.05	0.01
Bentonite	2.60	15	5.80	1.65
Corn Cob	1.10	1.5	1.40	0.39
Total			350	100

Table 2.
Sample composition 2

Material	S.G	*Weight* (gram)	Volume (ml)	% Vol (350 ml)
Water	1	343	343	97.95
Caustic Soda	2.13	0.10	0.05	0.01
Bentonite	2.60	15	5.80	1.65
Corn Cob	1.10	1.5	2.7	0.78
Total			350	100

Table 3.
Sample composition 3

Material	S.G	*Weight* (gram)	Volume (ml)	% Vol (350 ml)
Water	1	343	343	97.95
Caustic Soda	2.13	0.10	0.05	0.01
Bentonite	2.60	15	5.80	1.65
Corn Cob	1.10	4.5	4.1	1.17
Total			350	100

From the three Table 1, Table 2 and Table 3, the samples will be sequentially mixed according to the specified time for each ingredient, approximately 5-10 minutes per component.

In this research, testing will be conducted using two laboratory instruments: the Fann VG Meter and the API Filtration Loss apparatus. The Fann VG Meter will be used for rheology testing of the drilling mud, including plastic viscosity (PV), yield point, and gel strength. The rheology testing will be performed using the Fann VG Meter with dial readings at 300 RPM and 600 RPM. The PV value is calculated by subtracting the dial reading at 300 RPM from that at 600 RPM. For the yield point, the PV value is subtracted from the dial reading at 300 RPM. Gel strength is measured for both 10 seconds (initial gel strength) and 10 minutes (final gel strength), where initial gel strength assumes the first stop of mud circulation, and final gel strength represents mud circulation that has been ongoing for a longer period. To determine the mud's gel strength, the mud is stirred at 600 RPM for 10 seconds/10 minutes. Then, the instrument is turned off, and the mud is left undisturbed for 10 seconds. After 10 seconds, the Fann VG Meter rotor is set to 3 RPM, and the maximum deviation observed is taken as the gel strength value for the tested mud.

Additionally, filtration loss testing is conducted using the API Filter Press apparatus. The gas pressure will generate filtrate and mud cake from the drilling mud. These two parameters are crucial in analyzing the feasibility of the corn cob additive, as a high filtrate volume, along with a thick mud cake, can significantly impact the performance of the drilling mud.

To ensure reproducibility and reliability of the experimental results, each drilling mud sample (corn cob composition: 1.5 g, 3 g, and 4.5 g) will be prepared and tested in triplicate. For every composition, three independent batches will be mixed following the same procedure and time intervals. Rheological properties (plastic viscosity, yield point, and gel strength) and filtration loss parameters (filtrate volume and mud cake thickness) will be measured three times per batch. The mean value and standard deviation for each parameter will be calculated. Data consistency will be assessed by comparing the coefficient of variation (CV) across replicate measurements; a CV of less than 5% will be considered acceptable, indicating good repeatability. Any outlier results (deviating by more than two standard deviations from the mean) will be rechecked and, if necessary, the measurement repeated. This approach strengthens the statistical validity of the conclusions and allows other researchers to reproduce the study with confidence.

After conducting rheology and filtration-loss tests, an analysis will be carried out to compare the results with the mud specifications outlined in the American Petroleum Institute (API) 13A (Drilling Fluid Materials) and other reference studies, which serve as general standards for water-based mud. If the results meet the provided standards, the performance of the corn cob additive in drilling mud can be considered effective. On the contrary, if the values surpass or fall below the specified standards, corn cobs may not be suitable for use as an additive in freshwater-based drilling mud. This testing will then be extended to a higher temperature (200ºF) using the same process. Evaluating the performance of corn cob additives at different temperatures will aid in determining their behavior and suitability with respect to rheological properties and filtration loss in freshwater-based drilling mud.

3. Result and discussion

3.1 Plastic viscosity analysis

Plastic viscosity is the resistance or hindrance to flow caused by mechanical friction in the borehole, resulting from the concentration of solids, the size and shape of solids, and the viscosity of the drilling fluid. Factors influencing plastic viscosity include the concentration, size, and shape of solids, as well as the mud viscosity.

Based on Figure 1, the results of the plastic viscosity testing for the three samples show an increase after the addition of the corn cob additive. At a test temperature of 80°F, the value increased from 21 cp to 23 cp, and at 200°F, it increased from 13 cp to 14 cp. This increase is attributed to the influence of lignin and cellulose content, which enhances water absorption capacity, leading to aggregation in the interlayer of the mud and resulting in a more viscous mud (Ahmed-Haras et al., 2013) Furthermore, the cellulose content in the corn cob interacts with bentonite particles, forming a stronger internal structure that can increase resistance to flow (Assi & Haiawi 2021; Wastu et al., 2026). However, due to the different test temperatures, the results at 200°F decreased, reflecting the sample's expansion and reducing the plastic viscosity despite the initial increase. Even though a decrease occurred, all three mud samples achieved plastic viscosity (PV) values that meet the criteria of secondary data references, falling within the range of 10–25 cp, and complying with the API standard of less than 65 cp for water-based mud.

3.2 Yield point analysis

Yield point is the resistance of the fluid to flow due to the attractive forces between mud particles caused by charges on the particle surfaces dispersed in the fluid phase (Rabia 2002; Rubiandini 2012). The yield point value indicates the dynamic force of the mud to resist and lift drill cuttings to the surface. Yield point can be measured using a Fann VG meter by subtracing the Plastic Viscosity value from the dial reading at 300, yielding a result in unit of lb/100ft^2 (Wastu et al., 2026).

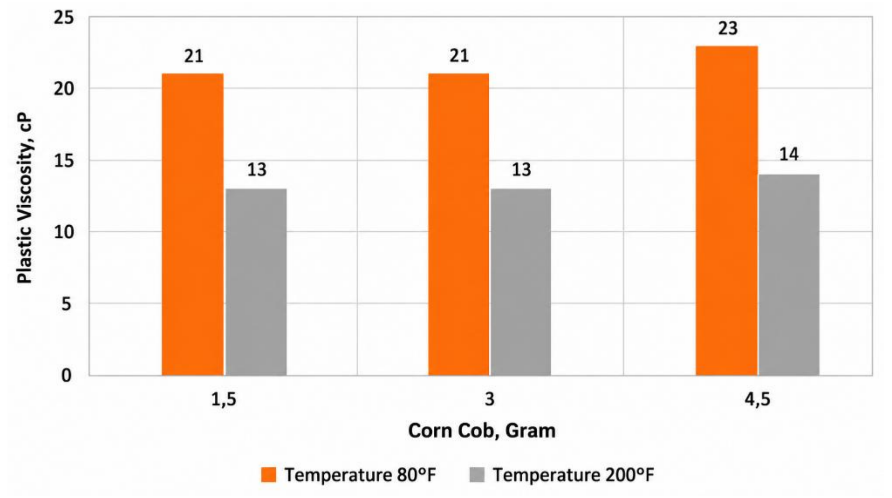

Figure 1.
Effect of Corn Cob concentration on plastic viscosity

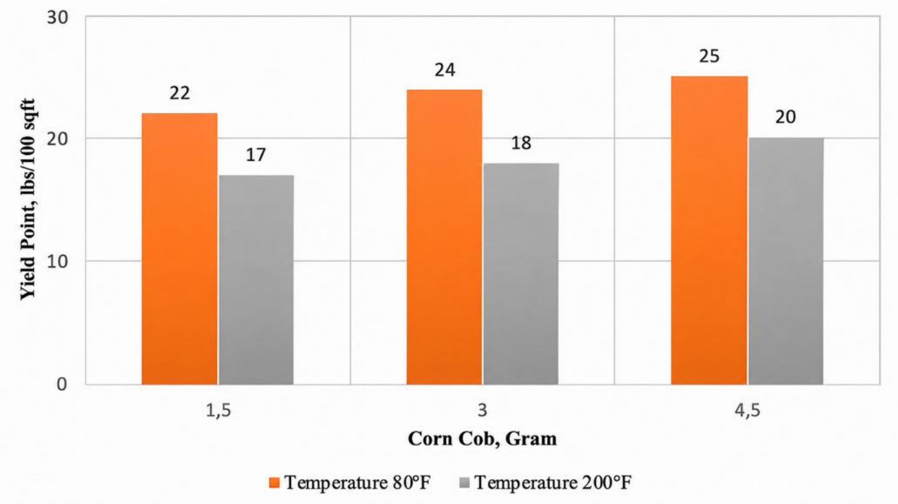

Figure 2.
Effect of Corn Cob concentration on plastic viscosity

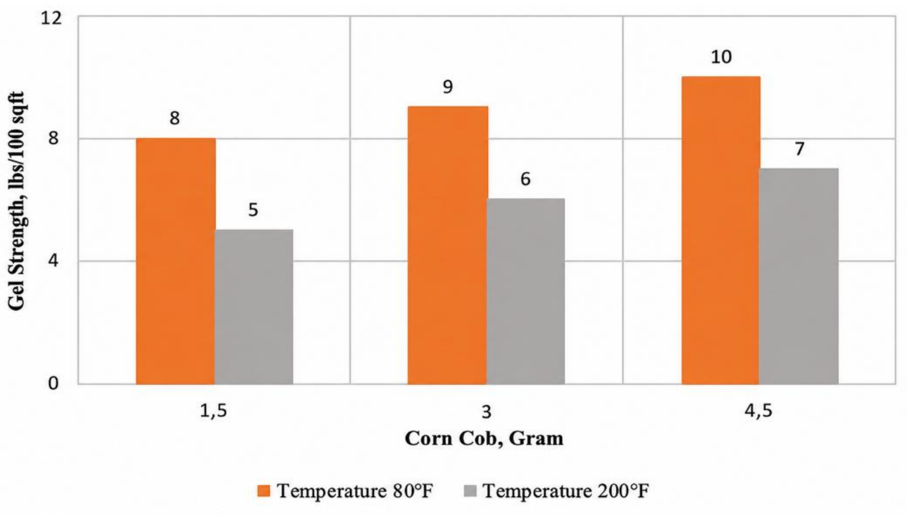

Figure 3.
Effect of Corn Cob concentration on gel strength for 10 seconds

Based on Figure 2, at 80°F, it can be observed that in sample 1 (1.5 grams of corn cob) shows a yield of 22 lbs/100 sq ft. In sample 2, with a concentration of 3 grams of corn cob, there is an increase of 2 lbs/100 sq ft, reaching 24 lbs/100 sq ft. Meanwhile, in sample 3 with a concentration of 4.5 grams of corn cob, there is an increase of 1 lb/100 sq ft from the previous sample, bringing the total to 25 lb/100 sq ft.

The increase in temperature for each sample leads to a decrease in the yield point values, resulting in smaller values than those at 80°F. The yield points at 200°F are as follows: 17 lbs/100 sq ft, 18 lbs/100 sq ft, and 20 lbs/100 sq ft for each additional 1.5 grams of corn cob added in each sample. This increase is caused by the interaction between cellulose and bentonite particles, which forms a stronger internal structure and increases resistance to flow (Assi & Haiawi 2021; Wastu et al., 2026)

The increasing values of the yield point with each addition of corn cob additive, both at 80ºF and 200ºF, demonstrate the ability of corn cob additive to modify the yield point values to higher levels. This is influenced by the cellulose content in corn cobs and its impact on the rheology of water-based mud. The presence of increased contaminants in the mud also affects the higher yield point values of the mud.

Based on the observations in Figure 2, the yield point values of the mud samples with the addition of corn cob meet (ANSI/API Recommended Practice for Field Testing Water-Based Drilling Fluids 2017). A good yield point value, according to the API standards, is not greater than three times the plastic viscosity value. Therefore, all three mud samples comply with the reference standard for YP values.

3.3 Gel strength analysis

Gel strength is the mud's ability to form a gel and hold cuttings when circulation is stopped. This is caused by the attractive forces between particles in the mud system when it is in a static state (Rabia 2002; Rubiandini 2012). Gel strength values need attention, as low gel strength can lead to settling of drill cuttings when circulation stops. Conversely, if the gel strength is too high, the pump may have difficulty restarting circulation (Rabia 2002; Rubiandini 2012).

In Figure 3, the test results for gel strength at 10 seconds for the three mud samples at 80ºF and 200ºF show an increase in gel strength after the addition of 1.5 grams of corn cob additive. The values for the three samples at 80ºF are 8, 9, and 10 lbs/100 sqft, respectively. Meanwhile, at 200ºF, the gel strength values are lower, at 5, 6, and 7 lbs/100 sq ft. The increase in gel strength at two different temperatures demonstrates the corn cob additive's ability in increase attractive forces within the mud in a static state, due to the cellulose content in corn cobs.

At higher temperatures, the effectiveness of natural polymers tends to decrease, as evidenced by lower gel strengths at 200ºF than at 80ºF. The temperature and pressure in the roller oven influence this, causing the settling of solid content in the mud, resulting in in the attractive forces between particles. The graph of the observed 10-minute gel strength values for mud samples with corn cob added at 80ºF and 200ºF is provided below.

Based on the results in Figure 4, at 80ºF, sample one has a gel strength of 15 lbs/100 sq ft, while samples two and three follow with values of 16 and 17 lbs/100 sq ft, respectively. A decrease in gel strength is observed for the mud samples at 200ºF, with sample one at 10 lbs/100 sqft, sample two at 11 lbs/100 sqft, and sample three at 13 lbs/100 sqft.

The increase in mud gel strength upon addition of the additive can be attributed to the cellulose and solids present in the corn cob additive. Gel strength represents the attractive forces between mud particles in a static state or the mud's ability to resist and bind drill cuttings, preventing them from falling into the wellbore. The 10-second gel strength is the value obtained when circulation is first stopped, while the 10-minute value is obtained when circulation has been ongoing for a long time and is then stopped. The gel strength values for mud with a corn cob additive comply with the standard gel strength references: 5–15 lbs/100 sq ft for initial gel strength and 20–30 lbs/100 sq ft for final gel strength.

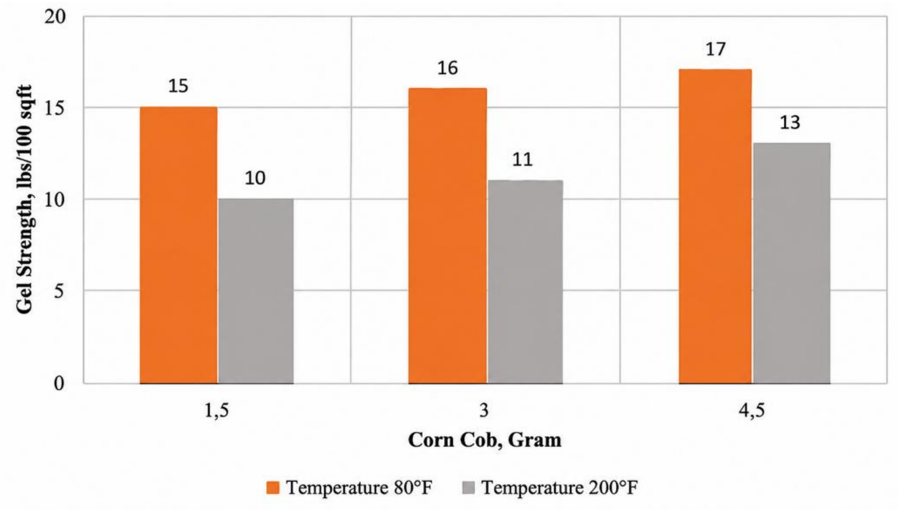

Figure 4.
Effect of Corn Cob concentration on gel strength for 10 minutes

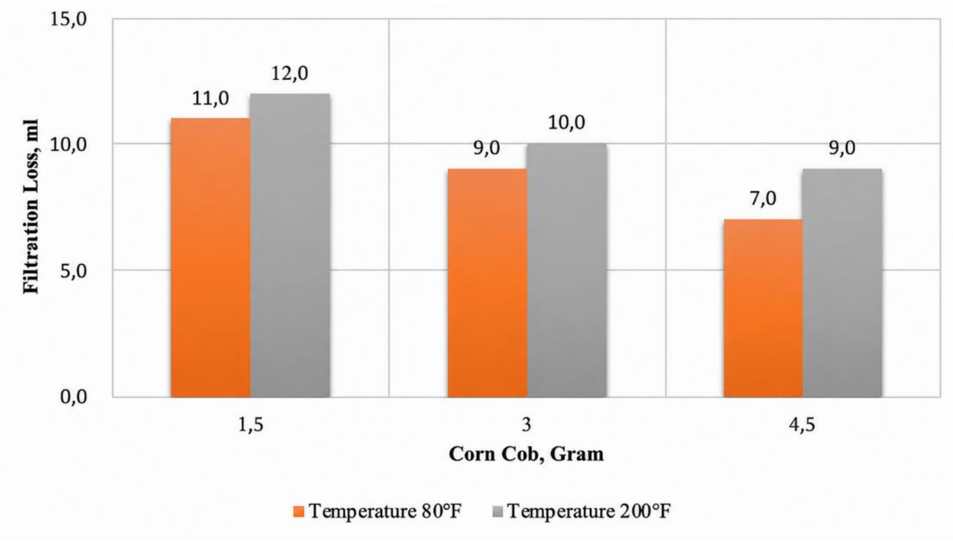

Figure 5.
Effect of Corn Cob concentration on filtration loss

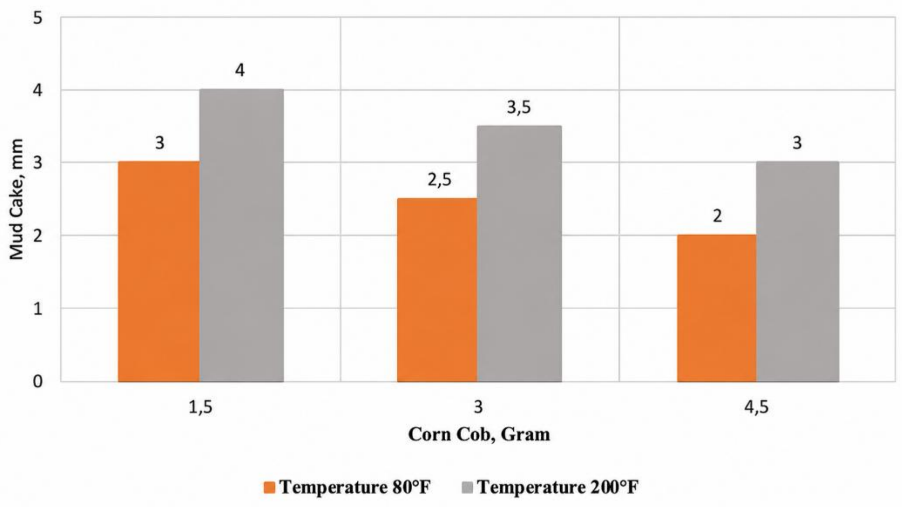

Figure 6.
Effect of Corn Cob concentration on Mud cake

3.4 Filtration and Mud cake analysis

Filtration loss is the fluid that enters permeable rock formations. When mud comes into contact with permeable and porous rock formations, the solid particles in the mud will filter out and adhere to the borehole walls, forming a mud cake (Rabia 2002; Rubiandini 2012). Both of these aspects need to be controlled to avoid issues in drilling operations through to the production stage. The filtrate entering the rock formation should be below the specified filtration loss limit, and the thickness of the mud cake should be thin yet robust. Excessive filtration loss can lead to various problems, including formation damage, water blocking, and errors in logging readings. A thick mud cake can result in a reduction in effective hole diameter and increase the likelihood of a stuck pipe, making it difficult to lift or rotate the pipe (Rabia 2002; Rubiandini 2012).

Based on Figure 5, the results of the filtration loss testing for samples one, two, and three show a decrease in filtration loss values with each addition of corn cob additive at both 80ºF and 200ºF temperatures. At 80ºF, sample one with 1.5 grams of corn cob additive produced 11 ml of filtrate, sample two with 3 grams of additive produced 9 ml of filtrate, and sample three with the highest additive composition of 4.5 grams produced the lowest filtrate volume at 7 ml. Meanwhile, at 200ºF, there is an increase in the volume of filtrate produced by each sample. This is influenced by the temperature and pressure applied to assess the ability of the corn cob additive when circulated into formations at higher pressure and temperature.

The reduction in mud filtrate with each addition of the corn cob additive is due to the cellulose and hemicellulose content, which can reduce filtration loss in the mud. High anionic polymers will reduce filtration rate by plugging the filter cake pores, thereby decreasing its permeability and reducing the rate of filtrate flow into the formation. The more corn cob additive added, the better its hydration ability in the mud fluid system. At 200ºF, there is an increase in the volume of filtrate produced by each sample. This increase is influenced by the temperature and pressure applied to the samples, which assess the ability of the corn cob additive when circulated into the wellbore under high-pressure, high-temperature conditions.

Based on the results in Figure 5 for a temperature of 200ºF, there is a difference, indicating that as the temperature increases, there is an increase in the volume of filtrate produced by mud samples with corn cob additive. Sample one produces 12 ml of filtrate; sample two, 10 ml; and sample three, 9 ml. Although the filtrate values are higher than those at 80ºF, the filtration loss trend with each addition of corn cob remains decreasing, indicating that corn cob is capable of reducing mud filtrate even at higher temperatures. Based on the observation data, the volume of filtrate produced by the three mud samples with the corn cob additive remains below the maximum API 13A specification limit of 15 ml, thus meeting the standard.

As the volume of filtrate entering the rock formation decreases, the thickness of the formed mud cake also decreases. The measurement results for the mud cake from the three mud samples at 80ºF and 200ºF are shown in Figure 6 below.

Based on Figure 6, the mud cake results obtained for each mud sample show a significant decrease with the increasing composition of corn cob additive in the mud samples. The mud cakes produced in samples 1, 2, and 3 at 80ºF have thicknesses that are not too different: 3 mm, 2.5 mm, and 2 mm, respectively. This is due to the addition of a corn cob additive, which contains cellulose that plugs pores and reduces mud cake thickness, resulting in reduced filtrate outflow and thinner mud cake formation. However, due to the temperature increase from 80ºF to 200ºF, the 200ºF mud sample experiences a slight increase, although the trend with each addition of corn cob additive composition still decreases.

The mud cake results obtained at 200ºF are as follows: sample 1 yields 4 mm, sample 2 yields 3.5 mm, and sample 3 yields 3 mm. An increase in temperature can result in a larger filtrate volume, leading to a thicker mud cake. A thin mud cake serves as a good cushion between the drill pipe and the borehole surface, helping prevent the pipe from getting stuck during drilling operations. The maximum allowable thickness for a good mud cake, according to (Ghazali et al., 2015) is 9.525 mm or 3/8 inch. The observation data show that the thickness of the mud cake produced by the mud with corn cob additive meets the criteria for an ideal mud cake.

4. Conclusion

The conclusion obtained from this study is that the addition of corn cob as an additive in water-based mud has a positive effect on the rheological and filtration properties of the mud, although its effectiveness decreases slightly at high temperatures. The values of plastic viscosity (PV), yield point (YP), and gel strength increase with higher dosages of the corn cob additive; however, all decrease when the temperature is raised from 80°F to 200°F. Nevertheless, all mud samples still meet API 13A standards for PV, YP, and gel strength at both room and high temperatures. In terms of filtration, corn cob is proven effective in reducing filtrate volume and mud cake thickness; the higher the corn cob content in the mud, the less filtrate is produced, with a minimum of 7 ml at 4.5 grams added at 80°F. This corn cob, which is rich in cellulose, low-cost, and environmentally friendly, has been shown to improve overall mud performance, making it highly suitable for use as a filtration control additive and for enhancing the rheological properties of water-based mud. The application of corn cob as a drilling mud additive delivers a significant positive impact on the modern drilling industry, particularly regarding occupational health and safety and environmental sustainability. Unlike legacy conventional materials such as asbestos which is highly toxic, carcinogenic, and generates hazardous waste corn cob offers a completely non-toxic, biodegradable organic alternative that is safe for rig personnel to handle. Although asbestos excels under extreme temperatures, corn cob has proven highly effective in meeting API 13A standards under low-to-moderate temperature conditions (up to 200°F), making it a safe, efficient, and sustainable substitute.

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6. Declarations

6.1 Author contribution

A.R.R. Wastu: conceptualization, methodology, investigasi, data curation, formal analysis, software, visualization, writing original draft, writing review & editing. R. Husla: Supervision (co), visualization, methodology, validation, writing review. G. Yasmaniar: Supervision (co), methodology, validation, writing review & editing. A.Nugrahanti: Supervision (co), methodology, validation, writing review & editing. V.C.R Kalalo: Supervision (co), methodology, validation, writing review & editing. R.H.K Oetomo: Supervision (co), methodology, validation, writing review & editing. S. Azizah: Supervision (co), methodology, validation, writing review & editing.

6.2 Funding statement

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

6.3 Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

6.4 The use of AI or AI-assisted technologies

The author(s) used Deepseek Copilot to assist. After using this tool, the authors review and edit the content as needed and take full responsibility for the publication’s content.

7. Glossary of terms and symbols

Terms & Symbols	Definition	Unit
PV	Plastic Viscosity	cps
YP	Yield Point	Lbs/100ft^2

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