

## Sustainable Replacement of Commercial Calcium Carbonate (CaCO<sub>3</sub>) with Waste Eggshell Powder in Geothermal Drilling Fluids

Muhammad Abdullah<sup>1</sup>, Ch. Ali Hamza<sup>2</sup>, Elvin Allahverdiyev<sup>1</sup>, Khizar Abid<sup>1</sup>, Mian Umer Shafiq<sup>3</sup>, Baharak Sajjadi<sup>1</sup> and Catalin Teodoriu<sup>1</sup>

<sup>1</sup>University of Oklahoma, Norman, OK, USA

<sup>2</sup>Vizdom Solutions Pvt. Ltd.

<sup>3</sup>Nazarbayev University, Astana, Kazakhstan

[cteodoriu@ou.edu](mailto:cteodoriu@ou.edu)

**Keywords:** eggshell, calcium carbonate, water-based drilling mud, geothermal, high-temperature wells

### ABSTRACT

Drilling mud is a critical component in geothermal well planning, where environmental sustainability and economic feasibility are key considerations. Conventional additives often come with significant costs and environmental impacts. The commercial calcium carbonate (CaCO<sub>3</sub>) is an established weighting/fluid-loss control agent added to the water-based mud (WBM), valued for its thermal stability (maintaining structure and rheological behavior up to 120 °C in HPHT tests), compatibility with barite/bentonite/xanthan systems, and its ability to form thin, low-permeability filter cakes that reduce fluid invasion. As waste eggshells are composed of ~70-95% CaCO<sub>3</sub> (mostly calcite form) and are an abundant agro-industrial waste, this study analyzes and defends the use of waste eggshells (finely ground, <125 µm) as a low-cost, sustainable alternative to commercial CaCO<sub>3</sub> in geothermal drilling fluid systems.

As part of the methodology, the WBM samples were prepared using standard additives (barite, bentonite, xanthan gum). Eggshell powder and, for comparison, commercial CaCO<sub>3</sub> were added to the base mud at increasing concentrations (10 g, 20 g, 30 g, and 40 g). Laboratory tests measured mud density, plastic viscosity (PV), yield point (YP), gel strength, pH, resistivity, and filtration characteristics (filtrate volume and filter cake thickness).

Results demonstrate that eggshell powder performs comparably to commercial CaCO<sub>3</sub>, showing a near-linear increase in mud density and PV correlating with concentration. Eggshell powder effectively enhanced mud stability by promoting optimal (10 min) gel strength and reducing filtrate volume through rapid formation of thin, low-permeability mud cake, matching or exceeding the filtration control achieved by commercial CaCO<sub>3</sub> at equivalent quantities. At intermediate concentrations (20 g), YP and filter cake thickness were optimal, while higher concentrations showed a marginal decrease in YP and filter cake thickness. The pH and resistivity profiles confirmed chemical compatibility and stability within the drilling fluid system.

Considering CaCO<sub>3</sub>'s established thermal stability (up to 120 °C in CaCO<sub>3</sub> under HPHT conditions), the similar performance of eggshell powder suggests promising behavior under geothermal conditions. Given its cost advantage and environmental benefits, waste eggshell powder is validated as a viable additive for WBM in geothermal drilling. Its use delivers equivalent fluid-loss control, rheological stability, and mud density performance, while significantly reducing environmental footprint, supporting the UN Sustainable Development Goals.

### 1. INTRODUCTION

Geothermal energy development relies on efficient, reliable, and environmentally responsible drilling operations. Among all drilling systems, drilling fluid (Ben Mahmud et al.) plays a critical role in maintaining wellbore stability, transporting cuttings, controlling formation pressures, providing lubrication, and minimizing formation damage (Kelany et al. 2025). In geothermal wells, often characterized by elevated temperatures, extended circulation intervals, and environmentally sensitive locations, the selection of drilling fluid additives must balance technical performance, economic viability, and environmental sustainability (Nascimento et al. 2025, Kruszewski and Wittig 2018).

WBMs are the dominant drilling fluid system in geothermal drilling due to their low toxicity, regulatory acceptance, ease of disposal, and operational flexibility (Collins et al. 2024). Conventional WBM formulations commonly employ barite and commercial CaCO<sub>3</sub> to achieve the desired mud density and fluid-loss control (Collins et al. 2024, White et al. 2003). In particular, CaCO<sub>3</sub> is widely used as a weighting agent, formation-bridging material, and filtration control additive because of its chemical inertness, acid solubility, and compatibility with bentonite-polymer systems (Zima et al. 2025). CaCO<sub>3</sub>-based drilling fluids have demonstrated stable rheological behavior and effective filtration control under high-pressure, high-temperature (HPHT) conditions up to approximately 120 °C, making them suitable for low- to medium-enthalpy geothermal wells (Vivas and Salehi 2021, Shokry et al. 2024, Basfar and Elkhatny 2023).

The effectiveness of carbonate-based materials in drilling fluid design is well established. Fine and micro-sized CaCO<sub>3</sub> particles have been shown to significantly reduce API fluid loss and filter cake thickness by enhancing pore-bridging efficiency and

improving particle packing within the mud cake, often without adversely affecting mud density or pH (Shokry et al. 2024, Basfar and Elkatatny 2023). Carbonate species are also known to influence drilling fluid rheology by increasing YP and gel strength through enhanced electrochemical interactions among clay particles, while PV is typically only moderately affected due to the insoluble nature of carbonates (Basfar and Elkatatny 2023, Shokry et al. 2024). Other carbonate compounds, such as sodium carbonate and potassium carbonate, have been investigated as drilling fluid modifiers, demonstrating effective pH control and rheological tuning (Rasool et al. 2022, Onyekpe 2001, Nzerem et al. 2020, Zamir et al. 2021, Ben Mahmud et al. 2020). More recent studies involving potassium carbonate based deep eutectic solvents have reported improved rheological stability and filtration performance under elevated temperature conditions (Rasool et al. 2022); however, such chemically engineered systems introduce additional cost and processing complexity.

In parallel with advances in drilling fluid technology, increasing emphasis on sustainable energy development has driven interest in applying circular economy principles to geothermal drilling operations. This includes the utilization of waste materials as functional drilling fluid additives to reduce reliance on mined minerals and lower environmental footprint. Eggshell waste is an abundant agro-industrial by-product generated globally in large quantities. Eggshells consist predominantly of calcium carbonate (98.4%), primarily in the calcite form, with minor organic constituents (Gautron et al. 2021). This mineralogical similarity to commercial  $\text{CaCO}_3$ , combined with low toxicity, wide availability, and negligible cost, makes eggshell waste an attractive candidate for sustainable drilling fluid applications.

Several studies have explored the use of eggshell powder in water-based drilling fluids. Experimental results indicate that eggshell powder can increase mud density, enhance YP and gel strength, and reduce fluid loss by promoting the formation of thin, less permeable filter cakes (Onolemhemhen et al. 2019, Al-Hameedi et al. 2020, Iqbal et al. 2019). In many cases, eggshell powder exhibited minimal impact on mud pH, indicating good chemical compatibility with bentonite-based systems (Iqbal et al. 2019). Despite these encouraging findings, important gaps remain. Most existing studies focus on oil and gas drilling rather than geothermal applications, lack direct side-by-side comparison with commercial  $\text{CaCO}_3$  under identical conditions, or emphasize isolated properties such as pH or density rather than integrated rheological and filtration performance. Furthermore, the applicability of eggshell-derived  $\text{CaCO}_3$  to geothermal drilling, where prolonged static periods, thermal stability, and environmental stewardship are critical, has not been systematically evaluated using standardized testing protocols.

In this study, waste eggshell powder is evaluated as a sustainable replacement for commercial  $\text{CaCO}_3$  in geothermal water-based drilling fluid systems. Finely ground eggshell powder ( $<125 \mu\text{m}$ ) is directly compared with commercial  $\text{CaCO}_3$  using standardized American Petroleum Institute (API) RP 13B-1 laboratory procedures. The evaluation focuses on mud density, rheological properties, gel strength development, chemical stability (Collins et al.), electrical resistivity, and filtration behavior, including filtrate volume and filter cake thickness. By providing a controlled, side-by-side assessment, this work demonstrates the technical feasibility of eggshell-derived  $\text{CaCO}_3$  for geothermal drilling while highlighting its economic and environmental advantages. The results support the integration of waste-derived materials into geothermal drilling fluid design and contribute to sustainable resource utilization in alignment with the UN Sustainable Development Goals.

## 2. METHODOLOGY

### 2.1 Experimental framework and standards

All experiments were conducted following the American Petroleum Institute (API) recommended practice 13B-1 for laboratory testing of water-based drilling fluids. The objective was to evaluate waste eggshell as a sustainable replacement for commercial  $\text{CaCO}_3$  in geothermal WBM systems. The study focuses on rheological stability, filtration control, and chemical compatibility. Key performance parameters for geothermal drilling environments characterized by elevated temperatures, long circulation intervals, and environmental sensitivity.

All tests were performed at ambient laboratory conditions. Although HPHT testing was beyond the scope of this work, interpretation is supported by the well-established thermal stability of  $\text{CaCO}_3$ -based systems up to  $\sim 120 \text{ }^\circ\text{C}$  (Basfar and Elkatatny 2023, Shokry et al. 2024, Vivas and Salehi 2021), representative of low- to medium-enthalpy geothermal wells. The comparative methodology provides a reliable baseline for assessing eggshell powder performance in geothermal WBM applications. The approach supports future HPHT validation while demonstrating immediate sustainability and cost advantages. The use of standardized API testing procedures ensures reproducibility and relevance to field-scale drilling operations. All experiments were conducted in triplicate, and average values are reported.

### 2.2 Materials

The WBM system consisted of water, barite (weighting agent), bentonite (viscosifier and filtration control agent), and xanthan gum (suspension and shear-thinning polymer). Commercial  $\text{CaCO}_3$  was used as a reference additive, while waste eggshell powder served as the test material.

Waste hen eggshells were collected from local food outlets, reflecting an abundant agro-industrial waste stream with potential for sustainable geothermal operations.

### 2.3 Preparation of Eggshell Powder

Eggshells were cleaned using hot water immersion to remove organic matter and shell membranes, rinsed with tap water, and sun-dried for 48 hours. The dried shells were crushed and ground using a Fritsch Mortar Grinder Pulverisette 2. The resulting powder was sieved, and only particles with a size  $\leq 125 \mu\text{m}$  were retained. This size range was selected to ensure comparability with fine commercial  $\text{CaCO}_3$  grades commonly used for fluid-loss control and bridging in drilling fluids.

### 2.4 Drilling Fluid Formulation

All mud samples were prepared using 350 ml of water.

The base mud formulation comprised:

- 38.4 g barite (target density  $\approx 9$  ppg),
- 15 g bentonite (target PV  $\approx 7$  cP),
- 1.05 g xanthan gum (0.3% by volume of water).

Additives were weighed using an electronic analytical balance.

To assess additive performance, both commercial  $\text{CaCO}_3$  and eggshell powder were added separately to the base mud at concentrations of 10 g, 20 g, 30 g, and 40 g, resulting in one base mud and four modified samples for each additive.

### 2.5 Mixing Procedure

Mud samples were prepared using a Hamilton Beach Mud Mixer (Model HMD-200). Water was added to the mixing cup, followed by the sequential addition of additives while mixing. Each sample was mixed for 5 minutes at medium speed and 2 minutes at high speed, consistent with API RP 13B-1, to ensure uniform dispersion and hydration.

### 2.6 Density Measurement

Mud density was measured using a Fann Mud Balance (Model 140). The mud cup was filled completely to remove entrapped air, and the beam was leveled using the sliding rider. Density was recorded in pounds per gallon (ppg). Measurements were repeated three times and averaged. The mud balance was calibrated with fresh water before testing.

### 2.7 Rheological Measurements

Rheological properties were determined using a Fann Model 35SA rotational viscometer in accordance with API RP 13B-1. Dial readings were recorded at 3, 6, 100, 200, 300, and 600 rpm. PV and YP were calculated using Eqs. (1) and (2), respectively:

$$PV = \theta_{600} - \theta_{300} \quad (1)$$

$$YP = \theta_{300} - P.V \quad (2)$$

### Gel Strength

Gel strengths were measured after shearing the mud at 600 rpm for 10 seconds. The mud was allowed to remain static for 10 seconds and 10 minutes, after which the maximum dial deflection at 3 rpm was recorded in lb/100 ft<sup>2</sup>. These measurements are particularly relevant for geothermal wells, where circulation interruptions and effective cuttings suspension are critical.

### 2.8 pH and Electrical Resistivity

Mud pH was measured using a calibrated digital pH meter equipped with a temperature probe after allowing readings to stabilize. Electrical resistivity was measured using a digital resistivity meter with a lucite cell, ensuring no air entrapment. Both pH and resistivity measurements provide insight into chemical stability, ionic content, and additive compatibility under geothermal drilling conditions.

### 2.9 Filtration Properties

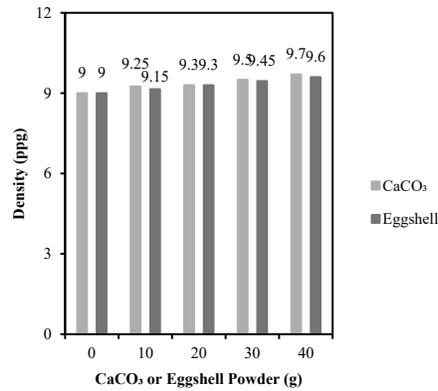
Filtration characteristics were evaluated using a Standard API LPLT filter press at 100 psi for 30 minutes, following API RP 13B-1.

A filter paper was placed at the base of the cell, and 350 ml of the mud sample was tested. Filtrate volume was recorded at one-minute intervals. After testing, the filter cake was carefully removed and its thickness measured. Filtration control and thin, low-permeability filter cake formation are essential to minimize fluid invasion and formation damage in geothermal reservoirs.

### 3. RESULTS and DISCUSSIONS

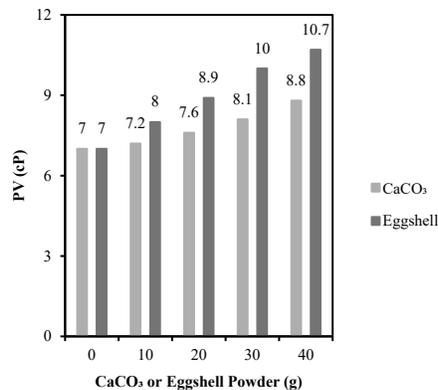
#### 3.1 Density and Rheology

The addition of both commercial  $\text{CaCO}_3$  and waste eggshell powder produced a predictable and near-linear increase in mud density with increasing additive concentration (Fig. 1). Commercial  $\text{CaCO}_3$  increased the mud density from 9.0 to 9.7 ppg, while eggshell powder increased density from 9.0 to 9.6 ppg at the highest loading (40 g). This comparable density response is attributed to the similar true densities and mineralogical composition of both materials (Kalaycı et al. 2025), as eggshell powder consists predominantly of calcite  $\text{CaCO}_3$  ( $\rho = 2.71 \text{ g/cm}^3$ ). Mud density in water-based drilling fluids is governed primarily by solid loading and particle density rather than particle origin; therefore, the slight difference observed at higher eggshell concentrations may be attributed to residual organic matter and marginally higher porosity inherent to naturally derived eggshell particles.



**Figure 1: Effect of varying quantities of commercial  $\text{CaCO}_3$  and eggshell powder on WBM density.**

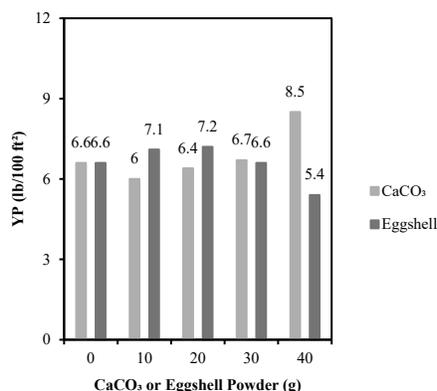
Plastic viscosity (PV) increased with increasing concentration for both additives (Fig. 2), reflecting the expected effect of increased solids content on flow resistance. Commercial  $\text{CaCO}_3$  increased PV from 7.0 to 8.8 cP, whereas eggshell powder resulted in a higher increase from 7.0 to 10.7 cP at 40 g loading. The relatively higher PV observed in eggshell-modified fluids is attributed to differences in particle morphology and surface characteristics. Unlike commercial  $\text{CaCO}_3$ , which is typically ground or precipitated to produce relatively smooth and uniform particles, eggshell powder consists of irregular, angular particles with rougher surfaces. These characteristics increase interparticle friction and hydrodynamic drag, thereby increasing the effective solid volume fraction and resistance to flow. Despite this increase, all PV values remained within acceptable operational limits for geothermal drilling, indicating that eggshell powder does not introduce excessive hydraulic penalties.



**Figure 2: Effect of varying quantities of commercial  $\text{CaCO}_3$  and eggshell powder on WBM PV.**

Yield point (YP) exhibited distinct trends for the two additives (Fig. 3). Commercial  $\text{CaCO}_3$  produced a gradual, monotonic increase in YP with increasing concentration, reaching 8.5 lb/100 ft<sup>2</sup> at 40 g. In contrast, eggshell powder exhibited an optimal YP response at intermediate concentration, peaking at 7.2 lb/100 ft<sup>2</sup> at 20 g, followed by a slight decrease at higher loadings. This non-linear behavior reflects a balance between electrochemical structuring and particle crowding effects. At low to intermediate eggshell concentrations,  $\text{CaCO}_3$  particles enhance clay-clay and clay-polymer interactions through edge-face electrostatic attraction (Villada et al. 2022), strengthening the structural network of the drilling fluid. At higher concentrations, excessive solid loading

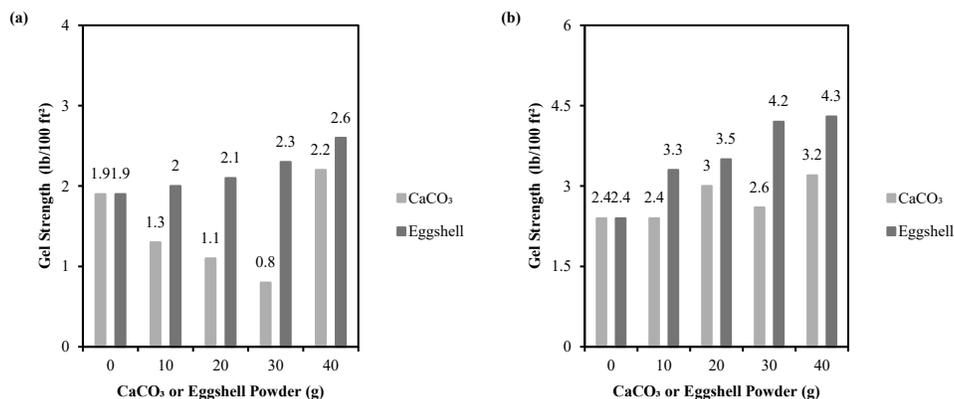
leads to particle crowding, which disrupts the continuous clay–polymer network and reduces the efficiency of stress transfer within the suspension, resulting in a reduced YP. This behavior is consistent with established carbonate–clay interaction models reported (Villada et al. 2022) for water-based drilling fluids and highlights the potential for rheological optimization using eggshell powder.



**Figure 3: Effect of varying quantities of commercial CaCO<sub>3</sub> and eggshell powder on WBM YP.**

### 3.2 Gel Strength Development

Gel strength measurements provide insight into the ability of drilling fluids to suspend cuttings during static conditions, which are common in geothermal drilling operations. Both additives increased gel strength with increasing concentration; however, eggshell powder exhibited a more pronounced and progressive gel development compared to commercial CaCO<sub>3</sub> (Fig. 4).



**Figure 4: Effect of varying quantities of commercial CaCO<sub>3</sub> and eggshell powder on WBM gel strength: (a) 10 s and (b) 10 min.**

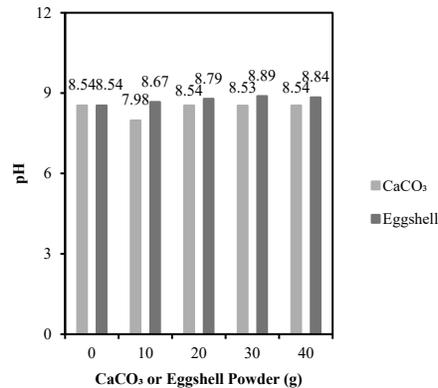
Commercial CaCO<sub>3</sub> increased the 10-minute gel strength moderately from 2.4 to 3.2 lb/100 ft<sup>2</sup>, indicating limited enhancement of the time-dependent structural network. In contrast, eggshell powder increased the 10-minute gel strength from 2.4 to 4.3 lb/100 ft<sup>2</sup>, demonstrating improved suspension capability under static conditions. Importantly, this increase occurred without abrupt spikes in initial gel strength, indicating favorable thixotropic behavior.

The enhanced gel development observed with eggshell powder is attributed to its heterogeneous surface chemistry and irregular particle morphology. Natural eggshell particles possess rough surfaces and trace organic functional groups (Kalaycı et al. 2025), which may promote weak, reversible interparticle interactions that develop progressively with time. These interactions may enhance network formation during static periods while allowing the structure to break down readily under shear. Such behavior is advantageous in geothermal drilling, where controlled gel buildup may be required to prevent cuttings sag during circulation interruptions without inducing excessive pump-start pressures.

### 3.3 Chemical Stability and Electrical Properties

The pH of all drilling fluid samples increased into a mildly alkaline range upon the addition of both commercial CaCO<sub>3</sub> and eggshell powder (Fig. 5). Commercial CaCO<sub>3</sub> stabilized near pH 8.5, while eggshell-modified fluids ranged from pH 8.5 to 8.8. This

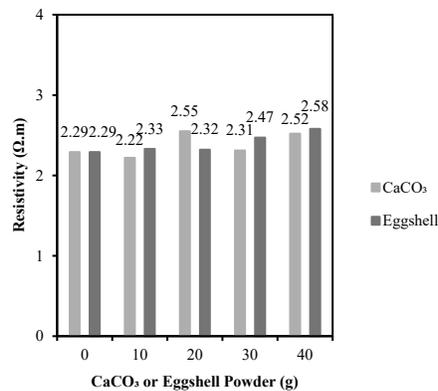
behavior reflects the buffering capacity of calcite, which maintains chemical equilibrium through the  $\text{Ca}^{2+}/\text{CO}_3^{2-}$  system (Sebonela et al. 2024). The slightly higher pH observed in eggshell-modified fluids may be attributed to trace alkaline components associated with residual shell matrix materials (Sebonela et al. 2024).



**Figure 5: Effect of varying quantities of commercial  $\text{CaCO}_3$  and eggshell powder on WBM pH.**

Maintaining a mildly alkaline pH is beneficial for water-based drilling fluids as it enhances bentonite hydration, stabilizes polymer additives, and reduces corrosion risks. The similar pH profiles observed for both additives confirm the chemical compatibility of eggshell-derived  $\text{CaCO}_3$  with bentonite–polymer systems.

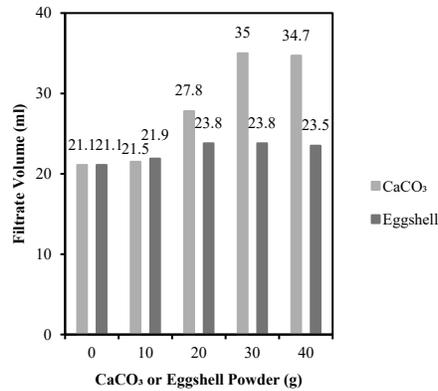
Electrical resistivity increased slightly with increasing additive concentration for both systems (Fig. 6). Commercial  $\text{CaCO}_3$  increased resistivity from 2.29 to 2.52  $\Omega \cdot \text{m}$ , while eggshell powder increased resistivity to 2.58  $\Omega \cdot \text{m}$  at the highest concentration. This trend is attributed primarily to increased solid content, which reduces the continuous conductive pathways within the fluid. The comparable resistivity behavior further confirms that eggshell powder does not introduce excessive ionic species or destabilize the chemical environment of the drilling fluid, supporting its suitability for geothermal applications.



**Figure 6: Effect of varying quantities of commercial  $\text{CaCO}_3$  and eggshell powder on WBM resistivity.**

### 3.4 Filtration Performance and Filter Cake Characteristics

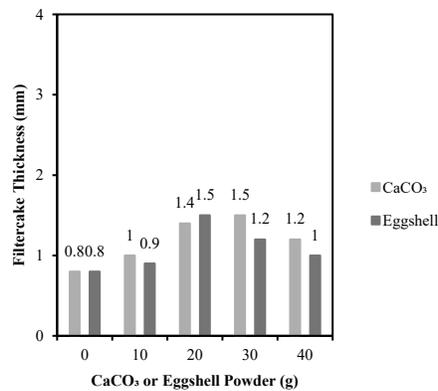
Filtration tests revealed notable differences between the two additives (Fig. 7). Commercial  $\text{CaCO}_3$  exhibited increasing filtrate volumes with increasing concentration, reaching approximately 35 ml before showing a slight reduction at the highest loading. This trend suggests delayed pore-bridging efficiency, particularly at lower and intermediate concentrations. In contrast, eggshell powder consistently limited filtrate volume to approximately 22–24 ml across all tested concentrations, demonstrating superior and more stable filtration control.



**Figure 7: Effect of varying quantities of commercial CaCO<sub>3</sub> and eggshell powder on WBM filtrate volume after a 30-min filtration test.**

The improved filtration performance of eggshell powder is attributed to differences in particle size distribution and morphology. Eggshell powder typically exhibits a broader particle size distribution and angular particle shapes, which enhance particle packing efficiency within the filter cake. According to particle packing and bridging theory (You et al. 2018), effective filtration control is achieved when particles of varying sizes rapidly seal pore throats and reduce cake permeability. The broader distribution of eggshell particles allows for multi-scale pore bridging, resulting in faster sealing and reduced fluid invasion.

Filter cake thickness measurements further support this mechanism (Fig. 8). Commercial CaCO<sub>3</sub> produced relatively thicker and less uniform filter cakes at lower and intermediate concentrations, with improved sealing observed only at higher loadings. In contrast, eggshell powder formed consistently thin and dense filter cakes across all concentrations, with thickness decreasing from 1.5 mm at 20 g to 1.0 mm at 40 g. Thin, low-permeability filter cakes are highly desirable in geothermal drilling as they minimize formation damage, reduce differential sticking risk, and limit filtrate invasion into geothermal reservoirs.



**Figure 8: Effect of varying quantities of commercial CaCO<sub>3</sub> and eggshell powder on the filter cake thickness formed by WBM after a 30-min filtration test.**

### 3.5 Implications for Geothermal Drilling

Waste eggshell powder demonstrated performance comparable to or exceeding that of commercial CaCO<sub>3</sub> in key drilling fluid functions, including density control, rheological stability, gel strength development, and filtration control. Table 1 consolidates the key rheological, chemical, and filtration parameters for drilling fluids formulated with commercial CaCO<sub>3</sub> and eggshell powder. Given its predominantly calcite CaCO<sub>3</sub> composition and the established thermal stability of CaCO<sub>3</sub>-based systems up to approximately 120 °C, the observed performance supports the applicability of eggshell powder in low- to medium-enthalpy geothermal drilling environments.

The use of eggshell-derived CaCO<sub>3</sub> offers a low-cost, environmentally sustainable alternative to mined commercial CaCO<sub>3</sub>, contributing to reduced material costs and lower environmental impact while maintaining drilling fluid performance. This aligns geothermal drilling practices with circular economy principles and sustainability objectives.

**Table 1. Comparative performance of commercial CaCO<sub>3</sub> and waste eggshell powder in water-based geothermal drilling fluid.**

Property	Commercial CaCO <sub>3</sub>	Eggshell Powder	Key Interpretation
Chemical composition	High-purity CaCO <sub>3</sub> (calcite)	~95% CaCO <sub>3</sub> (calcite)	Mineralogical equivalence supports substitution
Density contribution (ppg)	9.0 → 9.7 (0–40 g)	9.0 → 9.6 (0–40 g)	Comparable density control capability
PV (cP)	7.0 → 8.8	7.0 → 10.7	Eggshell shows slightly higher PV due to particle morphology
YP (lb/100 ft <sup>2</sup> )	6.6 → 8.5	6.6 → peak at 7.2 (20 g), then decreases	Eggshell exhibits optimal YP at intermediate concentration
10-s gel strength (lb/100 ft <sup>2</sup> )	1.9–2.2	1.9 → 2.6	Eggshell provides more consistent gel development
10-min gel strength (lb/100 ft <sup>2</sup> )	2.4 → 3.2	2.4 → 4.3	Improved static suspension for eggshell
pH range	8.54 → decreases to 7.98 (10 g), then stabilizes	8.54 → 8.89	Both provide mild alkaline buffering
Resistivity (Ω·m)	2.29 → 2.52	2.29 → 2.58	Comparable electrical behavior
API filtrate volume (30 min)	~21 → ~35 ml	~21 → ~24 ml	Eggshell shows superior fluid-loss control
Filter cake thickness (mm)	Decreases at high loading	0.8 → peak (1.5) → 1.0	Eggshell forms thin, low-permeability cakes
Sustainability	Mined, commercial	Waste-derived, circular	Eggshell significantly reduces the environmental footprint

#### 4. Conclusions and Future Perspective

This study evaluated waste eggshell powder as a sustainable replacement for commercial CaCO<sub>3</sub> in water-based drilling fluids for geothermal applications using standardized API RP 13B-1 testing. Finely ground eggshell powder (<125 μm) was directly compared with commercial CaCO<sub>3</sub> across key performance parameters, including density control, rheological behavior, gel strength development, chemical stability, electrical properties, and filtration performance.

The results demonstrate that eggshell powder provides density control comparable to commercial CaCO<sub>3</sub> over the investigated concentration range, confirming its suitability as a weighting and bridging additive in geothermal WBM systems. Rheological measurements showed acceptable PV values and an optimal YP at intermediate eggshell concentrations, indicating favorable flow behavior without excessive resistance to circulation. Gel strength development was more progressive and pronounced for eggshell-modified fluids, supporting improved cuttings suspension during static conditions common in geothermal drilling operations.

Filtration testing revealed that eggshell powder consistently reduced filtrate volume and formed thin, low-permeability filter cakes, matching or exceeding the performance of commercial CaCO<sub>3</sub>. These results indicate efficient pore-bridging and sealing behavior, which is critical for minimizing fluid invasion and formation damage in geothermal reservoirs. pH and electrical resistivity measurements confirmed chemical compatibility with bentonite–polymer systems and stable drilling fluid chemistry.

Considering the established thermal stability of CaCO<sub>3</sub>-based drilling fluids up to approximately 120 °C, the comparable performance of eggshell-derived CaCO<sub>3</sub> under API conditions suggests promising applicability in low- to medium-enthalpy geothermal wells. In addition to technical performance, the use of waste eggshell powder offers economic and environmental advantages by reducing dependence on mined materials and supporting circular resource utilization.

Future work should extend this evaluation to high-pressure, high-temperature conditions representative of high-enthalpy geothermal systems, including thermal aging and cyclic testing. Optimization of particle size distribution, blending strategies, and field-scale validation are also recommended to support broader adoption. Overall, waste eggshell powder represents a practical, low-cost, and environmentally sustainable additive for geothermal drilling fluids, aligned with the long-term sustainability objectives of geothermal energy development and the UN Sustainable Development Goals.

## References

- Al-Hameedi, A. T., Alkinani, H. H., Dunn-Norman, S. et al. 2020. Investigation Study of the Effectiveness of Eggshells Powder as a Multifunctional Eco-Friendly Additive in Water-Based Fluid. *Proc.*, 54th U.S. Rock Mechanics/Geomechanics Symposium.
- Basfar, S. and Elkatatny, S. 2023. Micronized calcium carbonate to enhance water-based drilling fluid properties (in eng). *Sci Rep* **13** (1): 18295.
- Ben Mahmud, Hisham, Mahmud, Walid, Ayanarappan, Rugen et al. 2020. Effect of Sodium Carbonate and Bicarbonate Contamination on the Rheological Properties of Water Based Mud. *International Journal of Engineering Research and Technology* **13**: 1019-1029.
- Collins, Ian R., Cano Floriano, Daniel, Paevskiy, Igor et al. 2024. Transition from oil & gas drilling fluids to geothermal drilling fluids. *Geoenery Science and Engineering* **233**: 212543. <https://www.sciencedirect.com/science/article/pii/S2949891023011302>.
- Gautron, J., Stapane, L., Le Roy, N. et al. 2021. Avian eggshell biomineralization: an update on its structure, mineralogy and protein tool kit. *BMC Molecular and Cell Biology* **22** (1): 11. <https://doi.org/10.1186/s12860-021-00350-0>.
- Iqbal, Raheel, Zubair, M., Pirzada, F. et al. 2019. An Experimental Study on the Performance of Calcium Carbonate Extracted from Eggshells as Weighting Agent in Drilling Fluid. *Engineering, Technology & Applied Science Research* **9**: 3859-3862.
- Kalaycı, Taner, Altuğ, Deniz Türköz, Kınaytürk, Neslihan Kaya et al. 2025. Characterization and potential usage of selected eggshell species. *Scientific Reports* **15** (1): 6241. <https://doi.org/10.1038/s41598-025-87786-y>.
- Kelany, Mohammed, Alsayed, Nabih A, and Nouh, Ahmed Z. 2025. A Review of the Effect of Drilling Technique and Fluid Type on Borehole Stability. *Journal of Petroleum and Mining Engineering*.
- Kruszewski, Michal and Wittig, Volker. 2018. Review of failure modes in supercritical geothermal drilling projects. *Geothermal Energy* **6** (1): 28. <https://doi.org/10.1186/s40517-018-0113-4>.
- Nascimento, Andreas, Mantegazini, Diunay Zuliani, Mathias, Mauro Hugo et al. 2025. O&G, Geothermal Systems, and Natural Hydrogen Well Drilling: Market Analysis and Review. *Energies* **18** (7): 1608. <https://www.mdpi.com/1996-1073/18/7/1608>.
- Nzerem, Petrus, Adejoh, Enyo, Ogolo, Oghenerume et al. 2020. Study of the Potential of Sodium Carbonate Extracted from Trona as a Drilling Fluid Additive. *International Journal of Engineering Research in Africa* **49**: 152-172.
- Onolemhemen, R., Olamigoke, Olugbenga, and Kaka, Abdul-Quadri Oladimeji. 2019. The suitability of egg shell and snail shell waste for pH and mud weight enhancement of water based drilling mud. *Petroleum and Coal* **61**: 371-376.
- Onyekpe, B. 2001. Investigation of the effects of carbonate contaminants on the rheological properties of drilling mud. *Industrial Lubrication and Tribology - INDUSTRIAL LUBR TRIBOLOGY* **53**: 108-112.
- Rasool, Muhammad Hammad, Zamir, Asif, Elraies, Khaled A. et al. 2022. Rheological characterization of potassium carbonate deep eutectic solvent (DES) based drilling mud. *Journal of Petroleum Exploration and Production Technology* **12** (7): 1785-1795. <https://doi.org/10.1007/s13202-021-01328-6>.
- Sebonela, Leon Karabo, Elephant, Dimphe Elvis, and Sithole, Nkanyiso Justice. 2024. Eggshells Improve Soil pH and P Availability in Sandy Loam and Sandy Clay Loamy Soil. *Agronomy* **14** (11): 2539. <https://www.mdpi.com/2073-4395/14/11/2539>.
- Shokry, Amir, Basfar, Salem, and Elkatatny, Salaheldin. 2024. Evaluation of using micronized saudi calcite in ilmenite-weighted water-based drilling fluid. *Scientific Reports* **14** (1): 12777. <https://doi.org/10.1038/s41598-024-63839-6>.
- Villada, Yurany, Busatto, Carlos, Casis, Natalia et al. 2022. Use of synthetic calcium carbonate particles as an additive in water-based drilling fluids. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* **652**: 129801. <https://www.sciencedirect.com/science/article/pii/S0927775722015564>.
- Vivas, Cesar and Salehi, Saeed. 2021. Rheological investigation of effect of high temperature on geothermal drilling fluids additives and lost circulation materials. *Geothermics* **96**: 102219. <https://www.sciencedirect.com/science/article/pii/S0375650521001760>.

- White, Craig C., Chesters, Adrian P., Ivan, Catalin D. et al. 2003. Aphron-based Drilling Fluid: Novel Technology for Drilling Depleted Formations in the North Sea. *Proc., SPE/IADC Drilling Conference*. <https://doi.org/10.2118/79840-MS>.
- You, Lijun, Tan, Qigui, Kang, Yili et al. 2018. Optimizing the particle size distribution of drill-in fluids based on fractal characteristics of porous media and solid particles. *Journal of Petroleum Science and Engineering* **171**: 1223-1231. <https://www.sciencedirect.com/science/article/pii/S0920410518307174>.
- Zamir, Asif, Rasool, Muhammad, Elraies, Khaled et al. 2021. Potassium carbonate based deep eutectic solvent (DES) as a potential drilling fluid additive in deep water drilling applications. *Petroleum Science and Technology* **39**.
- Zima, Grzegorz, Błaż, Sławomir, and Jasiński, Bartłomiej. 2025. Analysis of the Possibilities of Using an Organic Bridging Material for Sealing the Borehole Wall. *Applied Sciences* **15** (21): 11601. <https://www.mdpi.com/2076-3417/15/21/11601>.