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Article

Evaluating eggshells as sustainable weighting agents in water-based drilling muds: A novel approach for enhanced efficiency and environmental consciousness

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Abstract: This study investigates the utilization of eggshells, a renewable material, as a weighting additive in water-based drilling muds with different exploring concentrations. The primary objectives were to assess the impact of eggshells on the rheological properties of drilling muds and to determine the optimal concentration of eggshells for achieving desired density and stability, drawing comparisons with calcium carbonate ($CaCO_3$). Both eggshell powder (ESP) and $CaCO_3$ effectively increase mud weight to the target density of 8.75 ppg at 30 g. Notably, ESP exhibits favorable rheological properties at 20 g, maintaining low plastic viscosity 2.7, consistent yield points 1.1, and gel strength comparable to $CaCO_3$. Conversely, $CaCO_3$ shows signs of potential deterioration at 30 g indicated by increased viscosity to 3.5 and decreased yield point to 0.5. ESP demonstrates superior filtration performance, displaying a progressive increase in cake thickness with increasing weight 1.32 mm to 3.12 mm compared to the slower cake build-up of $CaCO_3$ 0.92 mm to 2.9 mm. Both additives slightly elevate mud pH, potentially enhancing overall stability.

Keywords: eggshell powder; calcium carbonate; drilling fluids; water-based mud; environmental sustainability; biodegradable materials

1. Introduction

It is essential to monitor the rheological parameters of the drilling fluid in the well. The data allows for precise estimation of frictional loss. Drilling fluid undergoes considerablechanges in its properties as it moves through the well and is subjected to varying conditions (such as temperature, pressure, time, etc.). This makes monitoring and controlling its rheological qualities more challenging [1]. Precisely determining the rheology to the last detail calls for a comprehensive knowledge of the drilling fluid, including the effect of relevant microstructure mechanisms on flow parameters [2].

Fluid loss must be effectively controlled in order for drilling operations to be efficient and safe, as uncontrolled fluid loss can cause formation damage when mud filtrate invades the exposed rock [3]. This infiltration not only affects productivity, but it also raises operating expenses owing to corrective efforts. Fluid loss has long been a major issue in the oil and gas sector, hurting production rates and operating efficiency. Despite developments, fluid loss management is crucial to improving drilling performance and maintaining well integrity [4].

Weighting additives are important for drilling fluids used in the oil and gas industry, especially water-based mud (WBM). These additives make the drilling fluid denser so that the pressure in the wellbore stays steady. Weighting additives keep formation fluids from getting into the well and prevents blowouts. Most of the time, barite and $CaCO_3$ are used as bearing additives [5]. However, as people become more aware of environmental issues [6], they seek other better environmental additives [7]. Drilling fluid is acomplex mixture that relies heavily on additives. Additives can be added to the drilling fluid depending on the intended performance and the challenges encountered. The drilling operation should go smoothly, and the additives should aid with that [8].

Eggshells are primarily composed of calcium carbonate ($CaCO_3$), which constitutes about 94%–97% of their dry weight. Calcium carbonate is a naturally occurring compound also found in minerals such as limestone, marble, and chalk. In addition to $CaCO_3$, eggshells contain small amounts of other minerals like magnesium carbonate (0.3%–0.6%) and calcium phosphate (0.5%–1.0%), as well as organic matter, including proteins and other organic compounds, which make up 2%–4% of the total composition [9]. The analysis of eggshell powder (ESP) further confirms that its primary component is the thermodynamically stable calcite phase of $CaCO_3$. This calcite structure contributes to the significant hardness of the eggshell, and the characteristic peaks observed align well with $CaCO_3$, confirming its rhombohedral structure. The findings indicate that $CaCO_3$ concentrations in eggshells exceed 90%, consistent with previous studies [10]. These properties make eggshells a viable alternative as a sustainable weighting agent in drilling muds, providing both environmental and functional benefits through their high $CaCO_3$ content and structural stability.

A hyperbolic fluid loss model for HPHT conditions was developed to improve fluid loss predictions, which is relevant for controlling fluid loss in eggshell-based muds [11]. Studies on salt contamination and temperature effects [12] and filter cake formation [13] offer insights into the performance of eco-friendly additives like eggshells. Further research highlighted the impact of contaminants on mud properties, emphasizing the need for stable additives [14]. A kinetic model for filter cake formation in HPHT environments would also be useful for assessing eggshell-based muds [15].

The objective of this study is to investigate the potential use of eggshells and naturally occurring weighting additives in water-based drilling muds, evaluate their effects on the rheological properties compared to traditional weighting agents such as $CaCO_3$, and determine the optimal concentration of eggshells required to achieve the desired density and stability, while benchmarking these results against those obtained with $CaCO_3$.

The paper is organized as follows: Section 2 describes how eggshells and $CaCO_3$ were used to examine essential rheological parameters such as viscosity, gel strength, filtration, and pH, following API guidelines; In Section 3, eggshells and $CaCO_3$ are compared for their ability to increase mud weight, stabilize plastic viscosity, maintain yield point, optimize mud cake thickness, and pH levels; Section 4 highlights the important findings, stressing eggshells' better performance in terms of stable rheological characteristics and increased filtering efficiency and defines the ideal concentration for field applications.

2. Experimental

Following API standards for water-based drilling mud API RP 13B-1, eggshells and $CaCO_3$ are separately incorporated into the base mud at concentrations of 10 g, 20 g, and 30 g based on the literature [16]. Each material is blended for 10 mins to ensure homogeneity. The research systematically investigates the influence of these additives on the rheological properties of the drilling mud such as the viscosity test measures how easily mud flows at different shear rates, which helps determine the mud's resistance to flow. Gelstrength tests measure a mud's ability to prevent cuttings from settling when circulation stops. API filtrate test measures the amount of fluid that escapes from the drilling mud under pressure within a specific time frame. pH test determines the acidity or alkalinity of mudusing a pH meter or pH indicator to measure the concentration of hydrogen ions. All experimental procedures for mud testing were conducted in accordance with established methodologies outlined in the literature [16]. **Table 1** shows the formulation of base mud used in this study.

Table 1. Formulation of base mud.

Additive	Description/Function	Quantity	Mixing Time
Deionized water	Base liquid	350 mL	-
Bentonite	Clay for viscosity/APIfiltrate control	14 g	10 min
Eggshells powder (ESP)	Weighting material	10 g, 20 g and 30 g	10 min
Calcium Carbonate ($CaCO_3$)	Weighting material	10 g, 20 g and 30 g	10 min

3. Results

This section presents the results of the experimental evaluation of ESP and $CaCO_3$ as weighting agents in water-based drilling muds. The results are discussed in terms of key parameters such as density, plastic viscosity, yield point, gel strength, mud cake thickness, and pH.

3.1. Density measurement

Both ESP and $CaCO_3$ successfully increased the mud weight, achieving the target density of 8.75 ppg at 30 g (**Figure 1**). At lower concentrations (10 g and 20 g), the densities for both additives were comparable, with a slight increase at 20 g,where ESP and $CaCO_3$ both reached 8.72 ppg. These results suggest that both additives are equally effective in increasing the mud density. However, considering all factors, 20 g of ESP appears to be the optimal concentration, providing a balance between effective density and desirable rheological properties.

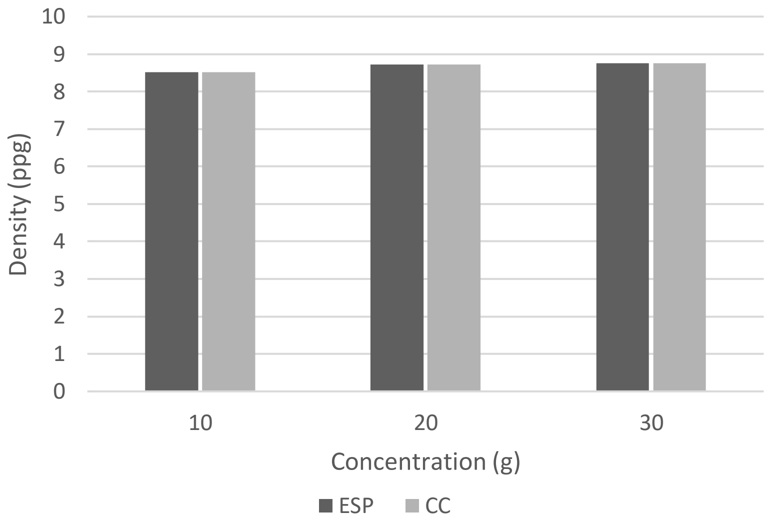

Figure 1. Results of density for both ESP and $CaCO_3$.

3.2. Plastic viscosity (PV)

Plastic viscosity is a key indicator of the flow characteristics of drilling mud. By using Fann viscometer both ESP and $CaCO_3$ measured at room temperature showed a decrease in plastic viscosity at 20 g compared to 10 g, suggesting improved flowability at intermediate concentrations (**Figure 2**).

At 30 g, ESP remained stableat a PV of 3, while $CaCO_3$ increased to 3.5, indicating potential deteriorating flow behavior in$CaCO_3$-based mud. This suggests that ESP maintains more stable rheological properties at higher concentrations, making it more suitable for scenarios where high mud weights are required without compromising flow.

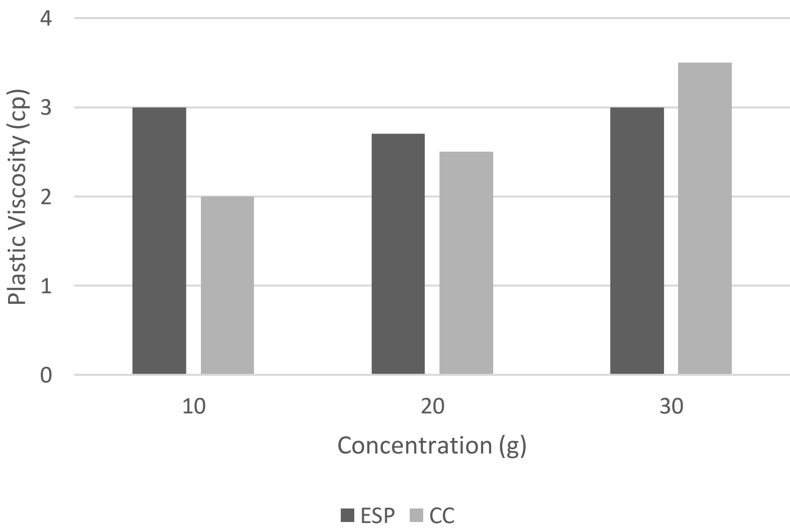

Figure 2. Plastic viscosity results for ESP and $CaCO_3$.

3.3. Point (YP)

Yield point reflects the ability of the mud to suspend solids under static conditions. By using Fann viscometer at room temperature. ESP exhibited consistent yield point values across all concentrations, maintaining a stable YP of 1 at 30 g (**Figure 3**). In contrast, $CaCO_3$ demonstrated a drop in YP at 30 g, falling from 1.5 at 20 g to 0.5 at 30 g, indicating potential challenges in maintaining wellbore stability and suspension capacity at higher concentrations. This highlights ESP's superior performance in maintaining wellbore stability.

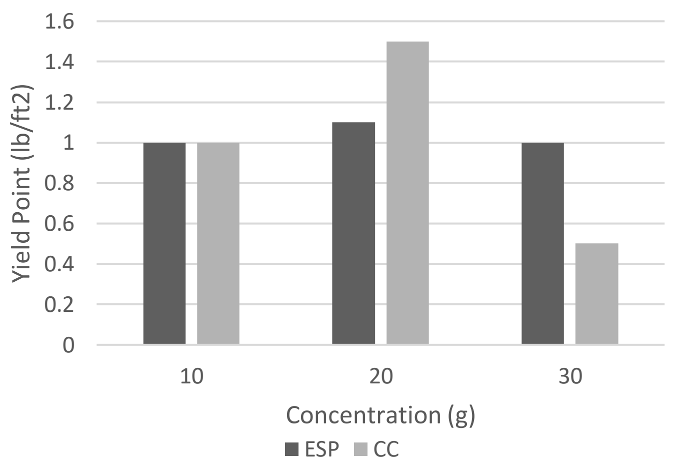

Figure 3. Yield point values for ESP and $CaCO_3$.

3.4. Gel strength (10 s and 10 min)

Gel strength measurements at 10 s and 10 min are critical for understanding the gelation behavior of drilling fluids. ESP demonstrated consistent gel strength at 2 for 10 s across all concentrations (**Figure 4**). $CaCO_3$, however, showed variability, with the 10-s gel strength increasing to 2 at 30 g. For 10-min gel strength, ESP maintained relatively stable values across concentrations, while $CaCO_3$ exhibited a more variable response, with a peak of 3 at 30 g (**Figure 5**). These results suggest that ESP provides more predictable and consistent gelation behavior, which is advantageous for maintaining wellbore stability during static conditions.

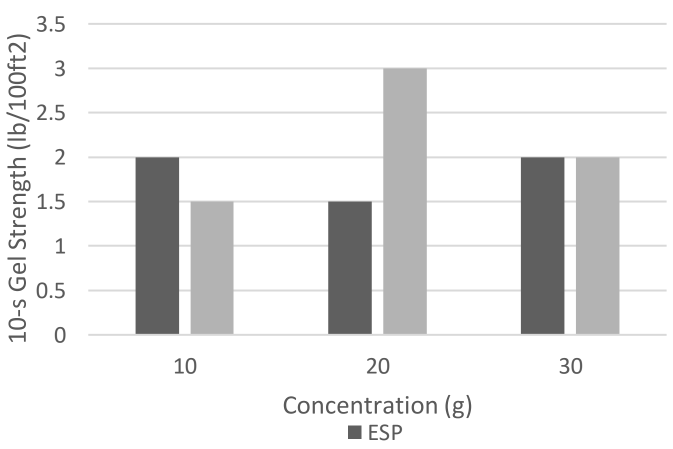

Figure 4. 10-s gel strength for ESP and $CaCO_3$.

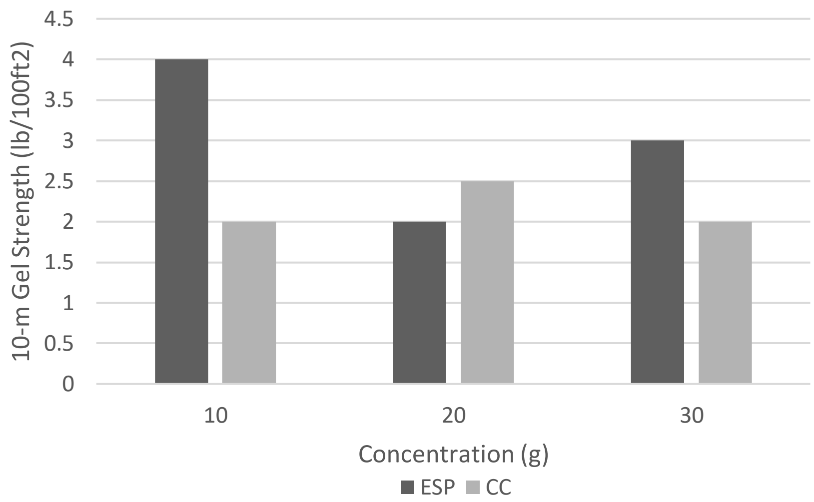

Figure 5. 10-min gel strength for ESP and $CaCO_3$.

3.5. Mud cake thickness

Mud cake thickness is an important factor in determining filtration efficiency. As shown in **Figure 6**, the mud cake thickness of ESP increased progressively with concentration, reaching 3.12 mm at 30 g. In comparison, $CaCO_3$ formed a thinner cake at 2.9 mm at 30 g. The rapid cake buildup of ESP suggests higher filtration efficiency, which could reduce fluid loss and enhance wellbore stability. The pronounced increase in ESP's mud cake thickness at higher concentrations highlights its superior filtration performance compared to $CaCO_3$.

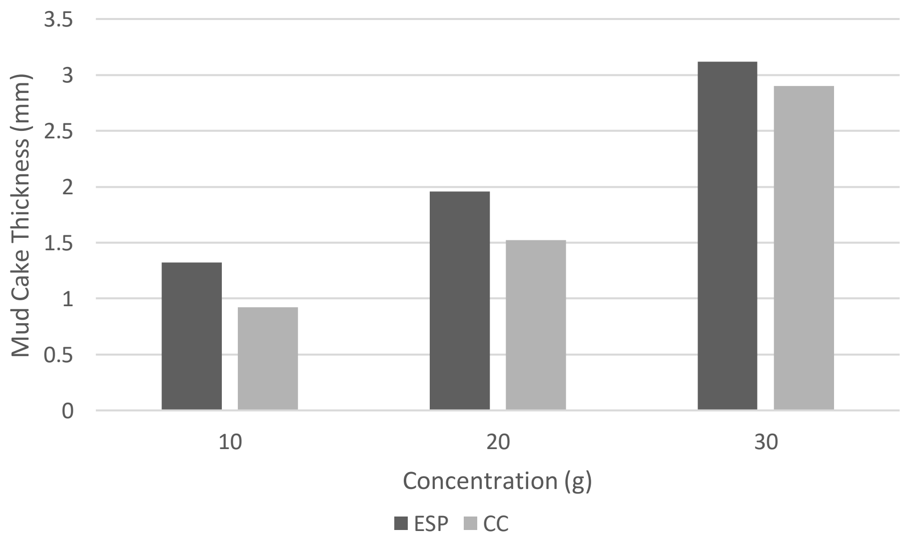

Figure 6. Mud cake thickness for ESP and $CaCO_3$.

3.6. PH

Both ESP and $CaCO_3$ slightly increased the pH of the drilling fluid, with pH rising from 9.0 to 9.6 for ESP and from 8.95 to 9.68 for $CaCO_3$ (**Figure 7**). The increase in pH contributes to enhanced drilling fluid stability by hindering the precipitation of certain compounds. At 20 g, ESP provides a moderate pH increase

(9.2), which strikes a balance between effective mud cake thickness and chemical stability, making it an optimal choice for operations requiring balanced mud performance.

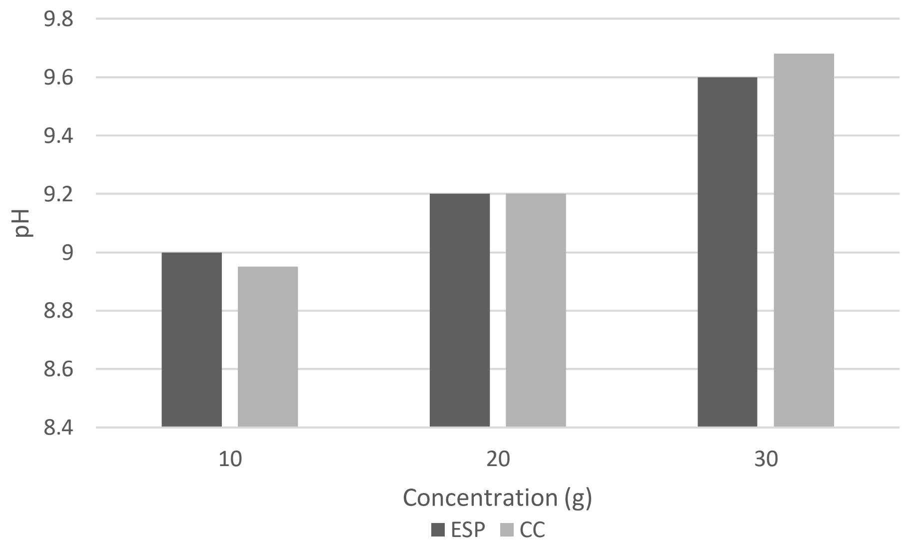

Figure 7. PH values for ESP and $CaCO_3$.

4. Discussion: Environmental impact and sustainability of eggshell powder in drilling fluids

The use of eggshell powder as a weighting agent in water-based drilling muds has a considerable environmental benefit due to its biodegradability and lower environmental effect when compared to synthetic additives commonly utilized in the oil and gas sector. As enterprises move toward more sustainable practices, the necessity for environmentally friendly materials in drilling operations has grown crucial. The oil and gas sector consumes plentiful resources like calcium carbonate, which requires large energy consumption and CO_2 emissions for extraction and processing. In contrast, ESP, a byproduct of the food industry, offers a renewable and low-carbon alternative that reduces waste and promotes the circular economy.

Research has demonstrated that integrating biodegradable compounds into drilling fluids can greatly minimize environmental concerns. Previous research [7] has proven the stability of synthetic-based mud using renewable resources, highlighting the potential of natural materials in sustainable drilling fluid systems. Similarly, another study [16] investigated the use of nano-sized tapioca starch as a natural polymer for filtration control in WBM, emphasizing the trend of replacing synthetic additives with biodegradable alternatives in drilling operations. Additional research [17] shown that adding eco-friendly additives such peanut shells in drilling fluids reduced fluid loss while simultaneously minimizing environmental impact during disposal. Similarly, research [18] demonstrated the possibility for biodegradable drilling fluid additives to boost performance while lowering environmental impact. These findings lend credence to the concept that ESP, as a biodegradable substance, helps to reduce environmental impact, particularly in drilling fluid disposal.

Our analysis confirms that ESP and $CaCO_3$ have comparable rheological characteristics, density, and mud cake thickness. However, the important differential is ESP's biodegradability, which provides a significant benefit in reducing the environmental effect of drilling operations. Furthermore, the presence of hazardous additives and chemicals makes it difficult to dispose of old drilling fluids, particularly in environmentally sensitive locations. Using a biodegradable and renewable substance such as ESP reduces the possibility of soil and water pollution, which aligns with regulatory initiatives to prevent environmental deterioration. This is especially significant in offshore drilling, where rigorous environmental rules require the use of materials that do little harm to marine ecosystems. The use of ESP in drilling muds not only addresses regulatory issues, but it also helps to reduce the total carbon footprint of drilling operations.

This study's findings are consistent with the overall drive in the oil and gas business toward more sustainable operations that focus on waste reduction and carbon emissions. As observed in earlier research [19], the change to eco-friendly drilling fluids is gaining pace, driven by the requirement for both performance and environmental responsibility. The use of ESP as a weighing agent, together with its good performance in raising mud density and maintaining rheological characteristics, demonstrates its feasibility as a long-term alternative to conventional materials.

To summarize, ESP not only equals the performance of traditional weighing materials, but also provides considerable environmental advantages. Its biodegradability and minimal environmental effect make it a very appealing alternative for drilling operations in the face of tightening environmental restrictions and industry-wide attempts to adopt greener technology.

5. Conclusion

ESP demonstrated comparable or superior performance to $CaCO_3$ across several key drilling fluid parameters. It maintained stable plastic viscosity and yield point values, particularly at higher concentrations, resulting in improved flow characteristics and enhanced wellbore stability. Additionally, ESP exhibited superior filtration efficiency, with more effective mud cake formation. At 20 g, ESP provided an optimal balance between density, plastic viscosity, yield point, and filtration performance, making it a viable and environmentally sustainable alternative for field applications in drilling operations. These findings highlight ESP's potential as a renewable, eco-friendly weighting agent for water-based drilling muds, supporting the industry's shift toward sustainable practices.

Author contributions: Conceptualization, AE and MZ; methodology, AE; software, AE; validation, AE and MZ; formal analysis, MZ; investigation, AE; resources, AE; data curation, AE; writing—original draft preparation, AE; writing—review and editing, MZ; visualization, AE; supervision, MZ; project administration, AE; funding acquisition, MZ. All authors have read and agreed to the published version of the manuscript.

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