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The Impact of Weighting Agents on Drilling Fluid Properties

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تأثير المواد المُثقِّلة على خصائص سائل الحفر

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Abstract:
Drilling fluid serves as the critical backbone of oil well drilling operations, playing a vital role in primary well control, lifting rock cuttings to the surface, and cooling both the drill pipe and bit. This research evaluates the direct impact of weighting materials on the properties of drilling fluids, while also addressing the economic factors involved in selecting the most suitable additives. A comprehensive review of previous literature was conducted to analyze the most effective materials, identify the environmental and health hazards associated with certain toxic additives, and compare their overall influence on fluid characteristics. Additionally, practical laboratory experiments were performed to investigate how variations in fluid density affect rheological properties and sand content. These tests were carried out using standard laboratory equipment, including a mud balance, Fann V-G meter, Marsh funnel, and a retort kit for solid content analysis.

Keywords: Yield Point, Gel strength, density, apparent viscosity, Plastic viscosity.

الملخص
تُعد سوائل الحفر الركيزة الأساسية لعمليات حفر آبار النفط، إذ تؤدي دوراً حيوياً في التحكم الأولي في البئر، ونقل نواتج الحفر الصخرية إلى السطح، وتبريد كل من أنابيب الحفر ورأس الحفر. يقيّم هذا البحث التأثير المباشر لمواد زيادة الوزن على خصائص سوائل الحفر، مع تناول الجوانب الاقتصادية المتعلقة باختيار الإضافات الأنسب. وقد أُجريت مراجعة شاملة للدراسات السابقة لتحليل المواد الأكثر فعالية، وتحديد المخاطر البيئية والصحية المرتبطة ببعض الإضافات السامة، ومقارنة تأثيرها العام على خصائص السائل. وبالإضافة إلى ذلك، أُجريت تجارب مخبرية عملية لدراسة كيفية تأثير التغيرات في كثافة السائل على الخصائص الريولوجية ومحتوى الرمل؛ حيث نُفذت هذه الاختبارات باستخدام معدات مخبرية قياسية، شملت ميزان الطين، وجهاز قياس اللزوجة (*Fann V-G*)، وقمع مارش، وجهاز التقطير (*Retort kit*) لتحليل المحتوى الصلب.

الكلمات المفتاحية: نقطة الخضوع، قوة الهلام، الكثافة، اللزوجة الظاهرية، اللزوجة البلاستيكية.

Introduction
The successful completion of an oil well is intrinsically linked to the seamless execution of casing and cementing operations. These critical processes rely on maintaining an ideal wellbore condition, a task for which drilling fluid is fundamentally responsible. Beyond its role in borehole preparation such as ensuring effective cleaning and optimizing fluid properties

drilling fluid is essential for the cementing phase, as it serves as the medium for displacing cement slurry to its designated location.
The history of drilling fluids dates back to the dawn of the twentieth century. In 1900, the first well drilled by the rotary method in Texas utilized a simple mixture of water and native clay from the penetrated formations. At that stage, the fluid's primary purpose was merely to clean the well bottom and transport rock cuttings to the surface. However, the reliance on such rudimentary fluids led to significant operational challenges, including well blowouts caused by inadequate subsurface pressure control, the inability to regulate viscosity, and the failure to maintain fluid properties when drilling through non-clay formations.
These challenges underscored the urgent need for detailed physicochemical studies and the formulation of drilling fluids with precise, controllable properties. This necessity drove the industry toward advanced research, resulting in the development of sophisticated fluid systems. Researchers replaced simple water-clay mixtures with stable, heat-resistant colloidal materials that remain resilient against contamination. Furthermore, the introduction of oil-based muds, emulsifiers, air, and foam systems revolutionized drilling efficiency. Consequently, the rapid evolution of drilling fluid technology has significantly mitigated common drilling hazards, such as pipe sticking and blowouts, thereby ensuring the success of modern rotary drilling operations [1].
This research focuses on the impact of weighting materials on drilling mud, specifically addressing how these additives influence critical properties such as density, viscosity, rheological characteristics, and filtration. By controlling the density to stay slightly above formation pressure, weighting materials play a pivotal role in preventing kicks and blowouts. Moreover, this study investigates their influence on the fluid's ability to transport cuttings and mitigate pipe-sticking risks. Finally, this project presents a comprehensive experimental analysis, using barite to demonstrate the relationship between the concentration of weighting materials and the resultant changes in the fluid's physical properties through detailed performance curves.

The theoretical framework

1. The Characteristics of Drilling Fluid

The performance of a drilling fluid is determined by several critical physicochemical properties, which must be monitored and maintained throughout the drilling process:
Density: Measured using a mud balance and expressed in g/cm^3. Density is paramount as it directly dictates the hydrostatic pressure of the drilling fluid column, which is essential for well control. Insufficient density poses a risk of well blowouts, whereas excessively high density can induce formation fracturing and subsequent circulation loss. [10].
Viscosity: This represents the fluid's resistance to flow. In field operations, relative viscosity is typically measured in seconds using a Marsh funnel. For a more precise, scientific analysis of rheological properties, the Fann V-G meter is utilized, with viscosity expressed in centipoise (Cp).
Gel Strength and Yield Point: The yield point arises from cohesive forces between particles, influenced by surface electrical charges. These forces depend on the type and concentration of solids, as well as ion concentration in the liquid phase. Elevated yield points may result from the mechanical grinding of solids by the drill bit or pipe, increased solid content, or contamination by substances such as salt and gypsum, which promote particle flocculation. Conversely, an insufficient concentration of thinning agents—which neutralize attractive forces can also lead to instability [6].
Plastic Viscosity: This parameter is a function of the concentration, size, and shape of solid particles, as well as the viscosity of the base liquid phase. Plastic viscosity generally increases with a higher volume of fine solid particles, which increases the specific surface area.

Conversely, it decreases with lower solid content or the presence of coarser particles due to reduced specific surface area [7].
pH: Defined as the negative logarithm of the hydrogen ion concentration, pH is a critical indicator of the fluid's chemical balance and its impact on additives.
Filtration: This refers to the migration of the liquid phase of the drilling mud into permeable formations under differential pressure, resulting in the formation of a filter cake on the wellbore wall. This property is evaluated using a filter press device.

2. Weighting Materials: Barite

To manage formation pressures effectively, the density of drilling mud is adjusted using weighting agents. Among these, Barite is the industry-standard, naturally occurring mineral used for this purpose.
Barite ($BaSO_4$) is a barium-based mineral characterized by a high specific gravity of approximately 4.50 g/cm³. Its chemical inertness and high density make it an ideal additive for formulating drilling muds. Beyond its primary function of increasing hydrostatic pressure to counteract high-pressure zones, Barite's relative softness acts as a lubricant, which helps prevent damage to drilling tools. The American Petroleum Institute (API) has established rigorous technical specifications for the quality and use of Barite in drilling fluid formulations [2] (Table 1).

Table (1) Physical Properties of Barite

Physical Properties of Barite	
Huss Chemical Classification	Sulfate
Color	Colorless, white, light blue, light yellow, light،red, light green
Mohs Hardness	25 to 3.5
Specific Gravity	4.5 g/cm3
Chemical Composition	Barium sulfate, BaSOA
Uses	Drilling mud; high-densit

2. Calcium Carbonate

Calcium carbonate is recognized as one of the most versatile minerals utilized by mankind, with extensive applications ranging from water-based drilling operations to medical industries. In nature, this mineral primarily appears in the forms of gypsum, limestone, and marble. Depending on specific requirements, it is supplied and exported globally in various physical forms, mesh sizes, and specifications.
Thermally, calcium carbonate undergoes decomposition at 900°C. Within the petroleum industry, it serves as a critical component in drilling muds, where it functions as both a bridging agent and a weighting material in oil-based, water-based, workover, and completion fluids. Furthermore, its use is essential for preventing fluid invasion into permeable zones and mitigating circulation losses during drilling, workover, and completion activities. Notably, calcium carbonate is compatible with a broad spectrum of drilling fluid systems, both aqueous and non-aqueous (Table 2) [2]. [9].

Table (2) Physical Properties of Caco3

Physical Properties of Caco3	
Huss Chemical Classification	Carbonate
Color	white powder
Specific Gravity	2.711g/cm3

Chemical Composition	Calcium carbonate caco3
Uses	Drilling mud; high-density

3. Hematite

Hematite is a metallic form of iron oxide (Fe_2O_3) characterized by its high density. In drilling operations, it serves as an effective additive to increase the density of drilling muds. It is utilized to achieve fluid weights exceeding 20 ppg in water-based drilling systems, and up to 19 ppg in oil-based drilling fluids. Hematite possesses a specific gravity greater than 5.05 (Table 3) [2].

Table (3) Physical Properties of Hematite

Physical Properties of Himtite	
Classification	Oxides
Color	Metallic grey, dull to bright "rust-red" in earthy, compact, fine-grained material, steel-grey to black in crystals and massively crystalline ores
Specific Gravity	5.05g/cm3
Composition	Fe2O3
Uses	Drilling mud; high-density

Effects of Weighting Materials on Drilling Fluid Properties

The introduction of weighting materials significantly alters the rheological and physical characteristics of drilling fluids. These effects are summarized below:

1. **Yield Point (YP):** The yield point represents the fluid's resistance to flow caused by electrochemical attractive forces between solid particles. As inert weighting solids are introduced into the system, particles are forced closer together, thereby increasing these inter-particle attractive forces and consequently raising the yield point.
2. **Plastic Viscosity (PV):** Plastic viscosity, which reflects flow resistance due to mechanical friction between solid particles and the surrounding liquid, increases with the addition of weighting materials. If these solids exceed the limits specified in the drilling program, they become undesirable; however, the viscosity can be managed through dilution or mechanical removal.
3. **Gel Strength:** Gel strength refers to the attractive forces within the fluid under static conditions. The addition of solid materials increases these forces. For fluids with a density of 1.67 kg/cm^3 or higher, maintaining low gel strength is preferable, as the fluid density is sufficient to transport rock cuttings. Conversely, in lower-density fluids, higher gel strength is required to prevent rapid cuttings deposition; for instance, a density of 1.14 kg/cm^3 typically requires a gel strength around 4 lb/100ft^2, whereas at a density of 2.16 kg/cm^3, the value should ideally approach zero.
4. **Mud Cake and Fluid Loss:** The addition of weighting agents increases mud cake thickness, which effectively seals the wellbore wall. This layer acts as a barrier, preventing excessive mud invasion into permeable formations and minimizing circulation losses in low-pressure zones.
5. **Funnel Viscosity:** Weighting additives typically induce a slight increase in funnel viscosity, primarily due to the presence of impurities associated with these materials.

Equations Related to Weighting

1. Hydrostatic Pressure

Hydrostatic pressure (P_H) is the force exerted by the weight of the fluid column on the wellbore, which is critical for controlling formation fluids and preventing collapse. It is a function of fluid density ($\boldsymbol{\rho}$) and True Vertical Depth (TVD). In the U.S. Oilfield unit system, the relationship is expressed as:

$$\boldsymbol{P} = \boldsymbol{\rho x H x}\ \mathbf{0.052} \ \ldots\ldots\ldots\ldots\ldots (1)$$

P-hydrostatic pressure (Ib/in2)
ρ-Mud weight(lb/gal)
H- the True Vertical Depth(ft)
Conversion factor 0.052 = 12 in/ft 231 in3/gal
Metric:

$$\boldsymbol{P} = \boldsymbol{\rho\ x H}/\mathbf{10} \ \ldots\ldots\ldots\ldots\ldots\ldots \ \ldots. (2)$$

P-hydrostatic pressure(bar)
ρ-Mud weight(kg/l)
H- the True Vertical Depth(m)

The density of drilling fluid must be more than the hydrostatic pressure in the range of (0.25-0.41) Ib/gal or (0.03-0.05)g/cc to balance the fluid pressure in the drilled formation

2. Calculate the amount of barite needed for weighting

Calculated from the following equations [1]
U.S. units:

$$\boldsymbol{Barite}(\boldsymbol{Ib}/\boldsymbol{bbl}) = \mathbf{1470}\ (\boldsymbol{\rho}\mathbf{2} - \boldsymbol{\rho}\mathbf{1})/\boldsymbol{\rho}(\boldsymbol{barite}) - \boldsymbol{\rho}\mathbf{2} \ \ldots\ldots\ldots\ldots (3)$$

Using (lb/gal) for density.
Density of barite=35(Ib/gal)
ρ2- The required mud density
ρ1- The original mud density
metric units:

$$\boldsymbol{Barite}(\boldsymbol{kg}/\boldsymbol{m}\mathbf{3}) = \mathbf{4200}\ (\boldsymbol{\rho}\mathbf{2} - \boldsymbol{\rho}\mathbf{1})/\ \boldsymbol{\rho}(\boldsymbol{barite}) - \boldsymbol{\rho}\mathbf{2} \ \ldots\ldots\ldots\ldots (4)$$

Using (kg/l) for density
Density of barite=4.2(kg/l)
ρ2- The required mud density
ρ1- The original mud density

Materials and Methods

The experimental program utilized a sample of KCl-based drilling fluid obtained from field operations, which was subsequently weighted with barite. A series of laboratory tests were conducted to evaluate the fluid's rheological properties, sand content, and filtration characteristics.

Laboratory Equipment and Testing Procedures

1. Filtration and Mud Cake Thickness Measurement To determine the filtration properties and the resulting mud cake thickness, a **Filter Press** device was employed. The test procedure involves applying a pressure of 100 psi to a drilling fluid sample within the filter press cell for a duration of 30 minutes at ambient temperature. Alternatively, a 7.5-minute testing period may be used, with the resulting filtrate volume multiplied by two to estimate the 30-minute value.

The procedure begins by placing the drilling fluid sample into the cell, ensuring proper filter paper placement, and sealing the unit before applying the required pressure. Following the filtration period, the device is disassembled, and the mud cake thickness is measured after careful washing (Figure 1).

Figure (1): filter press.

2. Measuring Sand Content in Drilling Fluid

The sand content of the drilling fluid is determined using a standard sand content kit, which includes a 200-mesh sieve, a funnel, and a graduated glass measuring tube. The tube is calibrated to provide a direct reading of the sand percentage, ranging from 0% to 20%. The testing procedure is performed as follows:

1. **Sample Preparation:** Fill the graduated glass tube with the drilling fluid sample up to the designated "mud" mark.
2. **Dilution and Filtration:** Add water to the tube up to the "water" mark, seal the tube securely, and shake it vigorously. Subsequently, pour the mixture onto the 200-mesh sieve.
3. **Rinsing:** Add an additional amount of water to the tube, shake again, and pour the contents onto the sieve to ensure the complete transfer of solids.
4. **Measurement:** Secure the funnel onto the top of the graduated tube. Wash the sand particles retained on the sieve into the tube using the funnel. Allow the sand to settle at the bottom of the tube, and directly read the sand content percentage from the graduated scale (Figure 2).

Figure (2): Sand ratio measuring device

3. Marsh Funnel Viscosity Measurement

The Marsh funnel (Figure 3) is a standard field instrument used to determine the relative viscosity of drilling fluids. The testing procedure is performed as follows:

- **Preparation:** Hold the funnel vertically and block the orifice tip with a finger.
- **Filling:** Pour the drilling fluid through the funnel's sieve until the fluid level reaches the screen, which corresponds to a volume of 1500 cm^3.
- **Measurement:** While holding the funnel by the handle, release the orifice tip and simultaneously start a stopwatch.
- **Recording:** Stop the watch precisely when 946 cm^3 (equivalent to one-quarter of a gallon) of fluid has been collected in a graduated cup. The recorded time in seconds represents the Marsh funnel viscosity of the mud.

Note: Although alternative testing variants exist such as using different volumes (e.g., 500 cm^3 or 1000 cm^3) or measuring the time required for the funnel to empty the aforementioned procedure is the recognized standard. If any variation is utilized, the specific volumes of the mud poured into the funnel and collected in the cup must be explicitly reported (Figure 3) [4].

Figure (3): marsh funnel

4. Measurement of Rheological Properties

The rheological properties of drilling fluids, specifically Plastic Viscosity (PV) and Yield Point (YP), are evaluated using the Fann V-G meter (Figure 4). The testing procedure is performed as follows:

1. **Sample Preparation:** Fill the sample container with the drilling fluid to the specified limit and immerse the rotor of the device into the fluid up to the designated mark.
2. **High-Speed Measurement:** Operate the device at a rotational speed of 600 revolutions per minute (rpm). Allow the pointer to stabilize and record the maximum deflection as the $Ø_{600}$ reading.
3. **Low-Speed Measurement:** Adjust the rotational speed to 300 rpm. Allow the pointer to stabilize and record the maximum deflection as the $Ø_{300}$ reading (Figure 4).

$PV = Ø_{600} – Ø_{300}$ CPS

$AV = Ø_{600} / 2$ CPS

$YP = Ø_{300} – PV$ lb/100ft2

Gel Strength Measurement:

Gel strength represents the attractive forces within the drilling fluid under static conditions and is measured in two stages using the same Fann V-G meter (Figure 4):

- **10-Second Gel Strength:** After recording the $Ø_{300}$ and $Ø_{600}$ readings, operate the device at 600 rpm for 15 seconds. Then, set the device to 3 rpm and stop the motor.

Allow the fluid to remain static for 10 seconds. Finally, start the motor at 3 rpm and record the maximum deflection of the pointer as the 10-second gel strength (lb/100 ft²).
- **10-Minute Gel Strength:** After the initial measurement, stop the device and allow the fluid to remain undisturbed for 10 minutes. Following this static period, start the motor at 3 rpm and record the maximum deflection of the pointer as the 10-minute gel strength (lb/100 ft²) (Figure 4)

Figure (4): Fann V-G meter

5. Drilling Fluid Density Measurement

The density (weight) of the drilling fluid is measured in the field using a Mud Balance (Figure 5). The procedure for determining the fluid density is as follows:

1. **Preparation:** Fill the mud balance cup with the drilling fluid sample.
2. **Sealing:** Place the lid securely on the cup and ensure that the excess fluid is expelled through the vent hole at the top. Clean the exterior of the cup to remove any residual fluid.
3. **Balancing:** Place the beam on the base support and adjust the sliding weight along the graduated arm until the spirit level indicates that the beam is in a perfectly balanced (horizontal) position.
4. **Reading:** Once balanced, record the density reading directly from the scale. The mud balance typically provides readings in multiple units, including grams per cubic centimeter (gm/cc), pounds per cubic foot (lb/ft³), and pounds per gallon (lb/gal) (Figure 5).
5.

Figure (5): mud balance

Procedures to Address Problems Caused by the Impact of Weighted Materials:
The use of weighting materials can affect the rheological properties of the drilling fluid. These issues are addressed as follows:

- **Treatment of Increased Yield Point:** The yield point is managed by adding chemical thinners such as lignosulfonates, lignites, tannathin, or phosphates. Alternatively, water dilution may be used, although this is often considered impractical as it may negatively alter mud specifications [13].
- **Treatment of Increased Plastic Viscosity:** Plastic viscosity is reduced by eliminating unwanted fine solids from the drilling fluid through mechanical separation methods [14]. [15].
- **Treatment of Increased Gel Strength:** High gel strength is treated using the same chemical thinning techniques applied for the reduction of the yield point [16].
- **Reduction of Filtration Volume:** Weighting materials contribute to the construction of a thin, low-permeability mud cake, which effectively reduces fluid loss into the formation [16].

RESULTS

A sample of KCl-weighted mud containing barite was collected from the active drilling rig, and laboratory tests were conducted using standard drilling fluid testing equipment to evaluate its properties.

1. Relationship Between Density and Yield Point

It is observed that as the mud density increases, the yield point value also increases. This phenomenon is attributed to the reduced distances between the solid particles, which leads to an increase in the electrochemical attraction forces between them (Figure 6).

Figure (6): The relationship between density and yield point

2. Relationship Between Density and Plastic Viscosity

It was observed that as the mud density increases, the plastic viscosity also increases gradually. This trend is a result of the higher concentration of solids and the reduced distance between particles, which leads to increased mechanical friction within the fluid (Figure 7).

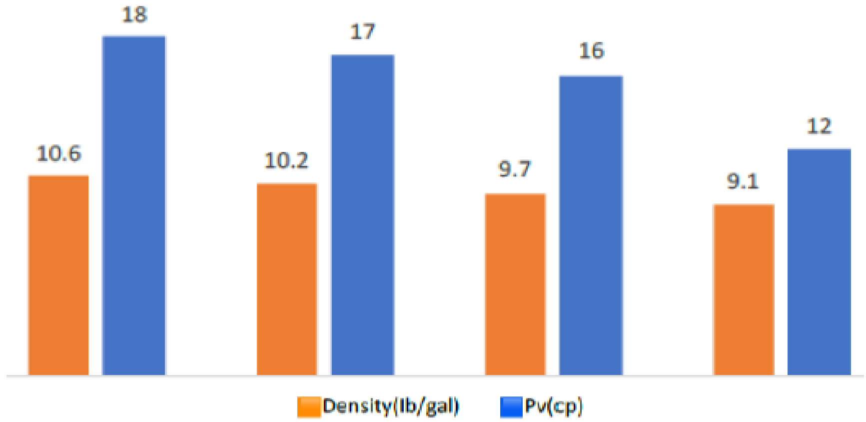


Figure (7): The relationship between density and plastic viscosity

3. Relationship Between Density and Apparent Viscosity
It is observed that the apparent viscosity increases proportionally with the increase in density, primarily due to the corresponding rise in both plastic viscosity and yield point (Figure 8).

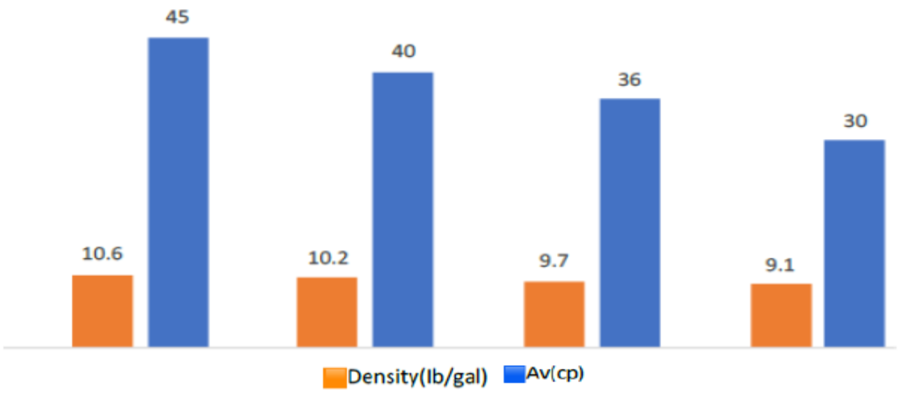
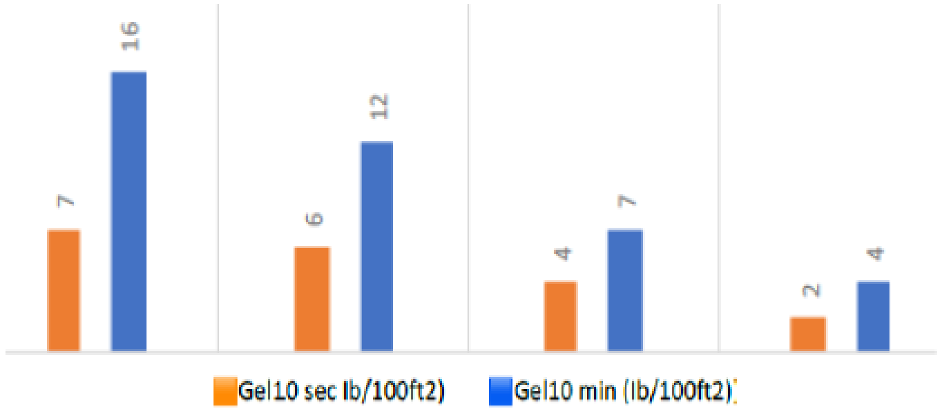


Figure (8): The relationship between density and apparent viscosity

4. Relationship Between Density and Gel Strength
It is observed that the gel strength increases with an increase in mud density. This is due to the higher concentration of solids, which enhances the electrochemical bonding forces between particles. This trend is evident as the density increases gradually (e.g., 9.1, 9.7, 10.2, and 10.6 lb/gal) (Figure 9).



Figer (9): The relationship between density and gel strength

5. Relationship Between Density and Sand Content

It was observed that as the mud density increases gradually (9.1, 9.7, 10.2, and 10.6 lb/gal), the sand content within the drilling fluid also increases accordingly (Table 4).

Table (4): The relationship between density and sand content

Density(ppg)	Sand content %
9.2	3
9.8	3.4
10.3	3.6
10.7	3.7

6. Relationship Between Density and Filtration

It was observed that as the mud density increases gradually (9.1, 9.7, 10.2, and 10.6 lb/gal), the filtration rate (fluid loss) decreases accordingly (Table 5).

Table (5): The relationship between density and filtration

Density(ppg)	Filtration velum (cc)
9.2	13.3
9.7	9.1
10.1	6.2
10.5	4.1

7. Effect of Barite on Increasing Drilling Mud Density

The addition of barite to the drilling fluid significantly impacts its density. In this experiment, four tons of barite were added sequentially to a drilling fluid sample initially having a density of 1.18 g/cc. The resulting changes in density were calculated mathematically using Equation (2.4) and are presented in Table 6.

Table (6): The effect of barite on increasing the density of drilling mud

Initial density(g/cc)	Added barite(ton)	Final density(g/cc)
1.16	1	1.22
1.22	2	1.24
1.26	3	1.25
1.27	4	1.27

CONCLUSION

The findings of this research regarding the impact of various weighting materials on drilling fluid properties lead to the following conclusions:

1. **Optimal Performance:** Barite demonstrated the most favorable rheological properties and the most effective filtration control compared to other evaluated weighting materials.
2. **Mud Cake Quality:** Barite produced a thinner and more uniform mud cake, which is critical for borehole stability.
3. **Application Specifics:** Calcium carbonate proved most effective for operations in depleted or high-porosity zones, whereas galena, despite its weighting efficiency, requires strict safety protocols due to its toxicity.

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4. **Rheological Synergy:** The addition of weighting materials increases particle interaction, leading to higher plastic viscosity, apparent viscosity, yield point, and gel strength.
5. **Filtration Control:** Higher density fluids, characterized by higher yield points and lower plastic viscosity, effectively mitigate fluid loss.

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